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ORIGINAL PAPER

A practical model to estimate photosynthetically active radiation using general meteorological elements in a temperate humid area and comparison among models

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Abstract Although accurately evaluating photosynthetically active radiation is important, much effort is required to measure this radiation using a quantum sensor. We develop a new model that makes estimates using only general meteorological data—solar radiation, atmospheric pressure, air temperature, and relative humidity. Root mean square deviations for eight datasets at five sites in Japan were smaller than 5.2 %, similar to error in other studies and to individual differences of quantum sensors. Most root mean square deviations of nine previous models and our eight datasets are larger than that of the new estimation model, which performed well. This suggests that the model is useful for estimating photosynthetically active radiation in a temperate, humid area of Japan.

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1 Introduction

Radiation emitted by the sun passes through the atmosphere and arrives at the Earth's surface. Energy of this solar radiation is reduced while passing through the atmosphere because part of it is absorbed and scattered by molecules and substances, including water vapor, dust particles, and various gases. The condition of the atmospheric layer is constantly changing, and the amount of absorption and scattering depends on the types and amounts of substances at the wavelength of radiation. A ground-based pyranometer and quantum sensor detect the incoming solar energy after passing through the atmosphere. Therefore, the relationship between global photosynthetically active radiation (PAR) and global solar radiation is not constant. However, PAR, which generally means radiation in the 400 to 700 nm waveband, is a part of solar radiation.

In general, a quantum sensor is used in PAR measurement. Several types of these sensors, including the widely used LI-190 (LI-COR, USA) (Mizoguchi et al. 2009), are currently available. However, there are concerns about the accuracy of quantum sensor outputs because there is no standard for these sensors. Mizoguchi et al. (2010) reported differences among sensor types with incident angle, azimuth angle, and secular distortion. Individual differences even among LI-190s are nearly 5 %, and stability is 2 % per year. Therefore, much attention and effort is required to maintain measurement accuracy. In addition, the number of PAR measurement points is not sufficient to analyze photosynthesis activity of plants worldwide.

There are various PAR estimation methods available. The simplest is a linear regression with global solar radiation. Estimation errors from such linear regression are not large, and error ranges are acceptable (Meek et al. 1984; Howell et al. 1983). However, the relationship between solar radiation and PAR changes with cloud condition and season, as Nagaraja Rao (1984), Skartveit and Olseth (1994), and others have indicated. Tsubo and Walker (2007) proposed a model to estimate PAR with clearness index k_t, the ratio of global solar radiation to extraterrestrial solar radiation. Wang et al. (2007) proposed approximation equations with site altitudes to portray atmospheric conditions. Kanniah et al. (2010) pointed out the influence of atmospheric aerosol and proposed an estimation method to indicate their effects, by dividing radiation into direct and diffuse components. Alados et al. (1996), Ge et al. (2011), and Aguiar et al. (2012) put forth estimation models using general meteorological data. Unfortunately, these studies were conducted in Europe and the Americas, where climate conditions like precipitation are different from those in eastern Asia, including Japan.

The demand for accurate and reliable PAR data is high. Although some estimation models have been proposed, they have not been validated with Asian site data. In this study, we propose a new model using general meteorological data from four sites in an Asian temperate humid zone. In addition, we compare and validate previous models using the same general meteorological data and those from one additional site.

2 Sites and measurements

2.1 Site description

Data of global solar radiation (S_d) and global PAR (P_d) were collected from five sites—Hitusjigaoka (HTJ henceforth), Appi (AsiaFlux site code API), Fujiyoshida (FJY), Kawagoe (KWG), and Yamashiro (YMS) (Table 1). Except for HTJ, these are forest meteorological research sites where general meteorological measurements were continuously conducted. HTJ is near the Sapporo Forest Meteorological Research Site (SAP; 42.98°N, 141.39°E, 182 m), where continuous meteorological measurements are also made. Meteorological data except S_d and P_d of SAP were used as alternatives to those of HTJ. All sites are at mid-latitudes and in zones classified as temperate or continental climates. Annual precipitation at every site exceeds 1,000 mm. Details concerning SAP, API, KWG, FJY, and YMS are listed on the website http://www2.ffpri.affrc.go.jp/labs/flux/.

Table 1 also shows information on study sites where the previous studies for developing the P_d estimation models were conducted. The sites Chabot Regional Park (Ge et al. 2011), Almeria (Alados et al. 1996), and Granada (Alados and Alados-Arboledas 1999) are also at mid-latitudes, but annual precipitation at these sites is less than at the present study sites. The Fazenda Nossa Senhora ranch and Jaru Biological Reserve (Aguiar et al. 2012) are at low latitudes and have high rainfalls, more than 2,000 mm per year.

2.2 Measurements

Continuous measurements of S_d and P_d were made on forest towers at all sites, except HTJ. Those of HTJ were made on a building roof. General meteorological measurements were made at all forest tower sites, except atmospheric pressure at YMS. Atmospheric pressure at YMS was supplemented with data from a nearby weather station (Nara; 34.69°N, 135.83°E). These were provided by the meteorological agency and downloaded from the Agriculture, Forestry and Fisheries basic numeric database.

Pyranometers CM-5 (Kipp & Zonen, Netherlands), another CM-5, MR-22 (EKO, Japan), CM-6F (Kipp & Zonen, Netherlands), and MR-22 were used at HTJ, API, KWG, FJY, and YMS, respectively. LI-190s (LI-COR, USA) were used as quantum sensors at all sites. Pyranometers and quantum sensors at API and HTJ were calibrated using a benchmark sensor prior to measurement. Quantum sensors at KWG, FJY, and YMS were compared to the other sensors and calibrated regularly. HMP-45Ds (Vaisala, Finland) were used as temperature–humidity sensors at SAP, API, KWG, FJY, and YMS. PTB-100As (Vaisala, Finland) were used as barometers at SAP, API, KWG, and FJY.

Measurements except S_d and P_d at HTJ and API were routine. Data were scanned at 10- to 60-s intervals, and recorded at 5- to 10-min intervals. Details of the routine measurements are described in Kitamura et al. (2012) for SAP, Yasuda et al. (2012) for API, Yasuda et al. (1998) for KWG, Mizoguchi et al. (2011) for FJY, and Kominami et al. (2008) for YMS. S_d and P_d at HTJ and API were measured and recorded at 1-min interval.

3 Empirical models

3.1 New model development

A new model was developed based on analysis of hourly mean data at four sites (HTJ, API, KWG, and FJY). Validation was performed using data from YMS. Data were excluded when S_d (in watt per square meter) was less than 5 W m^{-2}, to avoid sensor sensitivity and cosine response problems. P_d (in micromole per square meter per second) is a part of S_d, and the ratio of P_d to S_d is affected by conditions in the atmospheric layer penetrated by the solar beam. Numerous meteorological elements were included as parameters affecting attenuation of

Table 1 Description of study sites

Site name, country	Location	Elevation (m)	Annual precipitation (mm)	Period of datasets used for development of P_d estimation model (or validation)	Literature related to P_d estimation model
Hitsujigaoka (HTJ), Japan	43.00°N, 141.39°E	140	1,343[a]	June to December 2009	Present work
Appi (API), Japan	40.00°N, 140.94°E	825	1,882[b]	May to December 2009	Present work
Kawagoe (KWG), Japan	35.87°N, 139.49°E	26	1,285[c]	January 2000 to December 2001	Present work
Fujiyoshida (FJY), Japan	35.45°N, 138.76°E	1,030	1,578[d]	January 2007 to December 2008	Present work
Yamashiro (YMS), Japan	34.79°N, 135.85°E	226	1,012[b]	January to December 2002	Present work, for validation only
Chabot Regional Park, USA	37.75°N, 122.1°W[e]	260[e]	672[f]	1 day every 2 weeks from June through August 2007, and 2 days every week from March through August 2008	Ge et al. (2011)
Granada, Spain	37.18°N, 3.58°W	660	358[g]	January 1994 to December 1995	Alados and Alados-Arboledas (1999)
Almeria, Spain	36.83°N, 2.41°W	20	196[h]	June 1990 to December 1992	Alados et al. (1996)
Fazenda Nossa Senhora ranch, Brazil	10.75°S, 62.35°W	293	2,295[i]	January 2004 to December 2006	Aguiar et al. (2012)
Jaru Biological Reserve, Brazil	10.08°S, 61.93°W	140	2,354[j]	January 2004 to May 2005, and January to December 2006	Aguiar et al. (2012)

[a] In 2009
[b] In 2009
[c] In 2001
[d] In 2007
[e] Central location of park
[f] Moraga, near the site, California, USA (The Weather Channel, 2012)
[g] Climatedata.eu (2012a)
[h] Climatedata.eu (2012b)
[i] In 2000 (Zanchi et al. 2009)
[j] 16-year average at Porto Velho, the nearest meteorological station (Juárez et al. 2007)

solar radiation. Finally, three parameters were selected for the multiple linear regression approach—clearness index (k_t) that is related to the solar beam, optical air mass (m) related to the distance the solar beam traverses, and vapor pressure (e, in pascal) related to atmospheric water vapor content. The clearness index (k_t) is the ratio of S_d to extraterrestrial solar radiation (S_0), and the optical air mass (m) is calculated with the following equation (Kondo 1994): $m=p/(p_0 \cos\theta)$, where p is atmospheric pressure (in hectopascal), p_0 is standard atmospheric pressure (=1,013 hPa), and θ is zenith angle (in radian). These parameters can be calculated using general meteorological data, i.e., S_d, p, air temperature, and relative humidity, plus information on site location, latitude, and longitude.

3.2 Previous models

There are previous studies to estimate P_d using general meteorological data. The following nine models were validated with data of the present work and compared to the new model.

Model 1: $P_d=-0.1248+0.0069\ S_d+0.0035\ S_d \cos\theta-0.0024\ S_d\ k_t$ (Ge et al. 2011)
Model 2: $P_d/S_d=1.791-0.1901 \ln k_t+0.005\ T_d+0.049 \cos\theta$ (Alados et al. 1996)
Model 3: $P_d/S_d=1.832-0.191 \ln k_t+0.099 \cos\theta$ (Alados et al. 1996)
Model 4: $P_d=4.57\ (0.462\ S_d-1.162)$ (Aguiar et al. 2012)
Model 5: $P_d=4.57\ (0.425\ S_d-0.482)$ (Aguiar et al. 2012)
Model 6: $P_d=4.57\ (0.469\ S_d-11.761\ k_t+1.612)$ (Aguiar et al. 2012)
Model 7: $P_d=4.57\ (0.434\ S_d-16.509\ k_t+2.939)$ (Aguiar et al. 2012)
Model 8: $P_d=4.57\ (0.464\ S_d-3.210\ k_t+1.105\ e-26.505)$ (Aguiar et al. 2012)
Model 9: $P_d=4.57\ (0.435\ S_d-18.125\ k_t+0.467\ e-7.072)$ (Aguiar et al. 2012),

where T_d is dew point temperature (in degree Celsius). Although the unit of P_d estimated with model 4 to model 9 was watt per square meter, these models were multiplied by 4.57 μmol J^{-1} (McCree 1972) and converted to micromole per square meter per second for application to our datasets.

4 Results and discussion

4.1 Characteristics of radiation and parameters at each site

Annual precipitation at the study sites is from 1,000 to 2,000 mm. Minimum monthly vapor pressure ranged from 400 to 600 Pa in winter, and maxima at each site were from 1,800 to 2,500 Pa in summer (Fig. 1a). Seasonal trends at the sites were similar, and vapor pressure at KWG and YMS was larger than at the other sites.

All sites are at mid-latitudes in the Northern Hemisphere, where the peak of S_d generally occurs near the summer solstice. Although S_d at all sites were large in summer and small in winter, some in June or July were smaller than those before or after these months (Fig. 1b). This is because these months are the rainy season in these areas. In addition, summer is a foggy season at FJY (Mizoguchi et al. 2011).

The ratios of P_d to S_d at all sites changed seasonally. The ratios were large in the humid summer season and small in

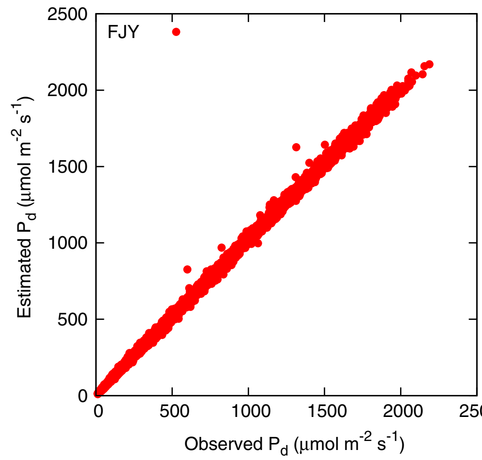


Fig. 2 Comparison between observed and estimated hourly mean photosynthetically active radiation (P_d) in 2007 at FJY

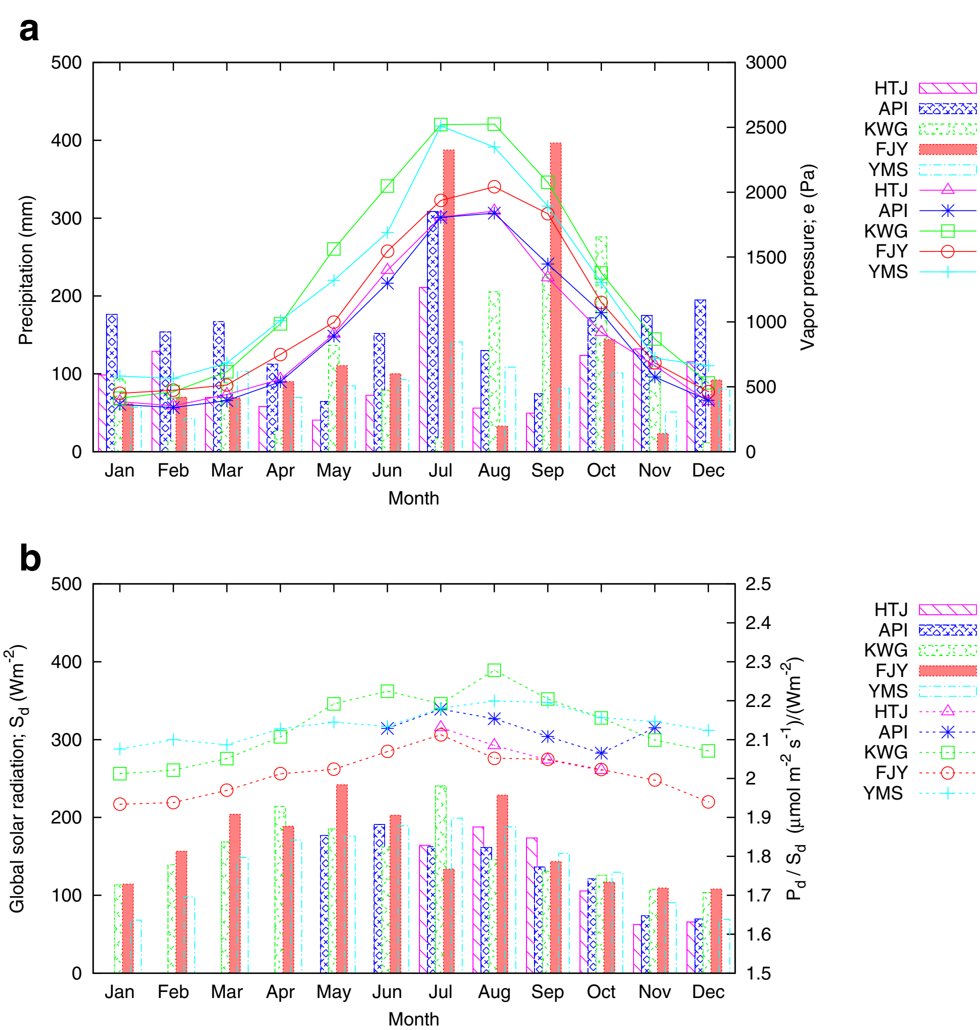
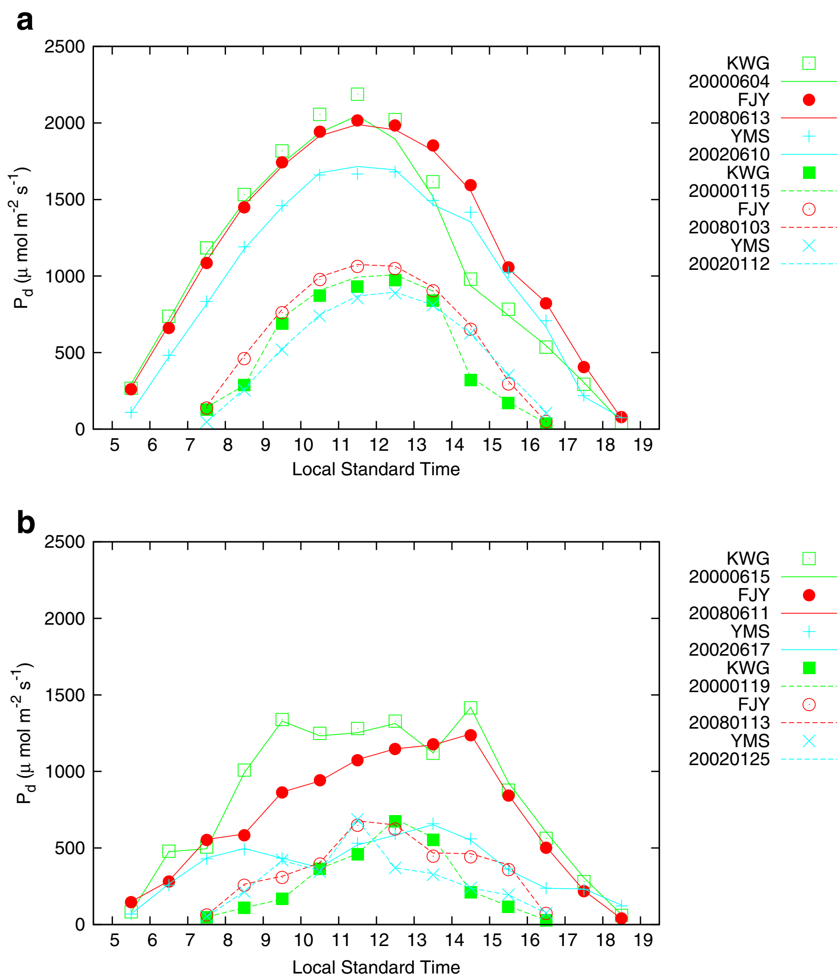


Fig. 1 Annual patterns of meteorological elements at HTJ (SAP) in 2009, API in 2009, KWG in 2001, FJY in 2007, and YMS in 2002. **a** Monthly precipitation (*bar*) and monthly mean vapor pressure (*line with marks*) and **b** monthly mean global solar radiation (*bar*) and monthly mean ratio of photosynthetically active radiation (P_d) to global solar radiation (S_d) (*line with marks*)

Fig. 3 Comparison of daily pattern of observed (*marks*) and estimated (*lines*) photosynthetically active radiation (P_d). **a** Typical sunny days in summer and winter and **b** typical cloudy days in summer and winter



the dry winter (Fig. 1b). This pattern is similar to that of previous studies, including Aguiar et al. (2012). The ratios at KWG and YMS were larger than those at HTJ and FJY, and the ratio at API was medium among the sites. This means that attenuation rates of radiation in the 400–700-nm waveband at KWG and YMS were lower than the rates at HTJ and FJY. Meanwhile, vapor pressure at HTJ (SAP) and API were similar but lower than at other sites, which means the trend of vapor pressure did not agree with that of the attenuation rates. This result suggests that it is

Table 2 Statistical results for developed model

Site	Year	Mean global photosynthetically active radiation P_d µmol m^{-2} s^{-1}	Mean bias deviation (MBD) %	Root mean square deviation (RMSD) %	Number of data
HTJ	2009	579	2.0	4.1	1,731
API	2009	602	−0.9	4.0	2,050
KWG	2000	699	−0.5	4.0	3,810
	2001	733	−3.1	5.2	3,742
FJY	2007	676	2.3	3.8	4,105
	2008	672	1.5	3.1	3,992
YMS	2002	617	−1.7	4.5	4,096

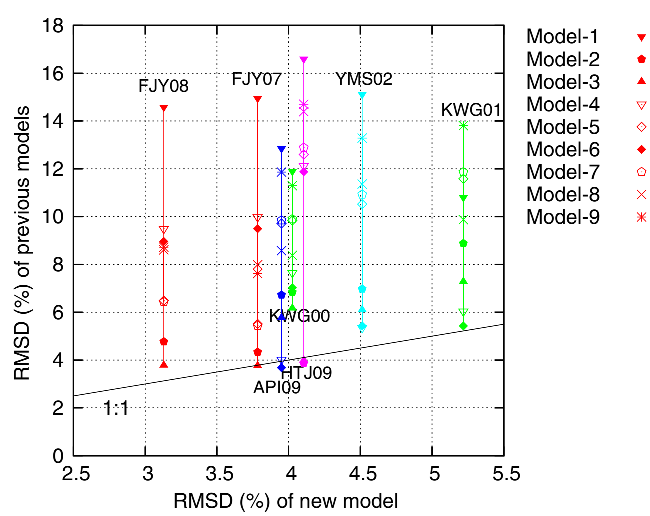


Fig. 4 Comparison of root mean square deviation (RMSD) between new and previous models. Starting from left, *lines* show datasets at FJY in 2008, FJY in 2007, API in 2009, KWG in 2000, HTJ 2009, YMS in 2002, and KWG in 2001

insufficient to use only one parameter related to atmospheric vapor content.

4.2 New empirical model and its validation

For hourly mean values of variables for six datasets of four sites (HTJ (SAP) in 2009, API in 2009, KWG in 2000 and 2001, and FJY in 2007 and 2008), the following expression was determined using the multiple linear regression approach.

$$P_d/S_d = -0.1255 \ln k_t - 0.02366 \ln m + 0.07268\, e + 1.873$$

Figure 2 shows the relationship between the observed and estimated values of hourly mean P_d in 2007 at FJY. The determination coefficient for all datasets was 0.9986. Coefficients for HTJ in 2009, API in 2009, KWG in 2000 and 2001, and FJY in 2007 and 2008 ranged from 0.9974 to 0.9987. The coefficient for YMS in 2002, which was not used in model development, was 0.997.

Figure 3 shows daily changes in observed and estimated P_d on typical sunny (Fig. 3a) and cloudy (Fig. 3b) days in summer and winter at KWG, FJY, and YMS. The estimates almost agree with observed values. Table 2 shows the mean P_d, mean bias deviation (MBD), and root mean square deviation (RMSD) for each dataset. MBD was from −3.1 to 2.3 %, and RMSD from 3.1 to 5.2 %. The determination coefficient of model 1 of Ge et al. (2011) was between 0.95 and 0.98. RMSD of model 2 and model 3 of Alados et al. (1996) ranged between 2.4 and 3.9 %. Estimated errors of the new model are similar to these previous models. These results suggest that the new model performs well and is useful for estimating P_d without much effort.

Meanwhile, P_d around noon on the sunny summer day at KWG was underestimated (Fig. 3a). The predominant wind direction in summer at KWG is southerly. The Tokyo metropolitan area, south of KWG, emits numerous artificial aerosols. The concentration of suspended particulate matter (SPM) around KWG was higher than those at other sites (National Institute for Environment Studies 2012). In addition, the distance between KWG and a heavily trafficked highway is shorter than 500 m. The influence of aerosol including SPM on radiation is not negligible (Kanniah et al. 2010). One reason for the estimation error at KWG might be from aerosol.

4.3 Comparison among models

RMSDs of the aforementioned nine models for seven datasets are compared with those of the new model in Fig. 4. RMSDs of models 4 and 6 for API, models 2 and 3 for HTJ, and model 3 for FJY in 2007 were smaller than those of the new model. Good performance at each site was reported in Aguiar et al. (2012), Alados et al. (1996), and Ge et al. (2011). Nevertheless, most RMSDs of the previous nine models were large, more than 5 % using our datasets. Maximum RMSD for the new model was 5.2 % at KWG in 2001. There are some models for some datasets with RMSD lower than 5.2 %; however, no model has lower RMSD for all datasets.

Models 1, 2, and 3 were developed for sites with dry conditions, and models 4 to 9 for sites in tropical zones at low latitude. Therefore, atmospheric conditions at the sites of the previous studies are very different from those at the present study sites in Japan. This might be the reason that models 1 to 9 did not perform well on datasets from the latter sites.

5 Conclusion

The newly developed P_d estimation model performed well, with RMSD 5.2 % or less. Estimation error was similar to previous models and to the observation error causing individual differences between the same sensor type. For field measurements over a long period, one must also consider sensor degradation from aging. Given the foregoing, the use of the estimation model is an option for acquiring P_d data. However, model estimation is limited by the difficulty in parameterizing aerosol effects with general meteorological elements. Quantification of the influence of air pollutants is a future issue.

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