Estimation of Daily Mean Photosynthetically Active Radiation under All-Sky Conditions Based on Relative Sunshine Data

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ABSTRACT

Photosynthetically active radiation (PAR) is absorbed by plants to carry out photosynthesis. Its estimation is important for many applications such as ecological modeling. In this study, a broadband transmittance scheme for solar radiation at the PAR band is developed to estimate clear-sky PAR values. The influence of clouds is subsequently taken into account through sunshine-duration data. This scheme is examined without local calibration against the observed PAR values under both clear- and cloudy-sky conditions at seven widely distributed Surface Radiation Budget Network (SURFRAD) stations. The results indicate that the scheme can estimate the daily mean PAR at these seven stations under all-sky conditions with root-mean-square error and mean bias error values ranging from 6.03 to 6.83 W m\(^{-2}\) and from -2.86 to 1.03 W m\(^{-2}\), respectively. Further analyses indicate that the scheme can estimate PAR values well with globally available aerosol and ozone datasets. This suggests that the scheme can be applied to regions for which observed aerosol and ozone data are not available.

1. Introduction

Solar radiation is the most important energy source driving almost all of Earth’s surface processes. The spectral portion of the solar spectrum that is used by plant biochemical processes in photosynthesis (light energy conversion to biomass) extends from 400 to 700 nm. These wavelength limits further define the photosynthetically active radiation (PAR), which covers both photon and energy terms (McCree 1972; Ross and Sulev 2000). PAR measurements are required in modeling simulations of the photosynthesis process in various fields of research (Frolking et al. 1998; Knyazikhin et al. 1998; Sivakumar and Virmani 1984; Wan et al. 2008).

There are two ways to obtain PAR values. One is to measure these values directly with instruments (Ross and Sulev 2000), and the other is to estimate them from other data (Guerymard 1989b; Pinker and Laszlo 1992). As is well known, PAR measurement stations are very sparsely distributed around the world. Moreover, these stations are mainly located in urban or suburban areas, and there are almost no stations in remote areas such as the Tibetan Plateau. Therefore, numerous methods have been developed to estimate PAR values by using relevant data sources. These methods can be broadly divided into two categories: satellite-based methods (Liang et al. 2006; Zheng et al. 2008) and site-based methods (Alados-Arboledas et al. 2000; Guerymard 1989a).

A satellite-based method uses remote sensing signals to retrieve information on the atmosphere, applies the retrieved parameters to drive a radiative transfer model
(or search a lookup table based on the radiative transfer model), and eventually obtains PAR estimates at Earth’s surface. The advantage of this method is that it allows one to obtain spatially continuous PAR estimates, whereas its weakness is that only instantaneous PAR values can be estimated at the time of satellite overpass. Some additional procedures are required to scale this instantaneous PAR value to the daily mean value (Wang et al. 2010). This upscaling process may lead to large uncertainties.

A site-based method, on the other hand, takes routine meteorological data collected at weather stations as inputs to estimate PAR values. One advantage of this type of scheme is that it enables the estimation of historical PAR values before the satellite era. Some schemes of this type are based on an empirical relationship between the global solar radiation (GSR) and the PAR that is constructed according to certain meteorological variables (e.g., near-surface air pressure, temperature, or humidity) (Escobedo et al. 2009; Jacovides et al. 2003). These empirical schemes require local calibration, which limits their applicability. Furthermore, they require GSR measurements as inputs—a prerequisite that also severely hinders their applicability because the number of radiation stations is spatially insufficient. Semiphysical schemes have also been proposed for PAR estimation (Alados-Arboledas et al. 2000; Gueymard 1989a). These schemes explicitly consider radiative extinction processes due to air molecules, aerosols, and water vapor. Most of these methods have focused merely on clear-sky conditions, and a few schemes have accommodated the effects of clouds on PAR (Udo and Aro 2000).

It is well known that the cloud amount observed at weather stations is, to some extent, subjective and may contain large uncertainties. Sunshine duration is another parameter that is often routinely recorded at weather stations. Its definition is the length of time in which the direct-normal solar irradiance is greater than or equal to a threshold value (WMO 2008). In terms of this definition, the sunshine duration more suitably reflects the influence of clouds on Earth’s surface radiation. In this study, a new scheme is presented to realize PAR estimation under all-sky conditions. First, a new physically based parameterization is developed to estimate PAR under clear-sky conditions. Then, a correction is proposed to take into account the cloud effect on the PAR using sunshine-duration data. To the best of our knowledge, such a correction for PAR estimation has not been reported in the literature. Last, the effect of multiple scattering on the PAR between the atmosphere and ground surface is taken into account in estimating the PAR.

This article is organized as follows. In section 2, the proposed scheme is described. The scheme is validated in section 3, and discussions are given in section 4. The study is summarized in section 5.

2. Scheme development

a. Scheme for clear skies

The basic idea for the PAR estimation scheme is to construct a broadband transmittance model for the PAR under clear skies and then to consider the cloud effects on the basis of sunshine-duration data to extend its applicability to all-sky conditions. The clear-sky spectral transmittance model presented in Leckner (1978) is the starting point for this PAR estimation scheme. The spectral model is briefly expressed below:

\[
\tau_b(\lambda) = \exp\left\{[-1.41 k_g(\lambda)m'][1 + 118.3 k_g(\lambda)m']^{0.45}\right\},
\]

(1a)

\[
\tau_R(\lambda) = \exp(-0.008735m'\lambda^{-4.08}),
\]

(1b)

\[
\tau_w(\lambda) = \exp\left\{[-0.2385 k_w(\lambda) mw][1 + 20.07 k_w(\lambda) mw]^{0.45}\right\},
\]

(1c)

\[
\tau_o(\lambda) = \exp(-mlk_o(\lambda)),
\]

(1d)

\[
\tau_d(\lambda) = \exp(-m\beta \lambda^{-1.3}),
\]

(1e)

\[
m = 1/[\sin h + 0.15(57.296h + 3.885)^{-1.253}],
\]

(1f)

\[
m' = mp/\rho_0,
\]

(1g)

where \(\lambda\) (\(\mu\)m) is the wavelength; \(\tau_{g}\), \(\tau_{R}\), \(\tau_{w}\), \(\tau_{o}\), and \(\tau_{d}\) denote the spectral transmittances for uniformly mixed gas absorption, Rayleigh scattering, water vapor absorption, ozone absorption, and aerosol extinction, respectively; \(k_{g}\), \(k_{w}\), and \(k_{o}\) are the absorption coefficients for uniformly mixed gas absorption, water vapor absorption, and ozone absorption, respectively; \(w\) (cm) is the precipitable water; \(l\) (cm) is the ozone layer thickness; \(\beta\) is the Ångström turbidity coefficient; \(m\) is the relative air mass depending on the solar elevation angle; \(m'\) is the pressure-corrected relative air mass; \(h\) is the solar elevation angle; \(p_s\) (Pa) is the site air pressure; and \(p_0\) (Pa) is the standard atmospheric pressure.

According to the spectral model, the clear-sky PAR band beam transmittance \(\tau_b\) and the diffuse transmittance \(\tau_d\) are defined as follows:

\[
\tau_b = Q_0 \int_{0.4}^{0.7} \int_{0}^{7} F_0(\lambda)\tau_g(\lambda)\tau_R(\lambda)\tau_w(\lambda)\tau_o(\lambda)\tau_d(\lambda) d\lambda
\]

(2a)
\[ \tau_d = 0.5Q_{00} \int_{0.4}^{0.7} I_{00}(\lambda)\tau_g(\lambda)\tau_w(\lambda)\tau_o(\lambda)[1 - \tau_R(\lambda)\tau_R(\lambda)] \, d\lambda, \]

where

\[ Q_{00} = \int_{0.4}^{0.7} I_{00}(\lambda) \, d\lambda \]

and \( I_{00}(\lambda) \) (W m\(^{-2}\)) is the spectral irradiance at the mean distance between the sun and Earth.

The instantaneous PAR under clear-sky conditions at the ground surface can be computed as

\[ Q_{b,clr}^{\text{clr}} = Q_{00}(d_0/d)^2 \sinh(\tau_b), \]

\[ Q_{d,clr}^{\text{clr}} = Q_{00}(d_0/d)^2 \sinh(\tau_d), \]

and

\[ Q_{g,clr}^{\text{clr}} = Q_{b,clr}^{\text{clr}} + Q_{d,clr}^{\text{clr}}, \]

where \( Q_{b,clr}, Q_{d,clr}, \) and \( Q_{g,clr} \) (W m\(^{-2}\)) denote the instantaneous beam, diffuse, and global PAR values under clear-sky conditions, respectively; \( d_0/d \) is the eccentricity correction factor for the mean sun–Earth distance; and \( h \) represents the solar elevation angle. Once these instantaneous values are available, their corresponding time-averaged values can be obtained by performing temporal integration as follows:

\[ Q_{b,a}^{\text{clr}} = \frac{1}{\Delta t} \int_{t} Q_{b,a}^{\text{clr}} \, dt, \]

\[ Q_{d,a}^{\text{clr}} = \frac{1}{\Delta t} \int_{t} Q_{d,a}^{\text{clr}} \, dt, \]

and

\[ Q_{g,a}^{\text{clr}} = \frac{1}{\Delta t} \int_{t} Q_{g,a}^{\text{clr}} \, dt, \]

where \( \Delta t \) (s) represents the integration period and \( Q_{b,a}^{\text{clr}}, Q_{d,a}^{\text{clr}}, \) and \( Q_{g,a}^{\text{clr}} \) (W m\(^{-2}\)) denote the time-averaged direct, diffuse, and global PAR under clear-sky conditions, respectively.

The solar spectrum and the spectral transmittances for each extinct component are irregular. Therefore, a numerical integration is required to obtain the integral values in Eqs. (2a)–(2c). This process is time consuming and limits their practical applications. In this work, we simplify this problem with the following approximations:

\[ \tau_b \approx \tau_g \tau_R \tau_w \tau_o \tau_a \quad \text{and} \]

\[ \tau_d \approx 0.5 \tau_g \tau_R \tau_o (1 - \tau_R \tau_a), \]

where \( \tau_g, \tau_R, \tau_w, \tau_o, \) and \( \tau_a \) denote the PAR band transmittance for uniformly mixed gas absorption, Rayleigh scattering, water vapor absorption, ozone absorption, and aerosol extinction, respectively.

The band transmittance for each extinction process is defined as follows:

\[ \tau_k = Q_{00} \int_{0.4}^{0.7} I_{00}(\lambda)\tau_k(\lambda) \, d\lambda, \]

where \( k \) can be \( g, R, w, o, \) or \( a, \) each representing one of the five extinction processes.

As is evident from Eqs. (1a)–(1c), \( \tau_k \) should be a function of \( m', mw, ml, \) or \( mb \) after the integration in Eq. (6). Thus, each band transmittance is approximated by the following form:

\[ \tau_k \approx \exp(a_k x^{b_k}), \]

where \( x \) denotes \( m', mw, ml, \) or \( mb \) and \( a_k \) and \( b_k \) are the two coefficients to be determined for each extinction process when Eq. (7) is fitted to the simulated values generated by Eq. (6) with different values of \( x. \)

The results of this fitting process are illustrated in Fig. 1. They indicate that \( \tau_k \) in Eq. (6) can be effectively parameterized by Eq. (7). In Fig. 1, the PAR transmittance for the uniformly mixed gas is not displayed for purposes of clarity, because its value is always approximately equal to 1.0 [see Eq. (8e)]. The fitted formulas are given as

\[ \tau_R = \exp[-0.14057(m')^{0.88384}], \]

\[ \tau_w = \exp[-0.00021(mw)^{0.70991}], \]

\[ \tau_o = \exp[-0.005218(ml)^{0.96054}], \]

\[ \tau_a = \exp[-2.18157(m\beta)^{0.93988}], \]

and

\[ \tau_g \approx 1.0. \]

It is well known that uniformly mixed gas absorbs solar radiation very weakly in the PAR band. Thus, the numerical results of Eq. (6) indicate that the corresponding transmittance is almost equal to 1, as shown in Eq. (8e). On the other hand, the validity of Eqs. (5a) and (5b) is justified in Fig. 2 by comparing the transmittance values (beam and diffuse) derived from Eq. (2) and the corresponding values derived from Eqs. (5) and (8).

b. Correction for cloudy skies

The fraction of cloudy days in many regions is comparable to that of clear days over a year. The PAR model above needs to consider cloud effects in order to apply the model to PAR estimation under all-sky conditions.
conditions. In this study, the cloud effect on global PAR values is corrected by using sunshine data to parameterize the PAR band cloud transmittance $\tau_c$ as follows:

$$\tau_c = f(n/N)$$  \hspace{1cm} (9)

where $n$ (h) is the actual sunshine duration, $N$ (h) is the maximum possible sunshine duration, and $n/N$, therefore, represents the relative sunshine duration. Thus, the time-averaged global PAR $Q_{all}^g$ under all-sky conditions can be calculated as follows:

![Diagram showing comparisons of PAR broadband transmittances for individual extinction processes and parameterizations.](image)

**Fig. 1.** Comparison of PAR broadband transmittances for individual extinction processes between spectral integration [Eq. (6)] and parameterization [Eqs. (8a)–(8d)] for (a) aerosol scattering, (b) Rayleigh scattering, (c) ozone absorption, and (d) water vapor absorption.

![Diagram showing comparisons of beam and diffuse transmittances at PAR band.](image)

**Fig. 2.** Comparisons of (a) beam and (b) diffuse transmittances at PAR band from Eqs. (2a) and (2b) and from Eqs. (5a) and (5b).
The commonly used mathematical form for $t_c$ is the linear or quadratic polynomial, which can be calibrated by fitting to hourly, daily, or monthly measurement data, as was done in the work by Yang et al. (2006) and many others (Menges et al. 2006). As mentioned above, the focus is on the daily mean PAR. The following formula, which was determined using GSR observations collected in Japan (Yang et al. 2007), is adopted without modification:

$$
t_c = 0.2495 + 1.1415(n/N) + 0.3910(n/N)^2. \tag{11}
$$

### 3. Validation under both clear- and all-sky conditions

#### a. Data

In this study, in situ measurements necessary for driving and validating the PAR estimation model are collected at seven radiation stations from the National Oceanic and Atmospheric Administration Surface Radiation Budget Network (SURFRAD; Augustine et al. 2000). Basic information on these stations is listed in Table 1. Three types of radiation-related parameters recorded at the SURFRAD stations are used. The first is the PAR measured by a Li-Cor, Inc., quantum sensor with an accuracy of $\pm 5\%$, the second is the direct-normal irradiance measured by an Eppley Laboratory, Inc., pyrgeometer with an accuracy of $\pm 9$ W m$^{-2}$, and the third is the downward and upward global solar irradiance measured by a Spectrolab, Inc., sensor and an Eppley pyranometer with an accuracy from $\pm 2\%$ to $\pm 5\%$. The photosynthetic photon flux density is the output ($\mu$mol s$^{-1}$ m$^{-2}$) of the quantum sensor. Although the use of McCree’s conversion factor of 4.6 introduces uncertainties, they are not substantial (McCree 1972). Thus, the quantum units are converted into energy units through this factor.

A set of strict standards is established to process the PAR and direct-normal solar irradiance measurements from all of the data collected at the seven SURFRAD stations. The temporal interval for radiation measurements at these stations was 3 min until 2008 and 1 min from 2009 onward. If any instantaneous PAR or direct solar irradiance measurement during a day at some station is missing, that day is excluded from subsequent processing. If the radiation measurements during a day satisfy the requirement above, the daily mean PAR is calculated for this day. Note that, although the daily sunshine duration is routinely collected at many weather stations throughout the world, it is not recorded at the SURFRAD stations. Therefore, the daily sunshine duration at these sites is converted from direct-normal solar irradiance values, according to the definition of sunshine duration (WMO 2008).

In addition to the data on sunshine duration, data on the turbidity coefficient, ozone thickness, air pressure, and precipitable water are also needed to drive the PAR estimation scheme. As seen in Eq. (1e), the Ångström exponent $\alpha$ for the aerosol optical depth is fixed at 1.3 in the proposed PAR model; hence, the corresponding Ångström turbidity can be obtained through the Ångström relation:

$$
B = \tau_\lambda \lambda^{1.3}, \tag{12}
$$

where $\tau_\lambda$ denotes the measured aerosol optical depth at wavelength $\lambda$ ($\mu$m).

In this study, the records of daily mean aerosol optical depth at a wavelength of 0.5 $\mu$m are used to compute the daily mean Ångström turbidity coefficient through Eq. (12) at the SURFRAD stations. The daily mean ozone observations at each SURFRAD station are processed in a way similar to that for the Ångström turbidity coefficient. As for the daily precipitable water, no direct observations are available. Hence, it is estimated with the following empirical formula (Yang et al. 2006):

$$
w = 0.00493 \times \text{RH} \times T^{-1} \exp(26.23 - 5416T^{-1}), \tag{13}
$$

where $w$ (cm) denotes the precipitable water in the atmosphere, RH (%) is the relative humidity of the near-surface...
air, and $T$ (K) is the near-surface air temperature. The latter two parameters are generally measured at weather stations.

**b. Validation**

In this study, daily mean PAR values are estimated and then compared with the measurements at the seven SURFRAD stations. The validation is first performed for clear-sky conditions and then for all-sky conditions. The daily relative sunshine duration is used to select clear-sky days with one of two standards (0.95 and 0.98). Three statistical indicators—the determination coefficient $R^2$, root-mean-square error (RMSE), and mean bias error (MBE)—are used to measure the performance of the proposed estimation scheme. When the lower standard (0.95) is implemented (Fig. 3a), $R^2$, RMSE, and MBE are equal to 0.995, 3.77 W m$^{-2}$, and $-0.138$ W m$^{-2}$, respectively. These three indicators are 0.995, 3.27 W m$^{-2}$, and $-0.3897$ W m$^{-2}$, respectively, when the higher standard (0.98) is adopted (Fig. 3b). Better results are expected for the higher standard because it selects days with less cloud cover and because the estimation scheme without considering the cloud effect is more appropriate for these days.

Figure 4 presents the validation results with all of the data collected at the seven SURFRAD stations. Figure 4 shows that the proposed scheme performs slightly worse on cloudy days than under clear-sky conditions, with $R^2$, RMSE, and MBE equal to 0.985, 6.40 W m$^{-2}$, and $-0.28$ W m$^{-2}$, respectively. This is unsurprising, because the cloud transmittance parameterization is empirical and may introduce more uncertainties than does the physically based estimation scheme for clear-sky conditions. All of the determination coefficients above pass hypothesis testing at a significance level of 0.0001. Figure 5 shows the statistical indicators under all-sky conditions for each SURFRAD station. RMSE and MBE values range from 6.03 to 6.83 W m$^{-2}$ and $-2.86$ to $1.03$ W m$^{-2}$, respectively.

**4. Discussion**

**a. Analysis of the cloud correction formula**

To investigate why the cloud transmittance scheme for the shortwave band could be applied to the PAR band and to explore further the possibility of improving the cloud transmittance parameterization in the PAR band, the three coefficients in Eq. (11) are obtained by fitting the ratio of the observed PAR values under
all-sky conditions to the modeled clear-sky PAR values. Figure 6a shows the ratios and the fitted curve. The curve given by Eq. (11) is also shown for comparison. The two fitted curves match well when the relative sunshine duration is greater than 0.6, but deviate slightly from one another when this duration is less than 0.6. A few points in Fig. 6a are likely to be physically erroneous because the small relative sunshine-duration values unexpectedly correspond to the relatively large cloud transmittance values at these points. After a simple criterion \( \left( \frac{\tau_c}{N} \right) \approx 0.5 \) is adopted to filter out these questionable points, the two curves match almost perfectly, as displayed in Fig. 6b. Note that the data points in Fig. 6 do not gather tightly but disperse around the fitted curves to some degree, indicating that the relative sunshine duration does not fully explain all the variance in the cloud transmittance.

As mentioned previously, Yang’s formula for the daily cloud transmittance was derived by using GSR data measured in Japan, and the newly fitted formula was obtained by utilizing the PAR observations from seven sites in the United States. The interesting point is that these two formulas are almost identical, implying that the broadband optical properties of clouds in the entire shortwave range and the PAR range are similar. In addition, the sum of the three coefficients in Eq. (11) should be equal to 1.0 when the relative sunshine duration \( n/N \) approaches 1.0. This was used as the constraint in Yang’s calibration procedure, whereas it was not applied in this work. The sum of the three newly fitted coefficients amounts to approximately 1.0, however, as shown in Fig. 6b. These results indicate that the cloud transmittance formula that was presented by Yang et al. (2006) gives a good estimation of the effect of clouds on both GSR and PAR.

b. Influence of different aerosol and ozone climatological datasets

As mentioned previously, precipitable water, ozone thickness, and aerosol turbidity must be provided to drive the PAR estimation scheme. In situ measurements of these parameters are used in the validation process above, except that precipitable water is estimated by routine meteorological data (relative humidity and air temperature). The turbidity coefficient and ozone amount are not usually measured at weather stations. Therefore, four global aerosol datasets converted to the Ångström turbidity coefficient and three global ozone datasets are used to replace the corresponding observations at the seven SURFRAD stations. Here, the aim is to examine the applicability of the proposed PAR estimation scheme.
estimation scheme when turbidity and ozone measurements are unavailable.

The first aerosol dataset is the Ångström formula, the second is the Global Aerosol Dataset (GADS) developed at the Max Planck Institute, the third involves Goddard Chemistry Aerosol Radiation and Transport (GOCART) model products, and the fourth comes from Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol products. For the three ozone datasets, the first is the satellite remote sensing product developed by the National Aeronautics and Space Administration Goddard Space Flight Center from the Total Ozone Mapping Spectrometer (TOMS) sensor, the second is the University at Albany, State University of New York, (SUNYA) climatological dataset, and the third is an empirical formula developed by Yang et al. (2006). For further details on these datasets, see Yang et al. (2007).

Figure 7 presents the estimation results with the four global aerosol datasets. The accuracies for three of the aerosol data sources (Ångström formula, GADS, and GOCART) are close to that using the measured turbidity data (Fig. 4), in terms of RMSE. For MBE, these three aerosol datasets cause negative biases in the PAR estimates, indicating that their aerosol loadings at the SURFRAD stations are higher than the actual loadings. For PAR estimates from the MODIS-derived turbidity, the RMSE value is higher than that obtained from in situ observations, and its MBE is positive and lower than those from when the other three aerosol datasets are implemented. This result indicates that with the MODIS dataset the aerosol loadings are underestimated at SURFRAD sites; moreover, the turbidity coefficients have larger random errors but smaller bias than the other three turbidity datasets. In this study, the mismatch in spatial scale between the coarse-resolution

![Figure 7](image-url)
aerosol datasets and the local site measurements is one reason for the differences in the biases of the PAR estimates across the four different aerosol datasets. At present, it is difficult to determine which of these four aerosol datasets should be selected.

The three ozone datasets (TOMS, SUNYA, and Yang’s empirical formula) are used as a substitute for observational data to estimate the PAR values. The results displayed in Fig. 8 indicate that the estimation accuracy changes very little in comparison with those results when measured ozone thickness data are used. In other words, any of these three ozone datasets can be used in the PAR model when in situ measurements are unavailable.

c. Multiple scattering between the atmosphere and surface

The PAR estimation scheme presented here does not account for the effects of multiple scattering of light between the atmosphere and the surface, as shown in section 2. This may cause uncertainties in the PAR estimates. To investigate how the omission of this effect has an impact on the accuracy of estimation, the 10 120 points used in the validation are grouped into five bins according to the ground albedo values at increments of 0.2, from 0 to 1. As shown in Fig. 9, both RMSE and MBE magnitudes increase as the albedo increases. This is unsurprising because the brighter the ground becomes, the greater is the multiple scattering of light between the atmosphere and the ground surface. The points with high albedo values (>0.4) occur mostly in winter when snow falls. Omission of multiple scattering partly explains why the bias of the estimated PAR values at the site DRA, which is located in a desert with relatively high albedo values, is much more negative than are those of other sites (cf. Fig. 5).

To rectify the deficiency above, Eq. (10) can be corrected to consider multiple scattering between the atmosphere and surface:

$$Q_{all}^{il} = \frac{\tau_c Q_{clr}^{il}}{1 - \rho_a \rho_g}$$  \hspace{1cm} (14)

where $\rho_a$ and $\rho_g$ denote the atmospheric spherical albedo and ground-surface albedo, respectively, at the PAR band.

Albedo $\rho_a$ can be evaluated as follows:

$$\rho_a = \frac{n}{N} \rho_{a,clr} + \left(1 - \frac{n}{N}\right) \rho_{a,cld}$$ \hspace{1cm} (15a)

$$\rho_{a,clr} = \tau_{d}$$ \hspace{1cm} (15b)

where $\rho_{a,clr}$ denotes the atmospheric spherical albedo under clear-sky conditions, which could be regarded as

FIG. 8. Comparison of daily mean PAR observations and estimates based on three different ozone datasets: (a) TOMS, (b) SUNYA, and (c) Yang’s empirical formula.

FIG. 9. Variation in statistical indicators of daily mean PAR estimation with increased surface albedo.
being equivalent to the diffuse transmittance $\tau_d$ when the relative air mass $m$ is equal to $3^{1/2}$ (Justus and Paris 1985), and $\rho_{\text{a,cld}}$ represents the cloud-base albedo, which is taken to be approximately 0.6 (Hay 1979).

To implement this correction scheme, the ground-surface albedo at the PAR band is required. The previous analysis indicates that a relatively large bias occurs only when the ground surface is mainly covered by snow; hence, the multiple-scattering correction scheme is only performed in those cases in which the shortwave albedo is greater than 0.4 so as to examine the effectiveness of the correction. At the seven SURFRAD stations, the upward PAR is not measured; thus, the in situ albedo at the PAR band is unavailable. Snow albedo values at both the shortwave and PAR bands are high, although the former are slightly lower than the latter. In the current study, the albedo values at the shortwave band are taken to approximate those at the PAR band when the above correction scheme is implemented, although this approximation would bring some uncertainties into the estimation results.

In Table 2, the results before and after considering multiple scattering between the atmosphere and surface are compared when the shortwave albedo is greater than 0.4. The proposed correction scheme clearly improves the estimation accuracy in terms of RMSE and MBE. In fact, the high surface albedo normally indicates snow cover. Under these conditions, the physiological activities of plants, which require PAR to carry out photosynthesis, decline drastically. Therefore, from a practical point of view, the uncertainties in omitting multiple scattering may not be significant in applications of the PAR estimation scheme to plant growth.

### 5. Summary

In this study, a clear-sky PAR estimation scheme is developed. In addition, the influence of clouds is taken into account using sunshine-duration data. This scheme is validated by comparing the estimated and observed PAR values under both clear- and cloudy-sky conditions at the seven SURFRAD sites. Various aerosol and ozone datasets are used to replace observational measurements to derive the PAR estimates in an effort to determine the applicability of the estimation scheme when observational aerosol and ozone data are unavailable. The results indicate that the estimation scheme could estimate the PAR effectively at the seven stations. Given that these sites are spatially well distributed, the results suggest that the scheme has the potential of being widely applicable. Moreover, the effect of multiple scattering of light between the atmosphere and ground surface can be incorporated into this scheme, indicating that the correction scheme can improve the estimation results when the surface albedo is high. The errors induced by this multiple scattering are negligible when the surface albedo is low.

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