Attenuation of visible solar radiation in the upper water column: A model based on IOPs

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Abstract - **For many oceanic studies, it is required to know the distribution of visible solar radiation (E_{PAR}) in the upper water column. One way to reach this is by remote sensing. This includes two components: First, E_{PAR} at surface is calculated based on atmosphere properties along with the position of the Sun. Second, the vertical attenuation of E_{PAR} (K_{PAR}) is derived from products of ocean-color remote sensing. Currently, K_{PAR} is estimated based on chlorophyll concentration ([C]) from ocean color. This kind of approach works well for waters where all optical properties can be adequately described by values of [C], but will result in large uncertainties for coastal waters where [C] alone cannot accurately describe the optical properties. In this paper, we present an innovative model that describes K_{PAR} as a function of water's inherent optical properties (IOP).**

I. INTRODUCTION

Solar radiation in the visible domain (E_{PAR}(350 – 700 nm), measured by downwelling irradiance in this text) encompasses the wavelengths shorter than 700 nm. The pioneer study of *Zaneveld et al.* [1] and subsequent studies [2-4] have demonstrated that the vertical penetration of E_{PAR} plays an important role in heat transfer of the upper water column. E_{PAR} at surface can now be adequately estimated from satellite measurements of atmosphere properties. It requires information of water's optical properties to determine the vertical attenuation of E_{PAR} (K_{PAR}) with depth. Historical measurements have shown that K_{PAR} not only changes horizontally with constituents in the water [1, 5], but also changes with depth for any water [6, 7].

To represent the steeper than exponential reduction of E_{PAR} with depth, multiple exponential terms [6, 7] were usually adopted, with an attenuation coefficient (or attenuation depth) assigned for each term. These attenuation coefficients are kept vertically constant, but horizontally vary with *Jerlov* [5] water types. Recently, simple and explicit models have been developed to incorporate satellite-derived chlorophyll concentrations ([C]) into the description of the attenuation of E_{PAR}. When [C] values are provided via satellite observations of ocean color [8, 9], the partition factors and attenuation coefficients of the terms could be calculated [4].

Such kind of approach works for Case-1 waters – where all optical properties are determined by [C] alone (with solar zenith angle explicitly or implicitly included) [10, 11]. For non-Case-1 waters, uncertainties arise due to that it is not a constant relationship between [C] and optical properties. To avoid such limitations associated with [C]-based models, another approach is to describe the vertical transmittance of E_{PAR} using water's optical properties [12, 13]. Following this strategy, and because that water's absorption (a) and backscattering coefficients (b_b) can be adequately derived from ocean-color remote sensing [14-16], we developed a model to describe the vertical transmittance of E_{PAR} using values of a and b_b.

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II. *Hydrolight* SIMULATED $K_{PAR}(z)$

As in earlier studies [17, 18], we used *HydroLight* [19] to get the necessary data sets: $K_{PAR}(z)$, and a and b_b. Unlike the simulations in *Ohlmann and Siegel* [18] where water's IOPs were determined by [C] only, IOPs in our simulations were simulated with varying [C] and independently varying CDOM and suspended sediments, as described in *Lee et al.* [14] and *IOCCG-OCAG* [20]. Later, $K_{PAR}(z)$ is modeled as a function of a, b_b and z. Numerous descriptions can be found regarding simulations by *HydroLight*. [19, 21-23]. The following summarizes the input settings carried out in this study.

The downwelling irradiance at sea surface from the Sun and sky is simulated by the spectral model of *Gregg and Carder* [24]. a and b_b values at 440 nm varied from 0.02 to 1.9 m^{-1} and 0.002 to 0.115 m^{-1}, respectively, and kept vertically constant. The wavelengths are in a range of 350 – 700 nm with a 10-nm spectral resolution. Five depths (excluding 0 m) were selected for each *HydroLight* run, with depths spread within and beyond the euphotic zone [25]. No bottom reflectance and inelastic scatterings (such as Raman scattering) are included in this study.

III. MODELING OF $K_{PAR}(z)$

With $E_{PAR}(z)$ simulated by *HydroLight* , $K_{PAR}(z)$ is calculated

$$K_{PAR}(z) = \frac{1}{z}\ln\left(\frac{E_{PAR}(0^-)}{E_{PAR}(z)}\right). \quad (1)$$

Figure 1 presents a few examples of $K_{PAR}(z)$. Clearly, $K_{PAR}(z)$ differs significantly for varying water properties. Also, consistent with earlier measurements, subsurface $K_{PAR}(z)$ changes a lot even for vertically homogeneous waters. This change is due to that water molecules absorb strongly in the longer wavelengths (large absorption coefficients). After photons pass through the subsurface layer (say 3 meters), the absorption is happened in the shorter wavelengths, where absorption coefficients are generally smaller, especially for oceanic waters.

For each vertical variation of $K_{PAR}(z)$, it is found that this vertical change could be modeled as,

$$K_{PAR}(IOP,z) = K_1(IOP) + \frac{K_2(IOP)}{(1+z)^{0.5}}. \quad (2)$$

Here K_1 is for the asymptotic value at greater depths, with K_2 more important to the subsurface K_{PAR} value. IOP here represents different combinations of absorption and backscattering coefficients. The dotted lines in Figure 1 show Eq.2 modeled $K_{PAR}(z)$ for those examples. Figure 2 presents the result of *HydroLight* $K_{PAR}(z)$ versus Eq.2-modeled $K_{PAR}(z)$, with the Sun at 30° from zenith. Apparently the modeled $K_{PAR}(z)$ matches the Hydrolight $K_{PAR}(z)$ very well (the average error is 2.2%, with maximum error of is 6.4%). Such results clearly demonstrate that Eq.2 is adequate to describe the vertical change of $K_{PAR}(z)$.

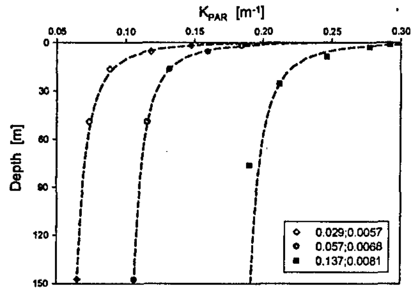

Figure 1. Examples of $K_{PAR}(z)$ for different water properties. The numbers in the box are values of $a(490)$ (left) and $b_b(490)$ (right). Symbol represents $K_{PAR}(z)$ from *HydroLight* simulations, while dotted lines are models from Eq.2.

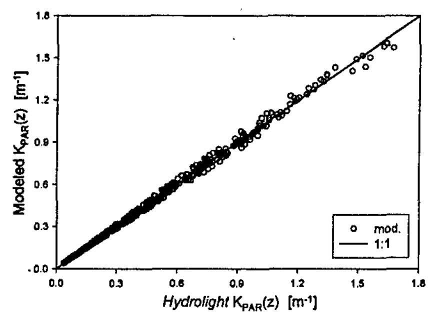

Figure 2. $K_{PAR}(z)$ from model (Eq.2) compared with $K_{PAR}(z)$ from *HydroLight* (30° solar zenith angle), indicating that $K_{PAR}(z)$ can be well described by Eq.2 with two parameters.

To apply IOP distributions obtained from satellite observation of water color, how $K_{1,2}$ vary with IOP needs to be known. For the $K_{PAR}(z)$ data with the Sun at 30° from zenith, it is found that K_1 and K_2 could be well modeled with IOPs at one wavelength *Zaneveld et al.* [12] *Barnard et al.* [13]:

absorption and backscattering coefficients at 490 nm, i.e.,

$$K_1(IOP) = \chi_0 + \chi_1 (a(490))^{0.5} + \chi_2 b_b(490), \quad (3a)$$

$$K_2(IOP) = \varsigma_0 + \varsigma_1 a(490) + \varsigma_2 b_b(490). \quad (3b)$$

$\chi_{0,1,2}$ and $\varsigma_{0,1,2}$ are model coefficients.

Since $K_{PAR}(z)$ also varies with solar altitude, we carried out *HydroLight* simulations with the Sun at 10° and 60° from zenith in order to include solar zenith angle into the model. From these simulations, we got

$$K_1(IOP,\theta_a) = [\chi_0 + \chi_1 (a(490))^{0.5} + \chi_2 b_b(490)](1 + \alpha_0 \sin(\theta_a)), \quad (4a)$$

$$K_2(IOP,\theta_a) = [\varsigma_0 + \varsigma_1 a(490) + \varsigma_2 b_b(490)](\alpha_1 + \alpha_2 \cos(\theta_a)). \quad (4b)$$

Here θ_a is the solar zenith angle above the surface. Now we got a model that can describe the vertical distribution of E_{PAR} for different IOPs, depth, and sun angle as

$$T(IOP,z,\theta_a) = \frac{E_{PAR}(z)}{E_{PAR}(0^-)} = e^{-K_{PAR}(IOP,z,\theta_a)z}. \quad (5)$$

In this model, there are nine model coefficients: $\chi_{0,1,2}$, $\varsigma_{0,1,2}$, and $\alpha_{0,1,2}$. To derive their values, T values from Eq.5 were fit against T values from *HydroLight* simulations with the model coefficients derived by least-square curve fitting [4, 18]. Values of derived $\chi_{0,1,2}$, $\varsigma_{0,1,2}$, and $\alpha_{0,1,2}$ are provided in Table 1. Figure 3 presents Eq.5 modeled $T(IOP,z,\theta_a)$ versus $T(IOP,z,\theta_a)$ determined from *HydroLight* simulations. For those T values (limiting to the range of ~0.001 to 0.8), bigger errors happened at $T < 0.003$, where the effects of E_{PAR} on heat transfer and photosynthesis in the water column are small. For $T > 0.003$, the average error is ~9%. These results indicate that the simple optical-property-based model (Eq.5) is adequate for describing the vertical profile of $E_{PAR}(z)$ for different waters.

IV. SUMMARY

In this study, an innovative model is developed for describing the vertical transmittance of visible solar radiation (E_{PAR}(350 - 700 nm), measured by downwelling irradiance in this study) in the upper layer of the oceans. Different from the traditional approaches, one exponential term is used for the vertical distribution of E_{PAR}. Its attenuation coefficient ($K_{PAR}(z)$), however, is modeled as a function of depth instead of vertically constant. $K_{PAR}(z)$ is also modeled as a function of solar zenith angle and water's optical properties (a(490) and b_b(490)) with data from *HydroLight* simulations. With the availability of a(490) and b_b(490) images obtained from satellite remote sensing, this $K_{PAR}(z)$ model can be adequately incorporated into physical oceanography models to study the effects of visible solar radiation on surface heating [26]. Also, it provides easy and reliable tool to predict the light level at desired depths, needed to plan the C^{14} incubation for *in situ* measurements of primary production [13].

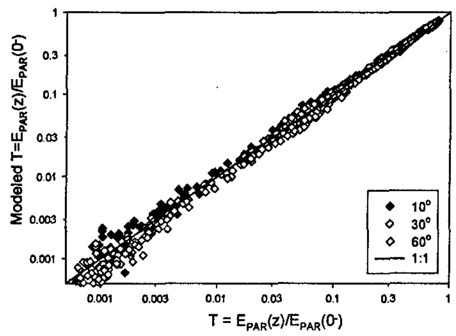

Figure 3. $T(z)$ from model (Eq.5) compared with $T(z)$ from *HydroLight* for three sun angles.

TABLE 1. MODEL COEFFICIENTS FOR $K_{PAR}(z)$

parameters	values
χ_0; χ_1; χ_2	-0.057; 0.482 ; 4.221
ς_0; ς_1; ς_2	0.183; 0.702; -2.567
α_0; α_1; α_2	0.090; 1.465; -0.667

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