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Review of PAR parameterizations in ocean ecosystem models

Do-Seong Byun [a,*], Xiao Hua Wang [b], Deirdre E. Hart [c], Marco Zavatarelli [d,e]

[a] *Ocean Forecasting Team, Korea Hydrographic and Oceanographic Administration, Busan 606-806, Republic of Korea*
[b] *School of Physical Environmental and Mathematical Sciences, University of New South Wales at Australian Defence Force Academy, Canberra, ACT 2600, Australia*
[c] *Department of Geography, University of Canterbury, Private Bag 4800, Christchurch, New Zealand*
[d] *Alma Mater Studiorum Università di Bologna, Dipartimento di Fisica e Astronomia, Viale Berti-Pichat 6/2, 40127 Bologna, Italy*
[e] *Alma Mater Studiorum Università di Bologna, Centro Interdipartimentale per la Ricerca sulle Scienze Ambientali, Via S. Alberto 163, 48100 Ravenna, Italy*

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A B S T R A C T

Commonly-used empirical equations for calculating downward 'photosynthetically available radiation' or PAR were reviewed in order to identify a more theoretically-sound parameterization for application to ocean biogeochemical models. Three different forms of broadband PAR parameterization are currently employed in biogeochemical models, each of them originating from the downward irradiance formulations normally applied to ocean circulation models, which produce poor attenuation estimates for PAR. Two of the PAR formulations, a single-exponential function and a double-exponential function, are parameterized by multiplying surface irradiance by a coefficient determining the portion of underwater PAR. The third formulation uses the second term of the double-exponential function. After elucidating the theoretical problems of modeling PAR using these parameterizations, we suggest an improved, R-modified double-exponential PAR formulation, including Paulson and Simpson's (1977) parameter values. We also newly estimate PAR penetration via least-squares fitting of values digitized from Jerlov's (1976) observations in different oceanic water types, and compare this PAR-observation derived parameterization with our new, theoretical, R-modified parameterization. Finally, we discuss a universal limitation inherent in current theoretical approaches to PAR parameterization.

1. Introduction

Around 90% of all marine life lives in the euphotic zone. The biological and physical processes that characterize this ocean surface layer, such as primary production and thermal dynamics, are fundamentally controlled by the penetration of sunlight through the water column. Modeling these processes, which sustain life across two thirds of our planet, requires an accurate and computationally-viable parameterization of the vertical distribution of underwater irradiance (Anderson, 1993; Liu et al., 2002; Kara et al., 2005).

To date, a simple light parameterization has been almost exclusively used in ocean general circulation models (OGCM) and biogeochemical models, implemented as standalone or coupled models. More accurate, spectrally-dependent bio-optical parameterization methods are typically not employed in such models because they are computationally expensive and due to the difficulties in parameterizing sunlight penetration through seawater with suspended phytoplankton, detritus and optically-active dissolved organic matter (e.g. Gallegos and Correl, 1990; Anderson, 1993).

In this study, we explore the characteristics of the simple downward irradiance parameterizations commonly used in OGCM and biogeochemical models in order to understand how to develop a more accurate, but still efficient, light parameterization for biogeochemical models. We examine three different types of photosynthetically active radiation (PAR) parameterizations, derived originally from the downward irradiance parameterizations used in physical models, before proposing a slightly-modified and theoretically-improved light parameterization for computing phytoplankton production. In addition, we explain a key limitation of using downward irradiance-derived PAR parameterizations compared to observed PAR behavior.

2. Methods: parameterizations of downward irradiance and PAR penetration

Biogeochemical models and OGCM are interested in the penetration of sunlight underwater for fundamentally different reasons.

* Corresponding author.
E-mail addresses: dsbyun@korea.kr, doseongbyun@yahoo.com.au (D.-S. Byun).

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In OGCM, the parameterization of *total* downward irradiance (300–2500 nm) is used to study ocean heat flux while in biogeochemical modeling *PAR* (350–700 nm) is parameterized in order to simulate primary production by phytoplankton. In both types of model, however, the vertical profile of downward irradiance (i.e. total or PAR) is generally calculated using a simple Lambert–Beer's Law formula, with a constant (depth-averaged) attenuation coefficient k (m^{-1}) and an assumption of optically homogeneous waters (e.g. Denman, 1973; Alexander and Kim, 1976; Chen et al., 1999) such that:

$$I(z) = I_0 \exp(-kz), \tag{1}$$

where $I(z)$ is the downward irradiance at depth z, and I_0 is the sea-surface irradiance at $z = 0$. It is recognized that using a single-exponential function in physical models yields a poor approximation of irradiance in the upper few meters (Paulson and Simpson, 1977; Zaneveld and Spinrad, 1980), leading to the overestimation of vertical light penetration (Simpson and Dickey, 1981). This is because longer wave lengths are disproportionately absorbed in near-surface waters.

Jerlov (1976, Table XXVIII) proposed an optical classification of seawater types with respect to water clarity or turbidity, based largely on the amount of particulate and dissolved matter. He defined 5 oceanic and 5 coastal water types, ordered from 1 to 5 in terms of increasing turbidity. According to this study, the infrared (IR > 700 nm) portion of the total downward solar radiation spectrum (300–2500 nm) is rapidly-absorbed within the first vertical meter of the oceans. Meanwhile PAR (350–700 nm) is more successful in penetrating below the surface, but undergoes a shift from the blue-green spectrum (400–500 nm) in open ocean waters to the green spectrum (500–550 nm) in coastal waters, according to increasing water column turbidity.

Jerlov's (1976) observations of selective downward irradiance absorption and penetration prompted other authors to develop improved heat flux parameterizations. A double-exponential parameterization (Paulson and Simpson, 1977) and an arctangent parameterization (Zaneveld and Spinrad, 1980) of the downward solar radiation profile in oceanic waters were recommended as more accurate approximations of the irradiance field for OGCM modeling. Simpson and Dickey (1981) revealed that these two parameterizations of the downward irradiance flux yield essentially equivalent results. The simpler, Paulson and Simpson (1977) double-exponential formulation was thereafter widely adopted in OGCMs such as the Princeton Ocean Model (POM) and Regional Ocean Modeling System (ROMS), using different empirical attenuation coefficients for Jerlov's different seawater types (e.g. Martin, 1997; Mellor, 2003; Vichi et al., 2003; Marchesiello et al., 2003). According to this parameterization, the vertical irradiance profile through optically homogenous waters is given by:

$$I(z) = I_0[R \exp(-k_1 z) + (1 - R)\exp(-k_2 z)], \tag{2}$$

where R is the empirical apportioning constant, k_1 and k_2 are the empirical vertical attenuation coefficients (m^{-1}), and these three empirical coefficients are adjusted to fit the observed downward irradiance distribution (see Appendix A for more details).

Although widely adopted in OGCM, the above simple formulation for the underwater attenuation of total irradiance (300–2500 nm) is of little use in biogeochemical models, where accurate irradiance estimates for the PAR (350–700 nm) spectrum specifically are crucial for modeling photosynthetic processes. It is typically assumed that incoming (sea surface) PAR comprises between 42 and 50% of the total incoming solar radiation (e.g. Parsons et al., 1984; Baretta-Bekker et al., 1997; Jacovides et al., 2003; Vichi et al., 2003; Byun and Cho, 2006; Byun et al., 2007). Such PAR apportioning is usually defined by inserting a PAR to total irradiance ratio (ε_{PAR}) into Eq. (1) as follows:

$$I_{PAR}(z) = I_0 \varepsilon_{PAR} \exp(-kz), \tag{3}$$

A double-exponential parameterization has sometimes been used for the estimation of downward PAR in biogeochemical models. For example, introducing the concept of the conversion factor from Eq. (3) into Eq. (2), Fasham et al. (1983) parameterized downward PAR as:

$$I_{PAR}(z) = I_0 \varepsilon_{PAR}[R \exp(-k_1 z) + (1 - R)\exp(-k_2 z)] \tag{4}$$

According to this method, the term $(1 - R)$ accounts for the PAR fraction belonging the blue-green wavelengths and R accounts for the remaining PAR fraction. Note that Fasham et al. (1983) also considered the effect of phytoplankton shelf-shading in order accurately to reproduce the development of the spring phytoplankton bloom in the Celtic Sea. Consideration of this effect is, however, beyond the scope of the present study.

Further, Kara et al. (2005), and Hamme and Emerson (2006), using the double-exponential parameterization in dynamic-mixed-layer models, pointed out that the second term on the right-hand side of Eq. (2) is related to the vertical PAR distribution, which is expressed as:

$$I_{PAR}(z) = I_0(1 - R)\exp(-k_2 z). \tag{5}$$

Eq. (5) is similar to Eq. (3) but it is derived from the double-exponential irradiance parameterization of Eq. (2). ε_{PAR} and $(1 - R)$ appear identical but in fact they differ as ε_{PAR} (as stated above) is the ratio of PAR to total solar radiation just above sea surface whereas both the R and k_2 terms of Eq. (5) are determined via a least-squares fit of downward irradiance observations from the subsurface water column, where only a portion of PAR exists.

In the following section we investigate the vertical light penetration characteristics exhibited by each PAR parameterization mentioned above and suggest a new R-modified PAR formulation.

3. Results and discussion

3.1. Evaluation of existing and new downward-PAR parameterizations

The double-exponential parameterization shown in Eq. (2) was derived from the spectrally-and depth-dependent attenuation of total solar radiation (300–2500 nm) in sea-surface waters, as explained in the previous section. It has already been noted that this double-exponential formulation, used in OGCM, is not useful for calculating PAR (350–700 nm), since PAR accounts for only about 42–50% of the total downward irradiance, and narrow bandwidths within the PAR spectrum are disproportionately able to penetrate the sea surface waters depending on particulate conditions. In contrast, the second exponential term in Eq. (2) could be used to estimate PAR without alteration since it explains only a portion of the visible irradiance, based on the fact that only a narrow band of PAR penetrates below the surface layer in oceanic waters.

In Eq. (4) the conversion factor for PAR (ε_{PAR}) is multiplied by a portion of the visible irradiance in the second term on the right-hand side, leading to the underestimation of downward PAR compared to when ε_{PAR} is not included in calculations, particularly for the subsurface layers. Additionally Eq. (5), which corresponds to the second exponential function of Eq. (2), typically underestimates PAR in the surface water column compared to observations. Based