

Short communication

The effect of estimated PAR uncertainties on the physiological processes of biosphere models

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ABSTRACT

Photosynthetically active radiation (PAR) energy reaching on the vegetated surface is a key determinant of plant physiological processes. Most of biosphere or crop models use the ratio of PAR to incoming solar radiation (R_s), PAR/R_s , to convert R_s into PAR in order to reduce weather data-input requirements. Several existing models simply specify a constant ratio, $PAR/R_s = 0.5$. However, some field experiments have reported that the ratio PAR/R_s may not be constant. Previous empirical equations of PAR/R_s were derived based on the data of monthly or daily timescales collected from only a few measurement sites, hence they may not be appropriate to be used in current global biosphere models usually with hourly simulation time steps. Here, we represent the exponential correlation between PAR/R_s and sky clearness index (0–1) using hourly data from 54 Ameriflux measurement sites. It is found that PAR/R_s increases up to 0.6 in cloudy conditions when the clearness index (CI) is below ~ 0.2 , whereas it is nearly constant at ~ 0.42 when CI is above 0.2. When the identified empirical equation is used in the model simulation, it results in -4 to 2% difference in the stomatal conductance compared to that using the constant ratio $PAR/R_s = 0.5$.

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1. Introduction

Plant physiological processes play a critically important role on the water and carbon cycles in terrestrial ecosystems (Eagleson, 2002). The amount of radiation absorbed by leaves is partially transformed into chemical energy to operate plant systems. Previous chamber experiments represented the environmental physiological characteristics based on radiation physics (Jones et al., 2003). The red light is most favorable for photosynthesis, while the blue light has an effect on stomatal behaviors (Baroli et al., 2008). Generally, photosynthetically active radiation (PAR) designates visible radiation over the spectral range from 400 to 700 nm (McCree, 1972), and it is a key determinant of physiological processes since plant activities are largely controlled by absorbed light energy in the ambient environment.

The variability in the incoming light energy plays a critical role in the simulation of plant physiological responses, e.g., stomatal opening, transpiration, CO₂ assimilation, etc. For example, the absorbed PAR determines the amount of dry matter that can be synthesized by each plant (Monteith, 1972). Zaehle et al. (2005) reported through a Monte Carlo-type stratified sampling approach

that the photosynthetic light use efficiency (LUE) is the most sensitive parameter to the uncertainty of terrestrial carbon modeling. The LUE directly mediates between environmental light conditions and the estimated photosynthesis, which is strongly coupled to the major physiological processes in biosphere and crop models. Namely, their results also imply the importance of PAR as forcing data for model simulations.

However, although the incoming PAR is essential to the estimation of physiological responses, its related parameters in biosphere or crop models are usually not prescribed since typically they are not measured. In order to estimating PAR in model simulation, the ratio of PAR to the incoming solar radiation (R_s) is commonly used to convert R_s into PAR. Therefore, if the values of PAR/R_s and R_s are available, then PAR can simply be derived without any additional data requirement. The early work by Monteith (1977) empirically prescribed PAR/R_s as a constant 0.5, and since then this value has been widely used in biosphere and crop models (Jones and Kiniry, 1986; Lizaso et al., 2003). However, some recent field measurement studies have reported that the value of PAR/R_s is not constant over a relatively long time scale (Udo and Aro, 1999; Lizaso et al., 2003; Finch et al., 2004).

Lizaso et al. (2003) estimated an empirical correlation between PAR/R_s and R_s using 4-year daily data from four measurement sites in Iowa. They argued that low solar elevation at early or late time of a day, and plentiful diffuse radiation on cloudy days, would cause

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not only low solar radiation, but also increased PAR/R_s . Under the condition of low R_s ($<200 \text{ W m}^{-2}$), PAR/R_s slowly increases as R_s decreases. To the contrast, when R_s is above $\sim 200 \text{ W m}^{-2}$, PAR/R_s is nearly constant at its lowest possible range. Finch et al. (2004) suggested that PAR/R_s is associated with the Clearness Index (CI ; 0–1) which is determined by dividing R_s by the extraterrestrial radiation R_{extra} (see Appendix A for its calculation method). Their daily data at southern African savanna showed that the value of PAR/R_s varies according to the seasonal change of CI , with days of a high CI corresponding to a low value of PAR/R_s .

Based on the above experimental evidences, it can be inferred that the value of PAR/R_s is in general not a constant. In biosphere and crop model simulations, the over-simplified specification of PAR/R_s value can cause large uncertainties in the simulations of ecosystem physiological response (Frouin and Pinker, 1995). If available, the empirically derived relations of PAR/R_s based on field measurements should be preferred than just specifying a constant value, and the empirical approach holds the promise to extrapolate to other regions with similar climatic conditions (Finch et al., 2004). However, their applications are not always suitable for other regions (Gueymard, 1989). Radiation data compiled from various climatic and geographical locations are necessary to derive the empirical relationships of PAR/R_s . In addition, PAR and R_s data on the hourly timescale are also required. Averaged monthly and daily data of PAR and R_s , as commonly used in previous studies, cannot accurately reflect the conditions of early and late daytime because most of these measurements were taken around noon time (Finch et al., 2004). As indicated by Lizaso et al. (2003), both early morning and late afternoon usually with lower R_s are expected to have higher PAR/R_s . Therefore, the impact of the diurnal variations of PAR/R_s can be significant at sub-daily or hourly timescale.

Numerous recent climate model studies are closely associated with the physiological effects of terrestrial ecosystems on the global terrestrial water and carbon cycles (Cao and Woodward, 1998; Gedney et al., 2006; Betts et al., 2007). However, there are very few studies on the sensitivity of the accuracy of estimated PAR to plant transpiration and carbon assimilation rates. Indeed, larger amounts of radiation data at independent measurement sites are required to develop the empirical relationships of PAR/R_s . In this study, the value of PAR/R_s , which is critical for the evaluation of physiological responses of ecosystems in the carbon and water cycle model simulation, is estimated empirically based on the in-situ measured data of PAR and R_s . The identified empirical relationship is expected to facilitate model calculation of PAR without detailed atmospheric data requirements (e.g., water vapor, aerosol and solar geometry) usually taken from high-resolution satellite imagery. To our knowledge, such an effort based on extensive measurement data has not yet been reported in the literature.

2. Methodology

2.1. Data

We have collected and compiled the data of PAR and R_s from 54 measurement sites of the Ameriflux network (Ameriflux, 2006). The 54 sites geographically cover a broad range of latitudes from 3°S to 70°N (see Table S1 in the supplement material for a list of measurement site details). The time resolution of data is 30-min or 1 h during the selected one-year period with continuous measurements. The radiation data are converted into quantum unit ($\mu\text{mol m}^{-2} \text{ s}^{-1}$) using $4.6 \mu\text{mol J}^{-1}$.

2.2. Analysis

Following Finch et al. (2004), we consider that the CI function is useful to understand the characteristics of PAR . Indeed, CI repre-

sents the influence of atmospheric conditions (e.g., cloudless) and also has commonly used in understanding the fraction of diffuse radiation in R_s . As in previous studies, we assume that the ratio of PAR to R_s is highly related with diffuse radiation. The PAR and diffused radiation should increase by atmospheric scattering and the interception of solar radiation. The CI , which indicates the degree of open sky, is calculated from the information on the Julian date, solar time, latitude and R_s . For the regression analysis between CI and PAR/R_s , we apply the following equation as suggested by Lizaso et al. (2003):

$$\frac{PAR}{R_s} = a + b \exp(-cCI) \quad (1)$$

where a , b , and c are regression coefficients: a represents the stable value of PAR/R_s when CI is relatively high, whereas b and c represent the rate of changes in PAR/R_s with respect to CI .

Most of the biosphere models used in Land Surface Models (LSMs) calculate incident PAR from R_s by using simple relationships such as $PAR/R_s = 0.5$, as early suggested by Monteith (1977). However, the SiB2 model (Sellers et al., 1996) estimates PAR using a variation of cloudless, CD (0–1), which as same as CI is also calculated from Julian date, solar time, latitude and R_s . Notice that the functional meaning of CD is exactly opposite to CI , thus CD can be considered as $1 - CI$. Therefore, PAR/R_s in SiB2 can be estimated as follows:

$$\frac{PAR}{R_s} = \frac{(d - eCD)}{(f - gCD)} \quad (2)$$

where the coefficients d , e , f , and g in SiB2 are specified as 580, 464, 1160 and 963, respectively. In fact, Eq. (2) in SiB2 and Eq. (1) have a rather similar form if the regression coefficients are suitably determined. Here, we will evaluate the physiological effects of using two empirical equations ((1) and (2)) in model simulations, and compared to that using the traditional constant value of $PAR/R_s = 0.5$ (Monteith, 1977). Our goal is to investigate how the different parameterizations of PAR/R_s , as shown in Fig. 1, can improve the accuracy of the model simulations of physiological response.

2.3. Modeling

The SiB2 simulates the biochemical processes of the water loss through transpiration and carbon uptake by photosynthesis (Farquhar et al., 1980; Collatz et al., 1991). Both transpiration and photosynthesis rates are controlled by the stomatal conductance (g_c), which is calculated from the following equation (Collatz et al., 1991):

$$g_c = m \frac{(A_g - R_d)h_s}{C_s} + bLAI \quad (3)$$

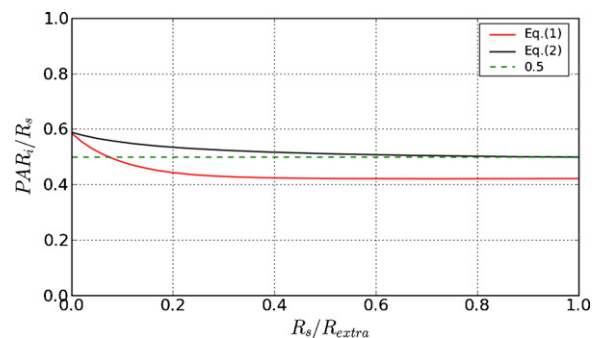


Fig. 1. The plot of PAR/R_s versus CI (i.e. R_s/R_{extra}) using Eq. (1) (with the average regression coefficients given in Table 1) and Eq. (2), respectively. Also plotted is the commonly used constant ratio of 0.5.

Table 1

Mean and standard deviation of the regression coefficients in Eq. (1) using the data of PAR and R_s from 54 measurement sites.

(n = 54)	a	b	c
Average	0.422	0.163	-10.031
Standard deviation	0.037	0.073	6.823

where m and b are empirical coefficients, A_g is the rate of gross carbon assimilation, C_s is the leaf-surface CO_2 concentration, h_s is relative humidity, R_d is plant respiration, and LAI is leaf area index. Basically, g_c calculated by Eq. (3) is strongly dictated by radiation variables, because the estimation of A_g is related with the determination of PAR. According to the following Farquhar et al. (1980), A_g is estimated from the assimilation rates as limited by the photosynthetic enzyme efficiency (W_c), the amount of PAR captured by the leaf chlorophyll (W_s), and the leaf capacity to transport or adopt the photosynthetic outcome (W_e).

$$A_g = \min(W_c, W_s, W_e) \begin{cases} W_c = V_m \left[\frac{C_i - \Gamma}{C_i + K_c(1 + O_2/K_0)} \right] \\ W_s = 0.5V_m \\ W_e = PAR(1 - \omega_\pi)\varepsilon[(C_i - \Gamma)/(C_i + 2\Gamma)] \end{cases} \quad (4)$$

where V_m is the maximum catalytic capacity of Rubisco, C_i is the partial pressure of CO_2 in leaf interior, O_2 is the partial pressure of oxygen in leaf interior, Γ is the CO_2 compensation point, K_c is the Michaelis–Menten constant for CO_2 , K_0 is the inhibition constant for O_2 , ω_π is the leaf-scattering coefficient for PAR, and ε is the intrinsic quantum efficiency for CO_2 uptake. Therefore, the major physiological response in the model is expected to be sensitive to the magnitude of PAR (Zaehle et al., 2005).

Model simulation for the sensitivity test is performed using the weather forcing data at the Tak measurement site of Northern Thailand (see Kim et al., 2003 for details). The simulation period is from August 2 to August 28, 2003, in total 27 days of simulation with the time step of one hour (see Figure S1 in the supplement material for the time series of weather forcing data). For the Tak measurement site, the vegetation type is mixed tropical deciduous forest and the leaf area index is specified as 5 according to Kim et al. (2003).

3. Results

The regression analysis of the relationship between CI (R_s/R_{extra}) and PAR/R_s in Eq. (1) is carried out by using the data set from 54 measurement sites (see Figure S2 in supplement material for regression analysis of all data sets), and the mean and standard deviation of the derived regression coefficients are shown in Table 1. The scatter plots between CI and PAR/R_s can include the error caused by the measurements; for example, installed radiometer sensor height, geological elevation, homogeneity distribution of cloud and aerosol particles, and so on. These errors are believed to be reduced as the number of the data used increases. As summarized in Table 1, the regression coefficient a in Eq. (1) is in average about 0.42, smaller than the constant value (0.5) as suggested by Monteith (1977). Fig. 1 plots the PAR/R_s versus CI (i.e. R_s/R_{extra}) using Eq. (1) with the average regression coefficients in Table 1, and Eq. (2) as used in SiB2. As shown in this figure, Eq. (2) in general gives a higher PAR/R_s than Eq. (1), and approaches the constant ratio 0.5 at larger CI . The curve of Eq. (1) is steeper than that of Eq. (2) at low CI , and it approach a smaller constant value (~ 0.42) than 0.5 as CI increases. Since the parameters in the Eq. (1) were estimated from the 54 measurement sites worldwide, it should reflect more general patterns of PAR/R_s than either Eq. (2) or the constant ratio 0.5. The PAR estimated by Eq. (2) is in general overestimated. The difference between two

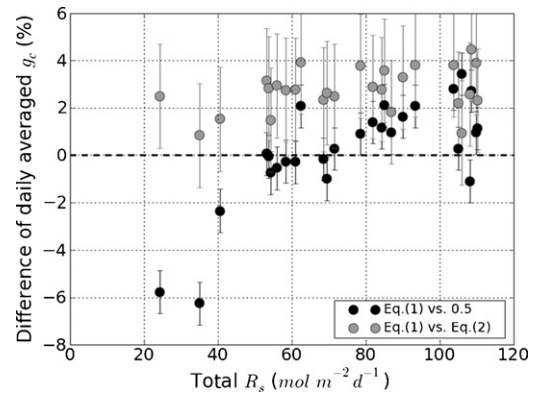


Fig. 2. Difference between the daily-averaged stomatal conductance (g_c) derived from using Eqs. (1) and (2) for converting R_s to PAR, and using the constant ratio of 0.5.

PAR estimated by Eqs. (1) and (2), respectively, becomes smaller when CI drops below ~ 0.2 . Therefore, significant differences in the calculated PAR of global simulations are expected to appear in the summer for temperate areas and in the dry season for tropical areas.

Stomatal behavior is directly related to transpiration and photosynthetic rate. Stomatal conductance (g_c) is estimated with environmental variables such as in Eq. (3), and light is the critical weather factor of g_c . Therefore, the absorbed PAR energy is sensitive to the estimation of g_c . Fig. 2 plots the differences between the daily-averaged g_c derived by using Monteith’s constant ratio of 0.5, Eqs. (1) and (2) in converting R_s to PAR. As observed in Fig. 2, the difference of g_s is between -6% and 4% . Negative percentage indicates the underestimation of g_c by previous PAR calculation methods (constant ratio 0.5 and Eq. (2)) compared to the empirical relation estimated in this study (Eq. (1)). When comparing g_c estimated by Eq. (1) to that by constant ratio 0.5, the percentage difference changes from being negative at low R_s to positive as R_s increases, while the difference between the g_c estimates from Eqs. (1) and (2) is within the ranges of about 2–4%.

4. Discussion and conclusions

In this study, we derived an empirical relationship between CI and PAR/R_s for the purpose of improving the parameterization of global biosphere models, based on the data collected from 54 measurement sites worldwide. To the best of our knowledge, similar attempt using hourly data from a relatively large number of measurement sites has not yet been reported in literature. It is found there is a -6 to 4% difference in the estimated stomatal conductance when using the identified empirical equation in PAR calculation compared to previous methods. The accuracy of estimated stomatal conductance has a direct influence on the plant water loss and CO_2 uptake. Our study may thus have significant implications for the land surface parameterizations used in climate modeling. Moreover, the sensitivity of model-estimated stomatal conductance to other simulation variables (e.g., runoff and biomass) can be potentially changed with the alteration of regional and global radiation caused by climate change and anthropogenic aerosols.

Although the empirical relationship identified using the data from 54 measurement sites is meaningful, it is necessary to examine more sufficient amount of data under various atmospheric conditions. Our empirical equation suggests that PAR/R_s is almost constant when CI is relatively high, which is appropriate for most measurement sites. However, some measurement data among 54 sites show slightly decreasing PAR/R_s when CI is increasing ($R_s > 0.7$). However, in order to describe simple and suitable empirical formula, we did not consider critically those situations due to occur rarely in this study.

The information on *PAR* is generally required when estimating global biomass product (e.g. net primary production (*NPP*)) using satellite remote sensing data. At that time, *PAR* is often estimated from the constant *PAR/R_s* value because of its calculation simplicity (Running et al., 1999). To overcome the limitation on developing suitable parameterizations of *PAR/R_s* at the global scale, some physically based models have been developed (Gueymard, 1989; Van Laake and Sanchez-Azofeifa, 2004). However, these models are not appropriate for all types of applications (Finch et al., 2004; Jacovides et al., 2007). For example, most of physical models for estimating *PAR* are suitable only for clear sky condition. Furthermore, they usually require the detailed data of the atmospheric conditions from high-resolution satellite imagery. If simple empirical formula can be derived by using data under various atmospheric conditions as performed in this study, they can commonly meet application demands (Jacovides et al., 2007).

However, enhanced physical understanding on the relations between *PAR* and *R_s* is also required in addition to empirical approaches for contributing to the accuracy of biochemical processes simulated in biosphere models and remote sensing-based applications. For example, the site elevation, radiative sensor height, the variations of aerosol and humidity profiles, have to be considered.

The *CI* function used in this study is also often used for the reasonable interpretation of the fraction of diffuse radiation to total *R_s*. Therefore, we can simply expect the positive relationship between the ratio of diffuse *PAR* to direct *PAR* and *PAR/R_s*. On its physiological effects, diffuse *PAR* causes more canopy photosynthetic activities than direct one because the dispersed radiation can better penetrate to the shaded leaves under the still light-limited state (Gu et al., 2003). Therefore, the change of transpiration and photosynthesis through the variation of *CI* should be caused by not only increased *PAR/R_s*, but also by raised diffuse *PAR*. Reasonably acceptable *PAR/R_s* is indispensable to evaluate the effect of diffuse *PAR* on canopy scale.

During the 20th century, the decadal trend of incoming radiation at land surface has dramatically changed as a combined result of anthropogenic emissions of greenhouse gases, aerosols from land use changes, and cloud cover through climate change. Sustained global decline in *R_s* at land surface has become apparent from 1960 to 1990, whereas brightening has been observed globally since 1990s (Wild et al., 2005; Pinker et al., 2005). However, recent brightening is not applicable to the whole global region. Various kinds of atmospheric aerosols cause the reduction of sunlight over the Amazon basin and India (Koren et al., 2004; Kumari et al., 2007). It is possible that the functional effects of vegetation physiology on the hydrological cycle will be changed by the fluctuation of radiation patterns in the context of recent global warming simulations. In that sense, more sophisticated estimation of *PAR* from *R_s* in the model is needed in order to better understand the light-limiting effects on physiological processes of plant ecosystems.

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Appendix A. The calculation of extraterrestrial radiation

$$\delta = 23.45 \sin \left(\frac{2\pi}{365} (284 + J) \right) \quad (\text{A1})$$

where δ is declination ($^{\circ}$).

$$\omega = 0.25 m \quad (\text{A2})$$

where ω is the hour angle of solar time ($^{\circ}$) and m is number of minutes from local solar noon.

$$R_{0n} = R_{sc} \left[1 + 0.033 \cos \left(\frac{2\pi J}{365} \right) \right] \quad (\text{A3})$$

where R_{0n} is the extraterrestrial normal radiation (W m^{-2}) and R_{sc} is solar constant (1353 W m^{-2}).

$$R_{extra} = R_{0n} (\sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega) \quad (\text{A4})$$

where R_{extra} is the extraterrestrial radiation on horizontal surface ($^{\circ}$) and ϕ is latitude ($^{\circ}$).

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2010.03.009.

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