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Effect of Aerosol Optical Depth on Diffuse Photosynthetically Active Solar Irradiance

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Abstract

Photosynthetically active solar irradiance (PAR, 400-700 nm) data measured with a Rotating Shadowband Radiometer (RSR) at Yonsei University, Seoul (37.57°N, 126.97°E) from 1996 to 2000 have been analyzed to investigate the dependence of solar irradiance on aerosol optical depth (AOD). It is found that diffuse solar irradiance is largely affected by solar zenith angle (SZA) and AOD. Diffuse solar irradiance increases with increasing AOD up to a certain critical value due to the increasing effect of aerosol scattering, but then decreases after the critical AOD value due to the excessive extinction by aerosol. The diffuse solar irradiance at a given SZA can be expressed as an empirical function of AOD, by fitting the long-term diffuse measurements. This empirical model is validated with its sensitivity tests for AOD. The empirical model was compared with the CLIRAD model over the globe, which showed reasonably good agreements.

Key words: Aerosol optical depth, solar radiation, diffuse, direct, PAR

1. Introduction

Recently, numerous studies have been conducted to investigate how increasing amounts of aerosol and trace gases in the atmosphere influence atmospheric circulation and climate change in terms of radiative forcing by analyzing extensive observation database and using comprehensive models. Despite extensive studies to date, IPCC (2007) still identified radiative effect of aerosol as one of the large uncertainties in understanding climate change. Aerosols of natural or anthropogenic origin change significantly the intensity of photosynthetically active radiation (PAR, 400- 700 nm) reaching the surface by direct extinction of solar radiation as well as by indirect process through modifying physical properties of clouds. Thus, aerosols influence plant growth as well as climate through the attenuation of shortwave radiation including PAR. The intensity of solar irradiance reaching the earth's surface from the sun is changed through two physical processes of scattering and absorption in the atmosphere. Aerosol, one of the important uncertainties in understanding the climate change, plays an important role in the scattering and absorption processes, especially in visible wavelengths, which correspond to the ranges of PAR.

Jayaraman *et al*. (1998) showed that the direct irradiance decreases by 42 ± 4 W m^{-2} and diffuse increase by 30 ± 3 W m^{-2} per unit aerosol optical depth (AOD) for the broadband irradiance shorter than 780 nm. Bergin *et al*. (2001) investigated the influence of aerosol dry deposition on PAR available to plants, where about 35% reduction in PAR can be accounted by dry deposition of water insoluble aerosol particles. There have been studies to evaluate the effect of aerosol on the direct and diffuse component (e.g., Nishizawa *et al*., 2004; Rajeev and Ramanathan, 2001), but dealt with the difference in irradiance between the clear sky and aerosol loaded case, that is

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radiative forcing. To evaluate the radiative forcing of aerosol, there have been extensive studies(e.g., Nakajima *et al*., 2003; Ramanathan *et al*., 2001) to investigate the difference in radiative flux, rather than the detail changes of flux with respect to the increasing AODs. Cho *et al.* (2003) analyzed the dependence of diffuse PAR on total optical depth (TOD) which adds up contributions of aerosol optical depth, Rayleigh scattering,absorption by ozone and water vapor, and the effect of clouds. In their work, the relationship between TOD and components of PAR has been investigated quantitatively based on observation, where the behavior of diffuse PAR with respect to TOD has been clearly derived, and the critical AOD values for the maximum diffuse component were derived as a function of solar zenith angle (SZA). They analyzed the dependence of diffuse PAR on TOD for all sky conditions, but not on the aerosol optical depth (AOD) separately. Wenny *et al.* (2001) showed a decrease in surface erythemal UV by 4 to 50% due to aerosol. However, there have been no systematic and quantitative study on the behavior and changes of diffuse PAR in particular with respect to increasing aerosol amount in the atmosphere.

The main purpose of this study are to understand the basic characteristics of solar diffuse irradiance with respect to aerosol optical depth (AOD) in the atmosphere, to establish an empirical formula for their relationship, and to compare the results with the sophisticated radiative transfer model. For this purpose, the PAR data measured with a Rotating Shadowband Radiometer (RSR) at Yonsei University for five years have been analyzed to investigate the dependence of the diffuse PAR on AOD. Also, the radiative transfer model was used to calculate the direct and diffuse components of solar irradiance with respect to AOD, which are compared with the current results. The results of this study are expected to contribute to the better understanding of the aerosol effect on the diffuse PAR in a quantitative way.

2. Measurements

PAR have been observed with the RSR on the rooftop of the Science Building at Yonsei University, located at the north-western part of Seoul (37.57°N, 126.97°E), since January 1996. The observed data by RSR over 5 years from 1996 to 2000 have been used in this study. RSR with a quantum sensor, LI-190SA (LI-COR, 1991) is designed specially to yield qualified indications of atmospheric optical depth at NOAA/ER2/ARL. The quantum sensor monitors a part of the solar spectrum that is active in photosynthesis (400-700 nm) with relative spectral response in the photosynthetic response of plants (LICOR, 1991). The response function, which shows trapezoidal shape with almost square type rise at each end of the PAR wavelength and monotonically increasing sensitivity across the wavelength range from 400 nm to 700 nm [see Fig. 1 of Cho *et al.* (2003)]. The uncertainty in the calibration of the sensor is ±5%. RSR has a distinct benefit from measuring method of different instruments (Harrison *et al*., 1994). While the shadow-band is at nadir, the measurement is for global-horizontal PAR. Shading the sensor from direct sun light with the rotating band, permits measurement of diffuse-horizontal PAR. RSR measures simultaneously the two PAR components from the same sensor, and direct-horizontal PAR can be obtained by subtracting the diffuse component from the global PAR.

In order to compare the PAR observation with model calculation, radiative transfer model, 6S (Vermote *et al.*, 1997) was used to calculate the direct and diffuse component of PAR for clear sky conditions. Figure 1 shows the comparison of the RSR data with the calculation by 6S for one year in 2001 as an example. The radiative transfer model calculation corresponds to clear sky with the minimal background AOD in Seoul. The coefficient of determination (R^2) and the slope are shown to be 0.94 and 0.81, respectively. The upper envelope of the data points corresponds closely to the line with slope of 1. The observed PAR irradiance is smaller than the calculated values in general, which can be attributed to the extinction due to the aerosols in the atmosphere over Seoul. The RSR measurements show reasonable agreement with the model results.

3. Analysis Method

TOD is deduced from the direct normal solar irra-

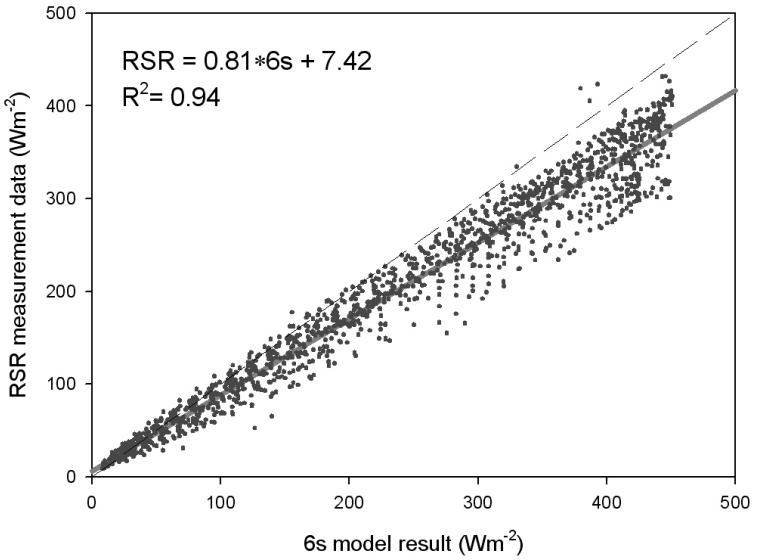

Fig. 1. Comparison of observed data by RSR at Yonsei University, Seoul, Korea with the calculated values by radiative transfer model, 6S.

diance in the Beer-Bouguer-Lambert's Law,

$$\tau_\lambda = \frac{1}{m} ln(\frac{E_{0\lambda}}{E_\lambda}) \quad (1)$$

where τ_λ means TOD at wavelength λ; E_λ is the direct-normal solar irradiance of the surface observed at wavelength λ; $E_{0\lambda}$ is the extraterrestrial-normal solar irradiance at λ; and m is the relative optical air mass calculated by the following equation (Kasten, 1966),

$$m = [cos\,\theta + 0.15\,(93.885 - \theta)^{-1.253}]^{-1} \quad (2)$$

To get TOD at wavelength λ, the extraterrestrial- normal solar irradiance in Eq. (1), $E_{0\lambda}$ is obtained by the Langley regression method. In this study wavelength λ represents effective wavelength over $D\lambda$ in the wavelength range of PAR. Hereafter, the subscript λ is omitted. TOD is thus a parameter that can be simply inferred from direct-normal solar irradiance regardless of respective extinction processes such as absorption and scattering. Theoretically, the Langley method can be applied only for the monochromatic radiation, but can be also applicable for wavelength bands of finite width. Thus the results of the analysis here need be regarded as effective values over the $D\lambda$ in the wavelength range of PAR. Similar analysis have been done in the previous work of Cho *et al.* (2003) and Lee *et al.* (2005). Cho *et al.* (2003) compared the extraterrestrial irradiance obtained by the Langley analysis from the RSR and compared with the results of World Radiation Center (WRC) where the difference was shown to be less than 1 %. Nowadays with the recent technology of narrow band, and even hyperspectral instruments to measure radiation, more accurate evaluation of ODs(optical depths) at a given wavelength is possible. However, these effective values of optical depth over PAR wavelengths from the RSR still contain useful information on the characteristics, especially the PAR which has significance in the photosynthesis of plants.

The Langley regression method can be applied only for the weather conditions that atmosphere is very clean, that is clear sky condition both in clouds and aerosols, and optically stable, during the several hours of measurements for the Langley method (cf. Liou, 2002). Detailed conditions and procedures of the Langley method is described in Cho *et al.* (2003). In case of a special observation site at altitude of over 4 km such as Mauna Loa, extraterrestrial-normal so-

lar irradiance is estimated very accurately by single regression at clean and stable weather conditions, but at other sites the direct-normal solar irradiance is estimated by averaging the several regression results (Harrison *et al.*, 1994). Thus, in this study, similarly as in Cho *et al.* (2003), the TOD was calculated by using the average value of extraterrestrial- normal solar irradiance estimated under the clear-sky conditions.

To obtain AOD, the Rayleigh optical depth deduced from the surface pressure and the optical depth for ozone absorption deduced from the ozone amount were subtracted from the TOD,

$$\tau_{aerosol} = \tau_{total} - \tau_{Rayleigh} - \tau_{ozone} \quad (3)$$

where $\tau_{aerosol}$, τ_{total}, $\tau_{Rayleigh}$ and τ_{ozone} mean AOD, TOD, the Rayleigh optical depth and the optical depth for ozone absorption, respectively. To calculate τ_{ozone} and $\tau_{Rayleigh}$ at 0.55 μm, Eqs. (4) and (5) are used, respectively.

$$\tau_{ozone} = 3.3162 \times 10^{-21} cm^2\ mole^{-1} \times N[O_3] \quad (4)$$

$$\tau_{Rayleigh} = 0.008569\lambda^{-4}(1 + 0.0113\lambda^{-4} + 0.00013\lambda^{-4})P/P_0 \quad (5)$$

where $N[O_3]$ is the ozone column density in molecules·cm^{-2}, λ is the wavelength in micrometers and P_0=1013.25 hPa.

4. Results and Discussion

a. Extraterrestrial-direct normal solar irradiance and TOD

By taking the clear-sky condition when relative optical air mass is between 2 and 6 and TOD is below 3.0, extraterrestrial-normal PAR, E_0, is calculated using the Langley regression method. An example of calculated results is presented in Fig. 2. The extraterrestrial values, E_0 are corrected to the mean Earth-Sun distance as a value of $\overline{E_0}$(= E_0 × eccentricity correction factor). TODs for all measured data were calculated by applying $\overline{E_0}$ to the Beer-Bouguer-Lambert's Law.

To see the actual contribution of clouds to the TOD,

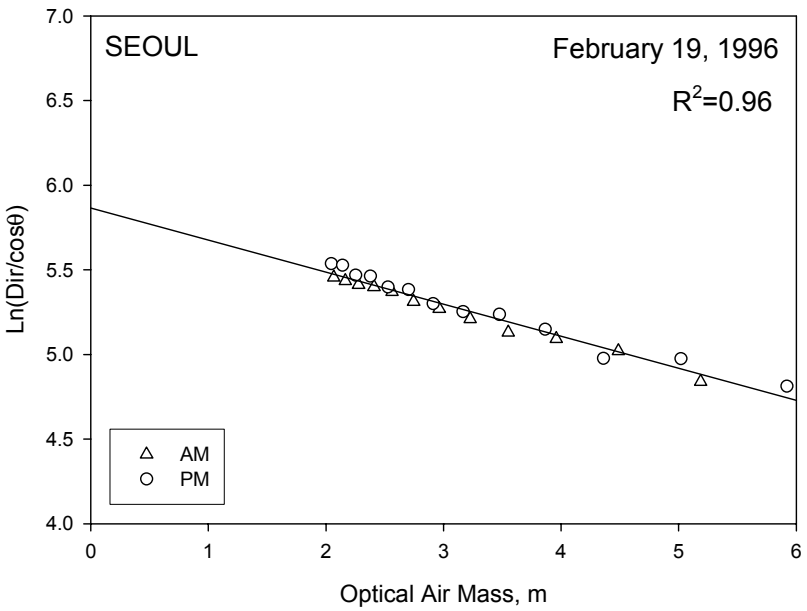

Fig. 2. Determination of extraterrestrial photosynthetically active radiation and total atmospheric optical depth using the Langley regression method.

relationship between daily mean cloudiness measured in tenth by human eye observation and TOD is compared in Fig. 3. As seen in the figure, the daily values of two parameters are correlated. It can be concluded that the TOD is significantly influenced by cloud. Thus, it is necessary to remove the cloud effects from the TOD by selecting clear days only in order to analyze the effect of AOD separately. Thus, the cases with observed cloudiness other than zero are excluded.

b. Dependence of surface diffuse PAR on AOD

In order to study the dependence of direct and diffuse PAR on AOD at the surface under clear sky, the changes in direct and diffuse solar irradiance with AOD for SZAs 40° to 70° in steps of 10° are calculated. The results are presented in Fig. 4. The direct solar irradiance decreases exponentially as AOD increases according to the Beer-Bouguer-Lambert's law. The exponential expressions for the direct component show excellent agreement with the observed data with the correlation coefficient of 0.99 for all SZAs. As AOD increases, the diffuse PAR gradually increases and shows a maximum value. Thus the diffuse PAR at a given SZA can be expressed as a function of AOD, which is fitted to the diffuse measurements by a regression as follows:

$$F_{diff}(\tau) = exp(a + b\tau + c\tau^2 + d\tau^3) \quad (6)$$

where F_{diff} is the diffuse horizontal PAR; τ is AOD (Cho *et al.*, 2003); and *a, b, c* and *d* are constants as listed in Table 1. The values of constants are determined from the diffuse PAR measurements by minimizing the root mean square error(RMSE) for each SZA. The advantage of the above empirical model lies in its simplicity, which provides diffuse PAR with a single parameter, AOD at a given SZA, while the computation of diffuse downward irradiance in radiative transfer models requires various parameters including SZA, AOD, single scattering albedo, asymmetry parameter, and surface albedo.

The model for diffuse PAR Eq. (6) for given SZAs is displayed in Fig. 5. As AOD increases, the diffuse PAR gradually increases up to certain AOD and then decreases for a given SZA. Physically, the diffuse component of PAR is mainly contributed by Rayleigh scattering when there is no aerosol, while the diffuse is expected to be zero eventually when the AOD becomes significantly large by blocking the incoming

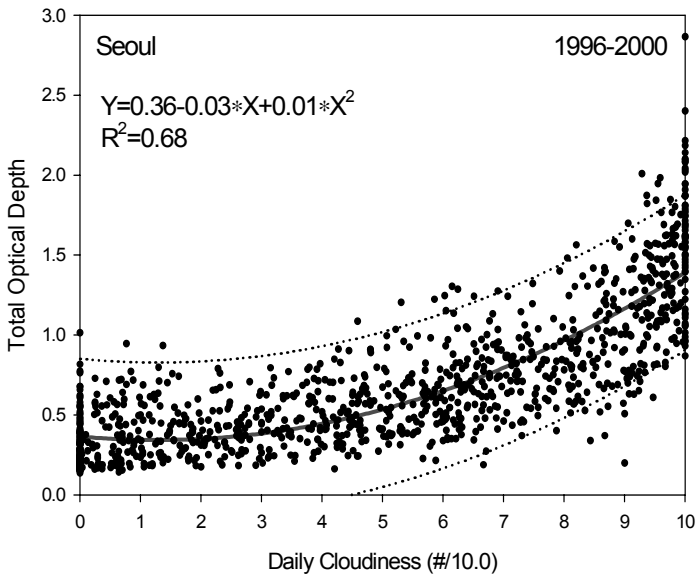

Fig. 3. Relationship between daily average cloudiness and total optical depth (1996-2000). Dotted lines represent prediction for the regression at confidence level of 95%.

Table 1. Model constants of diffuse PAR irradiance and coefficients of determination (R^2) for different SZA.

SZA	a	b	c	d	R^2
40°	4.09	1.68	-0.71	0.03	0.88
50°	3.84	2.04	-0.96	0.04	0.89
60°	3.70	1.94	-1.19	0.03	0.84
70°	3.47	1.93	-1.53	-0.18	0.78

solar radiation. This can be explained by the effect that diffuse solar irradiance increases with increasing AOD up to a certain critical value due to the increased scattering effect of aerosol, but then decreases after the critical AOD value because of the excessive extinction by aerosol (Cho *et al*., 2003). The critical AOD showing a maximum diffuse PAR increases as the SZA decreases. As seen in this figure, as the SZA increases from 40° to 70° in steps of 10°, the critical AOD indicating maximum diffuse PAR decreases to 1.29, 1.15, 0.85, and 0.57, respectively.

c. Empirical model validation and sensitivity to AOD

To validate the statistical models for the diffuse PAR, scatter plots are shown in Fig. 6 for different

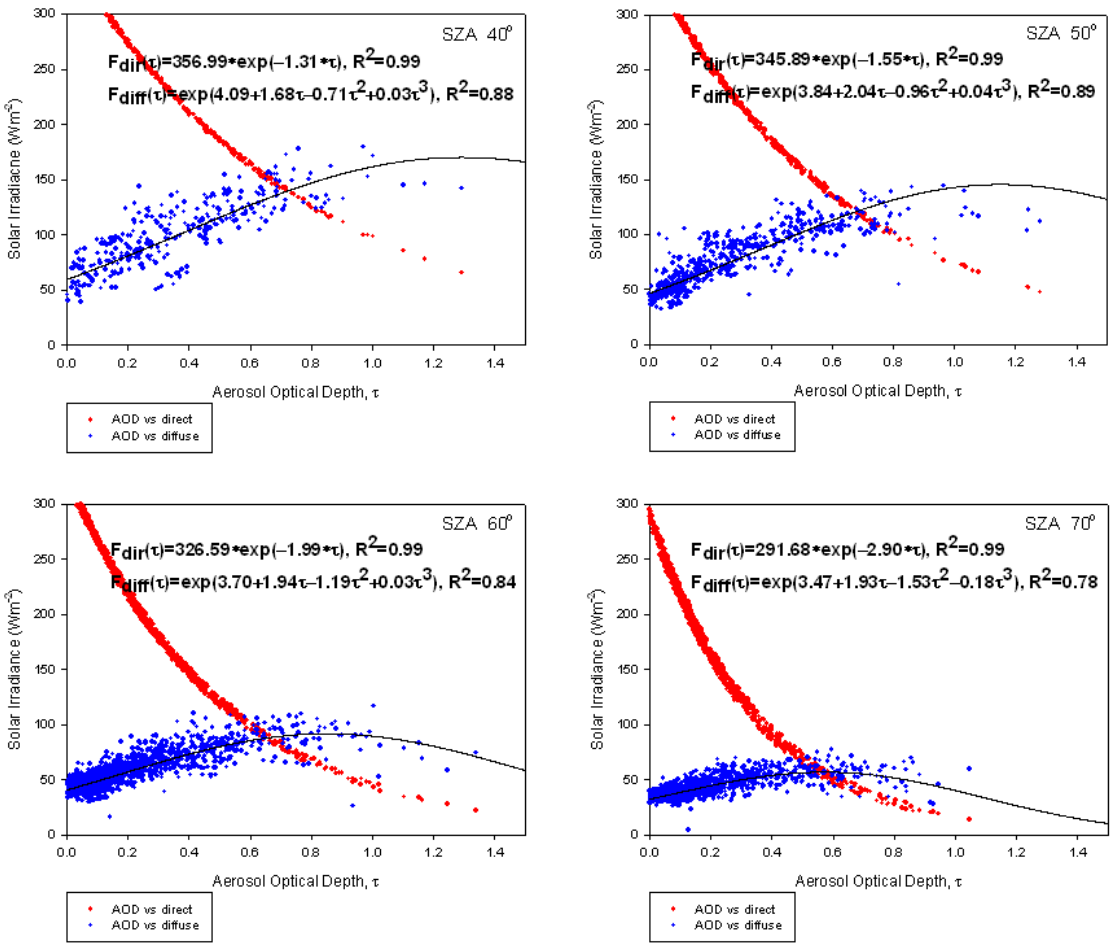

Fig. 4. Variations of direct and diffuse PAR with AOD under clear sky for different SZA: 40°, 50°, 60°, 70°.

SZAs between the model calculations and the measurements for the period of January through December 2001 which are independent of those used in the development of the model (from 1996 to 2000). As can be seen in the figure, the plots for diffuse PAR show slopes ranging from 0.72 to 0.99 depending on SZAs, and the coefficients of determination from 0.71 to 0.83 which are very good. The plots are somewhat dispersed from the regression in all cases, but the calculated diffuse PAR shows general agreement with the observed values for all SZAs. The RMSE for the diffuse component is somewhat high, but is comparable to the calculations by radiative transfer models in other studies (e.g., Halthore and Schwartz, 2000). The agreement for the direct component (not shown here) is excellent compared to that for the diffuse component as expected.

The sensitivity test is performed for models of the direct and diffuse components of the PAR. Figure 7 shows the relative change rates of direct and diffuse irradiance due to 1% change in AOD for the SZAs. From the figure, one can note that the relative change rates for direct PAR increase linearly with the increase of AOD at a given SZA. However, the change rates for diffuse PAR increase nonlinearly with the increase of AOD at a given SZA, and is more sensitive than direct component.

d. Extension of the empirical model over the globe

Based on long-term PAR measurements of direct and diffuse components, empirical models are suggested as a function of AOD and SZA. As the current empirical model of Eq. (6) allows us to calculate the diffuse components of PAR as a function of AOD and SZA, it is desirable to extend the calculation using the AODs over the globe as input to the empirical model. To extend the empirical model to the globe, Eq. (6) is scaled by a correction factor determined as a function of AOD and surface reflectance(a_{sfc}),

$$F_{diff}(\tau) = exp(3.70 + 1.94\tau - 1.19\tau^2 + 0.03\tau^3)\{1 + 0.19\tau + 0.4(\alpha_{sfc} - 0.2)\} \quad (7)$$

The previous Eq. (6) was derived over the urban area of Seoul, thus needs to be modified for different surface conditions because the diffuse radiation is affected also by surface albedo significantly in addition to the SZA and AODs. The correction factor is determined by an iterative processes to minimize the

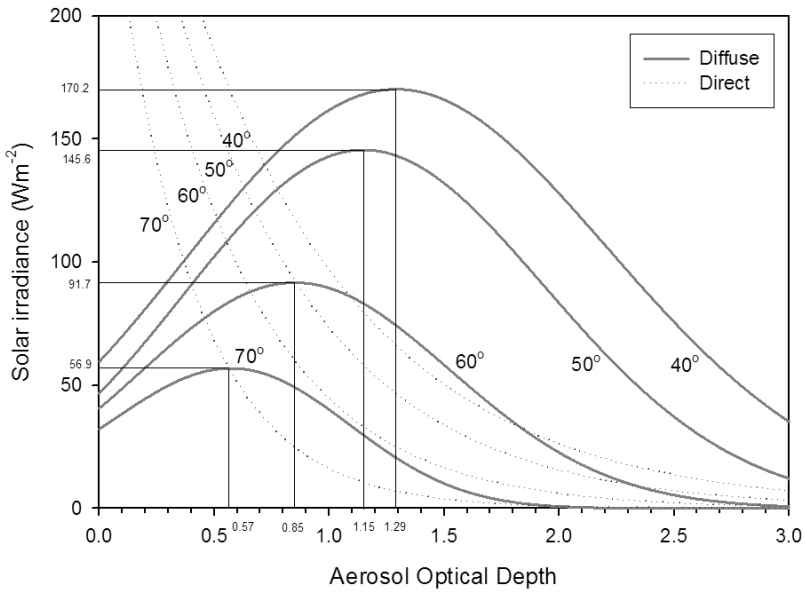

Fig. 5. Direct(dotted line) and diffuse(solid line) PAR for different SZA: 40°, 50°, 60°, 70°.

discrepancy.

To validate the Eq. (7), the widely-used band model (CLIRAD-SW) of Chou and Suarez (1999) is used for shortwave radiative transfer calculation, which includes the absorption and scattering due to major and minor trace gases, as well as clouds and aerosols. The solar radiation spectrum is divided into eight bands between 0.175 and 3.85 mm. Further details can be found in Chou and Suarez (1999). CLIRAD model provides both direct and diffuse components of solar irradiance at the surface in UV, PAR and NIR regions.

Both the empirical and CLIRAD models require AOD as input to calculate the diffuse PAR. The AOD data in Fig. 8a is the 5 years climatology (Apr. 2000 - Sep. 2004) of MODIS/Terra atmosphere monthly global product, and is at 550 nm for both ocean and land. This global AOD data from MODIS measurements are used as input for the CLIRAD model to calculate the diffuse PAR over the globe as shown in Fig. 8b in January. The calculated diffuse PAR by the CLIRAD model reflects the contribution of scattering by aerosols closely, showing enhancements in the East Asia, western part of the Central Africa, and so on. Simultaneously, the same AODs of Fig. 8a are used to calculate the diffuse PAR by the empirical model [Eq. (7)] as shown in Fig. 8c. Figure 8d shows the percentage difference between the CLIRAD (Fig. 8b) and empirical model (Fig. 8c). Both results show very good agreements, with the overall difference within 5% in most regions, which is surprising considering the simplicity of the above Eq. (7) and the complexity of the actual physical processes involved in determining the diffuse component as included in the

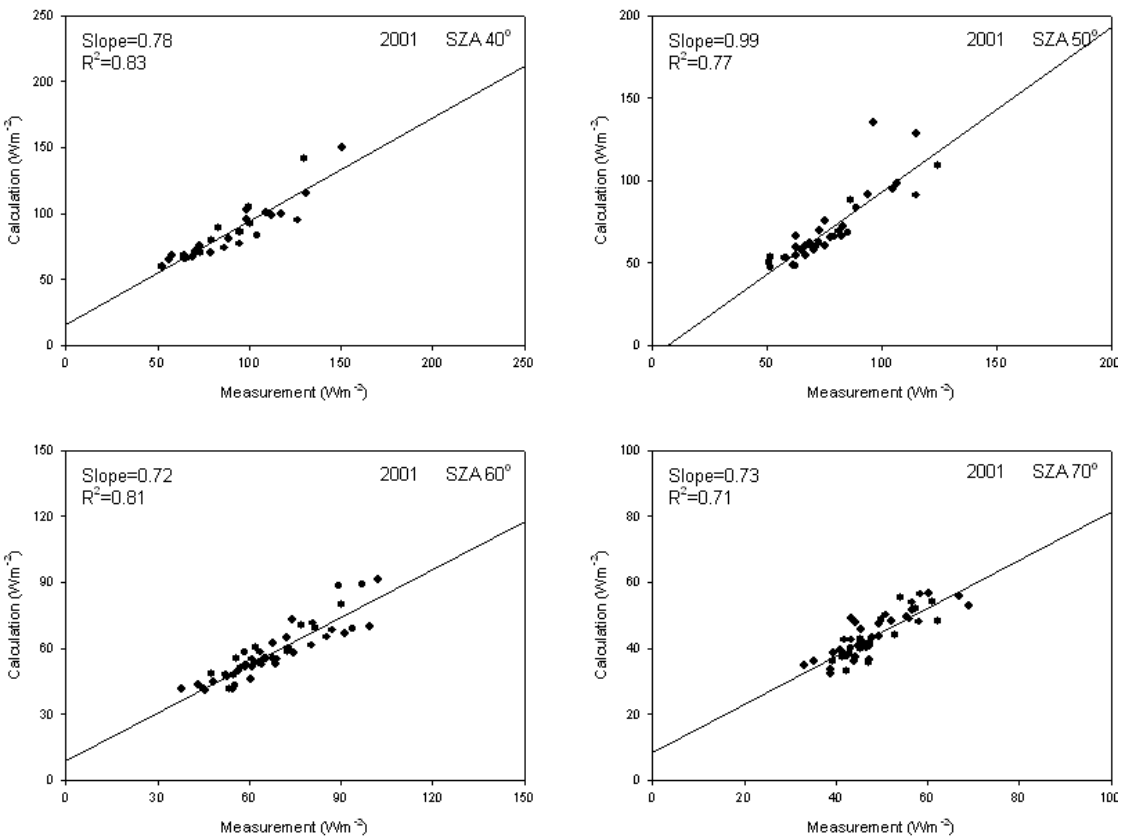

Fig. 6. Comparison of calculated and measured diffuse PAR at Seoul for one year of 2001. Calculated values are from the empirical model developed in this study.

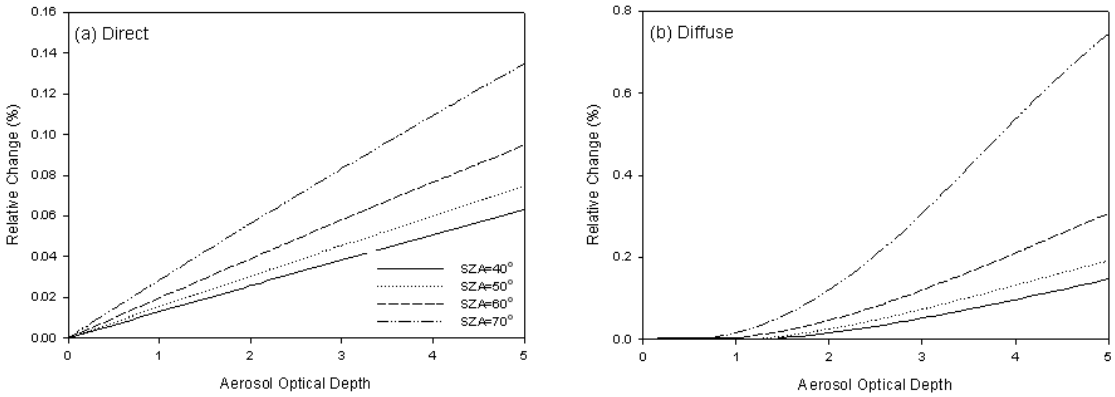

Fig. 7. Sensitivity of (a) direct and (b) diffuse irradiance with 1% change in AOD.

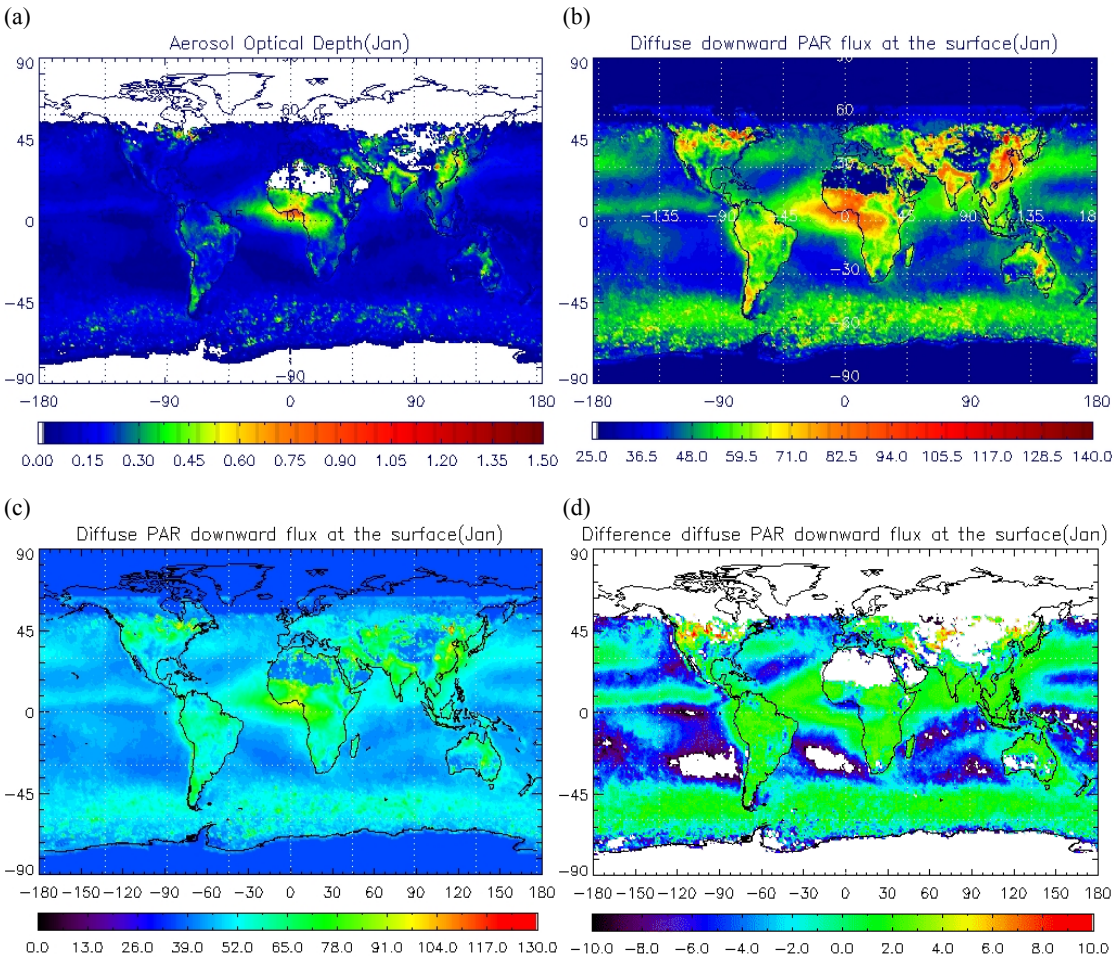

Fig. 8. (a) AOD data from the MODIS/Terra atmosphere monthly global product at 550 nm for both ocean and land, (b) diffuse solar irradiance in PAR from the CLIRAD model, (c) the diffuse PAR calculated by the empirical model based on long-term measurements, and (d) percentage difference of the diffuse PAR between the empirical model in (c) and the CLIRAD model in (b).

CLIRAD model.

The difference between the two in Fig. 8d can be explained by the different optical properties of aerosol type in other regions. The major aerosol type over Seoul, Korea is mainly from urban pollution and mineral dust from China. The pattern in Fig. 8d tends to reflect the absolute magnitude of the PAR irradiance and different optical properties of aerosol over other region. Although the purpose of the calculation is to show its expandibility to other regions, further refinements in the correction factors, such as optical properties including single scattering albedo for the empirical function need to be done in the future study.

5. Summary and Conclusions

The statistical features in components of the horizontal PAR and the dependence of the diffuse PAR on AOD for visible range were investigated from observed dataset for 5 years from 1996 to 2000. It is found that diffuse solar irradiance and its portions with respect to the global PAR are largely affected by SZA and AOD. Diffuse solar irradiance increases up to certain AOD and then decreases because of the increasing scattering effect and excessive extinction of aerosol, respectively. Based on our measurements, as the SZA increases from 40° to 70° in steps of 10°, the critical AOD indicating maximum diffuse PAR decreases to 1.29, 1.15, 0.85, and 0.57, respectively. Diffuse solar irradiance at a given SZA can be expressed as a function of AOD, based on the long-term observation of the diffuse component by regression.

The empirical model based on measurements was compared with the results of the CLIRAD model. The difference between model output and the global result based on observation in Seoul is within 5% in most regions. This result can be applicable for numerical models which require simple parameterization to see the effects of aerosol on diffuse components, and estimation of diffuse radiation for the photosynthesis of plants in aerosol-loaded conditions.

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