Parametric models to estimate photosynthetically active radiation in Spain

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Abstract

Different applications dealing with plant physiology, biomass production and natural illumination in greenhouses require knowledge of the photosynthetically active radiation. In absence of measurements of this flux, one must rely on parametric approaches. In this way, the radiant energy is computed using available atmospheric parameters. In the present work, we have developed a comparison among several cloudless sky parameterization schemes. For this purpose, data recorded at two radiometric stations are used. The first one is located at the University of Almería, a seashore location, while the second one is located at Granada, an inland location. The performance of the models has been tested in relation to their predictive capability of direct, diffuse and global components of the photosynthetically active radiation. After our study, it appears that the information concerning the aerosol radiative effects is fundamental to obtain a good estimation, especially for the direct and diffuse components. In order to improve the fitting of the model to the experimental data, several modifications have been suggested. The modified version of the models provide estimates of direct and global components of the photosynthetically active radiation with mean bias deviation below 2%, and root mean square deviation close to experimental error, with slightly worse results for the diffuse component. ©2000 Elsevier Science B.V. All rights reserved.

Keywords: Photosynthetically active radiation; Solar irradiance; Direct irradiance; Diffuse irradiance; Parametric models; Estimation model

1. Introduction

Incident photosynthetically active radiation (400–700 nm) is required to model photosynthesis of single plant leaves or complex plant communities. Photosynthetically active radiation is the general radiation term that covers both photon terms and energy terms. Photosynthetic photon flux density, $Q_p$, is defined as the photon flux density ($1 \mu$mol photons $m^{-2}s^{-1}$ or $6.022 \times 10^{17}$ photons $\mu$E $m^{-2}s^{-1}$). This is the number of photons in the 400–700 nm waveband incident per unit time on a unit surface.

Taking into account that plants use both direct and diffuse photosynthetic photon flux densities, $Q_{pb}$ and $Q_{pd}$, knowledge of global horizontal photosynthetic flux density, $Q_{ph}$, is very important. On the other hand, natural surfaces are rarely horizontal, in many circumstances one must deal with inclined surfaces, thus the actual radiative flux available for plant photosynthesis is conditioned by the slope and surface orientation. Different models have been developed to estimate the
global irradiance on inclined surfaces (i.e., Hay and McKay, 1985; Skartveit and Olseth, 1986; Perez et al., 1990; Burlon et al., 1991; Gopinathan, 1991; Feurermann and Zemel, 1992; Olmo et al., 1999). Some of these models require knowledge of direct and diffuse horizontal components of the solar global irradiance. Thus, it appears that the knowledge of direct and diffuse components of photosynthetic photon flux density, $Q_{pb}$ and $Q_{pd}$, allow the use of this kind of model to estimate the global photosynthetic photon flux density, $Q_p$, incident on an inclined surface. Closed stands of plants can be treated as horizontal or inclined surfaces receiving the global irradiance corresponding to the surface inclination. However, isolated individuals can be treated as cylinders, spheres, etc., so that intercepted radiation can be estimated from measurements of direct and diffuse components (van der Hage, 1993, 1995; Berninger, 1994).

Different authors (Moon, 1940; Yocum et al., 1969; McCree, 1966; Britton and Dodd, 1976; McCartney, 1978; Ross, 1981; Varlet-Grancher et al., 1981; Stigter and Musabilha, 1982; Rodskjer, 1983; Howell et al., 1983; Papaioannou et al., 1993; Alados et al., 1996; Alados and Alados-Arboledas, 1999b) have studied the horizontal global photosynthetic photon flux density, $Q_{ph}$, while less attention has been devoted to the direct and diffuse components of this radiative flux, $Q_{pb}$ and $Q_{pd}$, (Rao, 1984; Karalis, 1989; Guémyard, 1989a, b; Olseth and Skartveit, 1993; Alados and Alados-Arboledas, 1999a).

This paper is devoted to the study of parametric models that provide an estimate of the different components of solar photosynthetically active radiation under cloudless conditions. This cloudless sky estimation, combined with the appropriate algorithm that takes into account the cloud effect, provides the estimation of photosynthetically active radiation by means of surface cloud observations or remote sensing data. In this paper, we consider broadband models, which are physically based. These models use broadband transmittances of the extinction process that takes place in the atmosphere, obtained by means of a parametric approach.

When the solar radiation propagates through the earth’s atmosphere it is attenuated by scattering (due to air molecules and aerosols) and absorption processes (mainly by ozone, water vapor, oxygen and carbon dioxide). The absorption occurs in lines and bands, while the scattering takes place over the whole solar spectrum, with more or less spectral dependence depending on the aerosols characteristics. The phenomena are complex since those factors that control the attenuation of solar radiation can change from one place to another or vary as a function of time.

In this work, we will only consider the real atmosphere with cloudless sky, and only models aimed at the computation of clear sky irradiances on a horizontal surface are considered here. In a previous study (Foyo-Moreno et al., 1993) some authors of the present work have shown the importance of a correct modeling of clear sky irradiances to obtain a good estimate under all sky conditions. This can be achieved by using a combination of an appropriate clear sky model with appropriate cloud transmission functions. By the way, the global evaluation of the solar irradiance over extended areas by means of satellite data, requires an appropriate but simple model in order to provide the cloudless sky value of the estimation algorithm (Olmo et al., 1996).

2. Data and measurements

The data set used in this study came from two radiometric stations. The first one is located in the outskirts of Granada ($37.18^\circ$N, $3.58^\circ$W, 660 m a.m.s.l), an inland location. The second station is located at the University of Almería, a seashore location ($36.83^\circ$N, $2.41^\circ$W, 10 m a.m.s.l). At Granada data collected at 1-min intervals during 1994 and 1995 has been used in the present study. At Almería the measurements cover the period 1993 and 1995, being registered as 5-min values. Solar global irradiance, $R_s$, was measured using a Kipp & Zonen model CM-11 (Delft, Netherlands), while another Kipp & Zonen model CM-11 with a polar axis shadowband was used to measure solar diffuse irradiance, $R_d$. Photosynthetic active photon flux density, $Q_{ph}$, has been measured by means of a LICOR model 190 SA quantum sensor (Lincoln, NE, USA). Another quantum sensor has been equipped with a polar axis shadowband in order to measure the diffuse photosynthetic active photon flux density incident on a horizontal surface, $Q_{pd}$. Finally, air temperature and relative humidity at 1.5 m, are recorded. Diffuse irradiance measurements obtained by means of the shadowband have been corrected following the
method proposed by Batlles et al. (1995). This method has also been applied to correct the diffuse photon flux density. From the original databases, hourly values have been generated, covering 1994–95 at Granada and 1993–94 at Almería. The corrected diffuse horizontal values of both radiative fluxes and the global horizontal fluxes are used to obtain the normal incidence direct beam components, both for the solar broadband irradiance, \( R_b \), and the photosynthetically active photon flux density, \( Q_{pb} \).

\[
R_b = (R_b - R_d) / \cos \theta_z \tag{1}
\]

\[
Q_{pb} = (Q_{ph} - Q_{pd}) / \cos \theta_z \tag{2}
\]

where \( \theta_z \) is the solar zenith angle.

Granada is located in the south-eastern of the Iberian Peninsula. Cool winters and hot summers characterise its inland location. Their diurnal temperature range is rather wide with the possibility of freezing on winter nights. Most rainfall occurs in spring and winter. The summer is very dry, with scarce rainfall in July and August.

The Almería radiometric station is located on the Mediterranean coast in south-eastern Spain and is characterised by a greater frequency of cloudless days, and high humidity.

Considering the period used, a complete range of seasonal conditions and solar angles is included among the samples. Analytical checks, for measurement consistency, were carried out to eliminate problems associated with shadowband misalignments, and other questionable data. Due to cosine response problems, we have limited our studies to cases with solar zenith angle less than 85°. Calibration constants of the radiometric devices used at Almería and Granada have been checked periodically by our research team. Degradation of less than a few tenths per cent per year has been observed in the CM-11 pyranometers. The drift of the calibration constants of the Quantum sensors have been evaluated both by means of a calibrated standard lamp and by field comparison with measurements performed by a well-calibrated field spectroradiometer (LI-1800). Measurements of solar global and diffuse irradiance have an estimated experimental error of about 2–3%, while the quantum sensor has a relative error less than 5%.

3. Parametric models

The parametric models included in this study compute broadband transmittances for the different atmospheric extinction process. The use of these transmittances allows the computation of the direct beam component. For the diffuse component some approximations have been used in order to parameterise the complexity of scattering process. Finally, the global irradiance is obtained by combination of the direct irradiance projected onto the horizontal surface and the diffuse horizontal irradiance. In order to consider the differences in the parametric approach analyzed we summarize the models main features.

CPCR2 is a two-band model proposed for the clear sky case and it is completely described in Gueymard (1989b). The solar spectrum is divided into a UV/VIS band (290–700 nm) and an infrared band (700–2700 nm). In our case, only the first band is relevant, considering the wavelength covered by the photosynthetically active spectrum.

We have included in our study a second model developed by Gueymard (1989a). This model that we call PAR MODEL has been developed considering specially the photosynthetically active spectrum. The transmittances related to the different atmospheric processes have been obtained considering only the waveband 400–700 nm.

Although the second model is specially developed for the photosynthetically active radiation, we have considered also the CPCR2 model, considering that it has been developed for the whole solar spectrum. Thus, by means of a simple execution of the same model we can obtain both fluxes, the photosynthetically active and that corresponding to the total solar spectrum.

Both models are based on the solar extraterrestrial spectrum proposed by the World Radiometric Center (WRC), with a solar constant value of \( I_{cs} = 1367 \text{ W/m}^2 \). The spectral bands considered in the CPCR2 model include about 46.04 and 50.57% of the total solar spectrum, respectively. For the PAR MODEL the solar extraterrestrial constant covering the photosynthetically active waveband is about 38.8% of the whole solar spectrum.

Both models give the beam irradiance at normal incidence by means:

\[
R_{ni} = \tau_{oi} \tau_{ri} \tau_{gi} \tau_{wi} \tau_{ai} R_{ci} \tag{3}
\]
where $R_{c_l}$ is the extraterrestrial irradiance for the corresponding waveband and $\tau_{ji}$ represents the integrated transmittances for the process $j$ in the waveband $i$. $\tau_{ai}$ correspond to the absorption due to ozone. $\tau_{ri}$ represents the transmittance due to Rayleigh scattering by molecules. $\tau_{ai}$ is the term associated to the absorption and scattering produced by aerosol particles. These three processes are the relevant for the spectral band considered. A complete description of the parameterization used for the corresponding transmittances used in model PAR MODEL and CPCR2 are included in Gueymard (1989a, b).

The aerosol optical transmittance for each band is parameterized following the Angström spectral aerosol transmittance model:

$$\tau_{ai} = \exp \left( -m_a \beta \lambda^{-\alpha} \right)$$

where $m_a$ is the optical air mass that can be computed from solar zenith angle following the procedure described by Kasten (1965) and $\alpha$ and $\beta$ are coefficient depending on the type and amount of aerosol particles. Considering the partitioning in spectral bands, it follows:

$$\tau_{ai} = \exp \left( -m_a \beta \lambda^{-\alpha} \right)$$

where $\lambda_{ci}$ are the effective wavelengths for each band that depend on optical air mass, $m_a$, $\alpha$ and $\beta$ (Gueymard, 1989b).

The diffuse component is modelled as a combination of three individual components corresponding to the two scattering layers (molecules, $R_{dri}$, and aerosols, $R_{dai}$), and to a multiple reflections, $R_{dni}$, process between ground and sky:

$$R_d = R_{dri} + R_{dai} + R_{dni}$$

The components of diffuse irradiance for each band are obtained as:

$$R_{dri} = F_i \tau_{ai} \tau_{asi} \left( 1 - \tau_{ri} \right) R_{c_l} \cos \theta_z$$

$$R_{dai} = F_a \tau_{ai} \tau_{ri} \left( 1 - \tau_{ai} \right) R_{c_l} \cos \theta_z$$

$$R_{dni} = \rho_g \rho_s (R_{asi} \cos \theta_z + R_{dai} + R_{dri}) \left( 1 - \rho_g \rho_s \right)$$

where $R_{asi}$ is the normal beam irradiance, $\rho_g$ and $\rho_s$ are the ground and sky albedo, respectively. For the aerosol contribution we have:

$$\tau_{ai} = \tau_{asi} \tau_{asi}$$

with

$$\ln \tau_{asi} = \omega_{asi} \ln \tau_{ai}$$

where $\omega_{asi}$ is the scattering single albedo that depends on the absorption features of the aerosol particles and $\tau_{asi}$ represent the aerosol transmittance due to aerosol absorption and pure scattering, respectively. Table 1 includes different values for this coefficient following Gueymard (1989a). The terms $F_i$ and $F_a$ represent the forward scatterance factor associated to Rayleigh and aerosols scattering. A fixed value of 0.5 has been considered for $F_i$, while a value of $F_a$ independent of wavelength has been computed following Robinson (1962):

$$F_a = 1 - \exp \left( -0.6931 - 1.8326 \cos \theta_z \right)$$

The diffuse irradiance due to multiple reflections between the earth’s surface and the atmosphere depends on the ground albedo, $\rho_g$, and on the sky albedo, $\rho_s$. In both models these albedos have been considered independent of wavelength. For the last, the expression proposed by Justus and Paris (1985) is used:

$$\rho_{si} = \left\{ (1 - F_i) \left( 1 - \tau_{ri}^t \right) + (1 - F_a) \left( 1 - \tau_{asi}^t \right) \tau_{ri}^t \right\} \times \tau_{asi}^t$$

where the prime indicates that the corresponding transmittance or forward scatterance factor have been computed at air mass 1.66, according to the diffusion approximation (Kondratyev, 1969).

The global component of photosynthetically active radiation is obtained from the corresponding diffuse and direct components according to Eqs. (1) and (2).

As indicated previously, the first band parameterised in model CPCR2 covers wavelengths between 290 and 700 nm. In order to obtain the photosynthetically active radiation (400–700 nm), Gueymard (1989b) proposed the following conversion functions, to obtain the direct, $R_{pb}$, and global, $R_g$, components of the photosynthetically active radiation:

$$R_{pb} = R_b \left( 0.87375 + 0.04031 m_a + 0.00358 m_a^2 \right)$$

$$R_g = R_s \left( 0.86225 + 0.02084 m_a + 0.00234 m_a^2 \right)$$
These expressions are valid for optical air masses, $m_a$, lower than 6. The diffuse component is computed from the direct and global ones.

When one is interested in rates of photosynthesis, it is more appropriate to express the radiation incident in terms of photosynthetically active photon flux rather than radiant energy flux, considering the effectiveness of photons between 400 and 700 nm in driving the light reactions of photosynthesis. Conversion of radiometric units to photon flux requires knowledge of the spectral distribution of the radiant flux. Diffuse radiation has a different spectral composition than direct radiation because shorter wavelengths are scattered by air molecules more effectively. However, larger particles such as dust and water droplets scatter all wavelengths equally. The spectral composition of the diffuse and direct radiation will depend on the atmospheric conditions: optical air mass, atmospheric turbidity, clouds, etc.

Thus, to compute the photosynthetic photon flux density, it is necessary to define an additional conversion function. Skartveit and Olseth (1994) have developed a model that depends on the sun height and atmospheric conditions: optical air mass, atmospheric turbidity, clouds, etc.

We have generated a set of pairs of photosynthetically active radiation (W m$^{-2}$) and photosynthetically active photon flux density (µE m$^{-2}$ s$^{-1}$) values by running the spectral code SPECTRAL-2 (Bird and Riordan, 1986) for a range of atmospheric conditions. Thus, the optical air mass has been varied from 1 to 5, the amount of precipitable water from 0.5 to 3.5 cm, the amount of ozone from 200 to 400 Dobson units. Finally, the Angstrom coefficient for aerosol extinction, $\beta$, has been varied from 0.01 to 0.4, and the Angstrom coefficient, $\alpha$, from 0.5 to 3. Using this set of data, we have tested the proposal by Skartveit and Olseth (1994). Fig. 1 (a, b) shows the deviation between the photosynthetically active photon flux density obtained by spectral computations (SPECTRAL-2) and that obtained by application of the Skartveit and Olseth conversion functions to the photosynthetically active radiation (W m$^{-2}$). We have included information on the Root Mean Square deviation, RMSD, and Mean Bias Deviation, MBD, expressed as a percentage of the mean experimental value of the corresponding photosynthetic photon flux density. These statistics allow for the detection of both the differences between experimental data and model estimates and the existence of systematic over or underestimation tendencies, respectively. It is evident the great deviation in the diffuse component, $Q_{pd}$. For the direct component, the MBD present a negligible value, nevertheless the RMSD is rather high indicating the spreading of the deviations. In view of these results, we have developed our own model. Thus, using the pairs of direct and diffuse values of photosynthetically active radiation in terms of irradiance, $R_{pb}$ and $R_{pd}$, and photon flux density, $Q_{pb}$ and $Q_{pd}$, we have obtained the following conversion functions:

$$\frac{Q_{pd}}{R_{pd}} = 6.4 + 2.3 \exp\left(\frac{-m_a}{0.65}\right) + (1.4m_a - 15.2) \beta$$

$$+ (41.3 - 3.9m_a) \beta^2 + (6.0m_a - 46.4) \beta^3$$

$$\frac{Q_{pb}}{R_{pb}} = 4.48 - 0.02m_a - 0.04m_a^2$$

$$+ 0.64\beta \exp(0.65m_a)$$

(16)

(17)

where $m_a$ is the relative optical air mass (Kasten, 1965). Fig. 1 (c,d) show the behaviour of these new functions, that consider explicitly the variability of the turbidity conditions. The RMSD and MBD values reflect the low spread of the deviation around zero. It is obvious that the greater improvement correspond to the diffuse component. Thus, we observe that, as indicated by some authors (Gueymard, 1989a, b; Skartveit and Olseth, 1994), under cloudless conditions the conversion factor for the diffuse component depends on turbidity more than that associated to the beam ratio.

4. Performance of models

As indicated by Gueymard (1993) a correct description of the transparency conditions is relevant for the kind of models analyzed in this study. In order to obtain the Angstrom coefficient, $\beta$, for the aerosol extinction we have followed the procedure developed by Gueymard (1998). For this purpose, broadband measurements of solar radiation have been combined with meteorological parameters.

The performance of the models was evaluated using the root mean square deviation (RMSD) and the mean bias deviation (MBD). We have analyzed also
Fig. 1. Deviation between Photosynthetic photon flux density computed from spectral data and that obtained by the use of conversion function: (a) Skartveit and Olseth function for the diffuse component, $Q_{pd}$; (b) Skartveit and Olseth function for the direct component, $Q_{pd}$; (c) New function for the diffuse component, $Q_{pd}$ (Eq. (16)); (d) New function for the direct component, $Q_{pd}$ (Eq. (17)). Mean measured value of diffuse photosynthetic photon flux density: 744 μE m$^{-2}$ s$^{-1}$. Mean measured value of global photosynthetic photon flux density: 1135 μE m$^{-2}$ s$^{-1}$. 
the linear regression between estimated and measured values, providing information about correlation coefficient, \( R \), and slope, \( b \). The first one gives an evaluation of the experimental data variance explained by the model. For this analysis we have forced the intersection through zero and in this way the slope, \( b \), can provide information about the relative underestimation or overestimation associated to the model. Separated results are presented for the direct, diffuse and global components of the photosynthetically active photon flux density.

For the selection of cloudless sky conditions we have used the meteorological observer criterion, that is total octas zero. In this sense, it is interesting to note the availability at both places of meteorological observations performed by the Spanish Meteorological Service. At Granada this observation is done at the same radiometric station, at Almería the observation performed in the Almería Airport, 1 Km away from the radiometric station, has been used. At both stations the cloud observations are not registered in hourly basis, for this purpose we have developed a cloudless sky criterion based on the analysis of the cloudless values of the hemispherical broadband transmittance, \( k_t \). The last term is defined as the solar global irradiance, \( R_g \), normalized to the extraterrestrial radiation, \( R_o \), projected onto the horizontal surface. This hemispherical broadband radiation is influenced both by aerosol and clouds, the latter being the more influencing factor. We have analyzed the hemispherical broadband transmittance, \( k_t \), for cloudless skies conditions, zero octas according to the meteorological observer record. These analyses have evidenced the great influence of the solar zenith angle, \( \theta_z \). Thus, we have fitted this dependence by means of a polynomial function of \( \cos \theta_z \). A threshold for the cloudless sky conditions have been defined by subtracting from this equation the standard deviation associated to the independent coefficient of this polynomial function. In this sense the criterion for cloudless sky conditions reads as follows:

\[
k_t > 0.53 + 0.31 \cos \theta_z - 0.15 \cos^2 \theta_z
\]  

(18)

This criterion allows the extension of the data used in this study. Nevertheless, it is interesting to note that the application of this criterion rejects in some circumstances cloudless sky data. A test applied over the data set registered at both locations indicates that the previous threshold, developed for data registered at Granada, rejects erroneously less than 3 and 5% of the zero octas data for Granada and Almería, respectively. On the other hand, this test considers as cloudless condition cases that the meteorological observer has characterized with a cloud amount greater than zero octas. A test of these ‘false’ inclusions as cloudless conditions reveals that they represent about 15 and 18% in Granada and Almería, respectively. In spite of the magnitude of these ‘false inclusions’ it is interesting to note that the analysis of these cases suggest that they correspond to cases where the radiative effect of clouds is not relevant due to factors such as the sun-cloud geometry and/or the cloud type present. In this sense, we consider that the threshold is appropriate for our purpose.

For both localities, considering the location of the radiometric station we have selected a surface albedo of 0.15. As indicated, for \( F_a \), the factor of forward scattering, we use the set of values proposed by Robinson (1962) as a function of the solar zenith angle. For the ozone amount we have used the latitudinal model proposed by van Heuklen (1979).

We have started our analysis with the data set registered at Granada. The first task we face is the selection of some aerosol parameters, such as the Angstrom exponent, \( \alpha \), and the single scattering albedo, \( \omega_o \). As a first step, we have selected for \( \alpha \) its climatic values 1.3. On the other hand, the selection of the single scattering albedo, \( \omega_o \), has been done following the values proposed by Gueymard (1989a). For different types of atmosphere they are: 0.965 for Maritime rural clear, 0.931 for Rural medium, 0.865 for Rural/Urban, 0.800 for Urban medium and 0.667 for Urban contaminated. After several trials, the best results are obtained using a single scattering albedo, \( \omega_o \), of 0.750. This value is less than that associated with an urban atmosphere (0.800). This in accordance with several studies over the optical properties of the aerosol at Granada that are under development. These studies find that the amount of soot particles in the aerosol present at Granada is greater than that present in an urban medium atmosphere.

Table 1 shows the results obtained with this selection of parameters. It is evident that the global photosynthetic photon flux density, \( Q_{ph} \), is obtained with a MBD close to experimental errors. Nevertheless, the MBD associated to the direct and diffuse components reveals opposite trends to under and overestimation,
respectively. These deviations are rather important, but the opposite signs lead to a compensation in the estimation of the global component. Obviously, the selection of $\omega_0$ influences the estimation of the diffuse component and through these affects also the estimation of the global component. We have selected the $\omega_0$ value that provides the better estimation of the diffuse component and that is appropriate for the atmospheric conditions considered. The estimation of the direct component can be improved using a different choice for the exponent $\alpha$. We have tested the use of an exponent $\alpha$ depending on the humidity as proposed by Gueymard (1994a, b), after some simulations with the spectral code MODTRAN. Nevertheless, at the radiometric station of Granada, operated jointly by the Spanish Meteorological Service (INM) and the University of Granada, the aerosol optical depth at several wavelengths has been measured routinely since the end of 1994 until the middle of 1998. As the sunphotometer measurements do not cover the complete period of photosynthetically active radiation analysed, we can not use this aerosol information as input in our study. However, as computations on this data have allowed the estimation of the Angstrom exponent, $\alpha$, we have developed a study on the relative humidity influence over this exponent. The values of the Angstrom exponent, $\alpha$, as a function of the relative humidity applicable to Granada conditions are: 0.76 for relative humidity less than 50%, 1.05 for relative humidity greater/equal than 50% and less than 70%, 1.09 in the relative humidity range 70–90% and 0.98 for relative humidity greater/equal than 90%. With this new information, we have estimated the different photosynthetically active radiation components. Table 2 shows the results obtained with MODEL PAR using the $\alpha$ values depending on relative humidity. It is evident that this choice provides an estimation of the direct photon flux density, $Q_{pb}$, with negligible MBD. The slope, $b$, of the linear fit of estimated versus measured values forcing the intercept through zero evidences the proximity to the line 1:1 of perfect fit. On the other hand, the overestimation associated to the estimation of the diffuse component show a reduction close to 30%, compared with Table 1. Nevertheless, it seems evident that the model overestimates the diffuse component. Considering this fact, we propose some modifications concerning the parameterization of the diffuse component. The first modification is based in a previous proposal by Bird and Riordan (1986) used in the spectral code SPECTRAL-2. These authors proposed a modified version of the diffuse contribution due to Rayleigh and aerosol scattering that reads as follows:

$$R_{\text{diff}} = F_i \tau_{\text{a}} \tau_{\text{as}} \left(1 - \tau_i^{0.95}\right) R_{ci} \cos \theta_z$$

In Table 3 we include the results obtained when this modifications applied. It is evident that these last modifications improve the estimation obtained both

### Table 1

Statistical results for the MODEL PAR using a fixed value for $\alpha=1.3$ and $\omega_0=0.750^a$

<table>
<thead>
<tr>
<th>PAR</th>
<th>Mean value (µE m^{-2} s^{-1})</th>
<th>$b$</th>
<th>$R$</th>
<th>MBD (%)</th>
<th>RMSD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>1469</td>
<td>1.054</td>
<td>0.987</td>
<td>5.0</td>
<td>7.2</td>
</tr>
<tr>
<td>Direct</td>
<td>1412</td>
<td>0.911</td>
<td>0.978</td>
<td>-9.3</td>
<td>10.2</td>
</tr>
<tr>
<td>Diffuse</td>
<td>374</td>
<td>1.401</td>
<td>0.798</td>
<td>46.0</td>
<td>50.9</td>
</tr>
</tbody>
</table>

$^a$ Granada data set. The coefficient $b$ represents the slope of the linear fit of estimated vs measured values forced through the origin. $R$ is the correlation coefficient of the linear fit of estimated vs measured. Mean Bias Deviation, MBD, and Root Mean Square Deviation, RMSD, expressed as percentage of mean experimental value. Total number of hourly data $N=1120$.

### Table 2

Statistical results for the MODEL PAR using $\alpha$ values depending on relative humidity and $\omega_0=0.750^a$

<table>
<thead>
<tr>
<th>PAR</th>
<th>Mean value (µE m^{-2} s^{-1})</th>
<th>$b$</th>
<th>$R$</th>
<th>MBD (%)</th>
<th>RMSD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>1469</td>
<td>1.080</td>
<td>0.991</td>
<td>7.7</td>
<td>9.2</td>
</tr>
<tr>
<td>Direct</td>
<td>1412</td>
<td>1.015</td>
<td>0.972</td>
<td>1.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Diffuse</td>
<td>374</td>
<td>1.201</td>
<td>0.835</td>
<td>25.1</td>
<td>31.1</td>
</tr>
</tbody>
</table>

$^a$ Granada data set. Total number of hourly data $N=1120$. Rest of symbols as in Table 1.

### Table 3

Statistical results for the MODEL PAR, modified according to Bird and Riordan (1986), using $\alpha$ values depending on relative humidity and $\omega_0=0.750^a$

<table>
<thead>
<tr>
<th>PAR</th>
<th>Mean value (µE m^{-2} s^{-1})</th>
<th>$b$</th>
<th>$R$</th>
<th>MBD (%)</th>
<th>RMSD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>1469</td>
<td>1.060</td>
<td>0.990</td>
<td>5.7</td>
<td>7.7</td>
</tr>
<tr>
<td>Direct</td>
<td>1412</td>
<td>1.015</td>
<td>0.972</td>
<td>1.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Diffuse</td>
<td>374</td>
<td>1.125</td>
<td>0.815</td>
<td>17.4</td>
<td>25.7</td>
</tr>
</tbody>
</table>

$^a$ Granada data set. Total number of hourly data $N=1120$. Rest of symbols as in Table 1.
Table 4
Statistical results for the MODEL PAR MODIFIED using $\alpha$ values depending on relative humidity and $\omega_0=0.750^a$

<table>
<thead>
<tr>
<th>PARM</th>
<th>Mean value $\mu$E m$^{-2}$ s$^{-1}$</th>
<th>$b$</th>
<th>$R$</th>
<th>MBD (%)</th>
<th>RMSD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>1469</td>
<td>1.014</td>
<td>0.984</td>
<td>0.9</td>
<td>5.5</td>
</tr>
<tr>
<td>Direct</td>
<td>1412</td>
<td>1.015</td>
<td>0.972</td>
<td>1.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Diffuse</td>
<td>374</td>
<td>0.937</td>
<td>0.794</td>
<td>-1.3</td>
<td>21.1</td>
</tr>
</tbody>
</table>

$^a$ Granada data set. Total number of hourly data $N=1120$. Rest of symbols as in Table 1.

for the diffuse and global components. Nevertheless, it is evident that the reduction in the diffuse component is not enough to obtain a good estimation of this component and through this of the global component. A better agreement is obtained by modifying also the aerosol contribution, for this purpose we include the single scattering albedo as a multiplying factor, following a procedure similar to that included in the solar broadband model Iqbal A (Iqbal, 1983). Thus, the contribution to the diffuse component due to aerosols reads as follows:

$$R_{dai} = \omega_0 F_{aoi} \tau_{ai}^{1.5} (1 - \omega_{ai}) R_{ai} \cos \theta_z$$  \hspace{1cm} (21)

From Table 4, we can see that the inclusion of the single scattering albedo as a multiplying factor in Eq. (21) provides the best results. Thus, the final model that we call MODEL PAR MODIFIED (PARM), provides estimation with negligible MBD and with RMSD close to the experimental errors.

In order to show the improvement obtained with the modified model we present some scatter plots. Fig. 2 shows the scatter plot for the three components of the photosynthetically active photon flux density estimated according to the selection used for the analysis shown in Table 1. For the sake of comparison, Fig. 3 includes the scatter plot of estimated versus measured when the estimation is performed with MODEL PAR MODIFIED. It is evident the improvement obtained, especially for the diffuse component. For the direct and global components we can see that the modifications proposed produce a closer fitting to the line 1:1 of perfect fit. The reduction in the initial overestimation of the diffuse component is also evident.

The tests performed over the model CPCR2 have followed similar steps. In Tables 5 and 6 we can see the results for the original model and that obtained with the inclusion of the modifications described earlier.
Table 5
Statistical results for the CPCR2 model using $\alpha$ values depending on relative humidity and $\omega_0=0.750$

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean value ($\mu E m^{-2}s^{-1}$)</th>
<th>$b$</th>
<th>$R$</th>
<th>MBD (%)</th>
<th>RMSD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>1469</td>
<td>1.098</td>
<td>0.991</td>
<td>9.5</td>
<td>10.9</td>
</tr>
<tr>
<td>Direct</td>
<td>1412</td>
<td>1.001</td>
<td>0.966</td>
<td>0.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Diffuse</td>
<td>374</td>
<td>1.304</td>
<td>0.834</td>
<td>36.1</td>
<td>40.6</td>
</tr>
</tbody>
</table>

* Granada data set. Total number of hourly data $N=1120$. Rest of symbols as in Table 1.

Table 6
Statistical results for the CPCR2 MODIFIED model using $\alpha$ values depending on relative humidity and $\omega_0=0.750$*

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean value ($\mu E m^{-2}s^{-1}$)</th>
<th>$b$</th>
<th>$R$</th>
<th>MBD (%)</th>
<th>RMSD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>1469</td>
<td>1.024</td>
<td>0.984</td>
<td>2.0</td>
<td>5.9</td>
</tr>
<tr>
<td>Direct</td>
<td>1412</td>
<td>1.001</td>
<td>0.966</td>
<td>0.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Diffuse</td>
<td>374</td>
<td>1.014</td>
<td>0.790</td>
<td>6.4</td>
<td>21.6</td>
</tr>
</tbody>
</table>

* Granada data set. Total number of hourly data $N=1120$. Rest of symbols as in Table 1.

After the inclusion of the modifications described for the last model, we achieve similar results to those presented in Table 4 for MODEL PAR MODIFIED both for the direct and global components. Nevertheless, the diffuse component presents an overestimation of about 6%. We call the modified version of the model CPCR2 MODEL, CPCR2 MODIFIED (CPCR2M).

Both models have been also tested using the data set registered at Almería. The preliminary tests have shown the value of the modifications introduced both in MODEL PAR and CPCR2. Considering the choice of the aerosol parameters that control the extinction process, we have used the aerosol type urban medium, with $\omega_0=0.800$. In Table 7 we present the results obtained for the original model PAR, using a climatolog-

Table 7
Statistical results for the MODEL PAR using a fixed value for $\alpha=1.3$ and $\omega_0=0.800$*

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean value ($\mu E m^{-2}s^{-1}$)</th>
<th>$b$</th>
<th>$R$</th>
<th>MBD (%)</th>
<th>RMSD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>1376</td>
<td>1.057</td>
<td>0.989</td>
<td>5.5</td>
<td>7.0</td>
</tr>
<tr>
<td>Direct</td>
<td>1384</td>
<td>0.948</td>
<td>0.973</td>
<td>-5.7</td>
<td>7.7</td>
</tr>
<tr>
<td>Diffuse</td>
<td>388</td>
<td>1.279</td>
<td>0.903</td>
<td>32.7</td>
<td>44.9</td>
</tr>
</tbody>
</table>

* Almería data set. Total number of hourly data $N=1376$. Rest of symbols as in Table 1.
Table 8
Angstrom exponent values as a function of relative humidity for different aerosol types (after Gueymard, 1994a, b)

<table>
<thead>
<tr>
<th>Relative humidity</th>
<th>0%</th>
<th>50%</th>
<th>70%</th>
<th>90%</th>
<th>99%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>$\alpha_1$</td>
<td>0.933</td>
<td>0.932</td>
<td>0.928</td>
<td>0.844</td>
</tr>
<tr>
<td></td>
<td>$\alpha_2$</td>
<td>1.444</td>
<td>1.441</td>
<td>1.428</td>
<td>1.377</td>
</tr>
<tr>
<td>Urban</td>
<td>$\alpha_1$</td>
<td>0.822</td>
<td>0.827</td>
<td>0.838</td>
<td>0.779</td>
</tr>
<tr>
<td></td>
<td>$\alpha_2$</td>
<td>1.167</td>
<td>1.171</td>
<td>1.186</td>
<td>1.256</td>
</tr>
<tr>
<td>Maritime</td>
<td>$\alpha_1$</td>
<td>0.468</td>
<td>0.449</td>
<td>0.378</td>
<td>0.232</td>
</tr>
<tr>
<td></td>
<td>$\alpha_2$</td>
<td>0.626</td>
<td>0.598</td>
<td>0.508</td>
<td>0.246</td>
</tr>
<tr>
<td>Tropospheric</td>
<td>$\alpha_1$</td>
<td>1.010</td>
<td>1.008</td>
<td>1.005</td>
<td>0.911</td>
</tr>
<tr>
<td></td>
<td>$\alpha_2$</td>
<td>2.389</td>
<td>2.378</td>
<td>2.357</td>
<td>2.130</td>
</tr>
</tbody>
</table>

*a Subscript is 1 for waveband 290–500 nm, subscript 2 is for waveband 500–2700 nm.

ical value of 1.3 for the Angstrom exponent, $\alpha$. As indicated previously, the estimation of the direct component can be improved using a different choice for the exponent $\alpha$. In this sense, we have tested the use of an exponent $\alpha$ depending on the humidity as proposed by Gueymard (1994a, b), after some simulations with the spectral code MODTRAN. Table 8 includes the different values proposed for different types of aerosols (Gueymard, 1994a, b). For MODEL PAR and CPCR2 we have computed the corresponding value of $\alpha$ by a weighted average between $\alpha_1$ and $\alpha_2$, considering the spectral distribution of the photosynthetically active radiation for the first one and that associated for the waveband 290–700 nm for CPCR2. Table 9 shows the $\alpha$ values considered for Almería, which are derived from those corresponding to the urban aerosol type in Table 8.

The results obtained with an Angstrom exponent dependent on the relative humidity are shown in Table 10. The direct photosynthetically active radia-

Table 9
$\alpha$ values as a function of relative humidity for the photosynthetically active radiation waveband corresponding to the urban aerosol type

<table>
<thead>
<tr>
<th>Relative humidity</th>
<th>0%</th>
<th>50%</th>
<th>70%</th>
<th>90%</th>
<th>99%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ (PAR)</td>
<td>1.055</td>
<td>1.060</td>
<td>1.073</td>
<td>1.102</td>
<td>0.921</td>
</tr>
<tr>
<td>$\alpha$ (CPCR2)</td>
<td>1.019</td>
<td>1.024</td>
<td>1.037</td>
<td>1.052</td>
<td>0.855</td>
</tr>
</tbody>
</table>

Table 10
Statistical results for the MODEL PAR using $\alpha$ values tabulated in Table 9 and $\omega_0=0.800$

<table>
<thead>
<tr>
<th>PARM</th>
<th>Mean value (µE m$^{-2}$ s$^{-1}$)</th>
<th>$b$</th>
<th>$R$</th>
<th>MBD (%)</th>
<th>RMSD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>1376</td>
<td>0.998</td>
<td>0.984</td>
<td>-0.5</td>
<td>5.7</td>
</tr>
<tr>
<td>Direct</td>
<td>1384</td>
<td>0.993</td>
<td>0.972</td>
<td>-0.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Diffuse</td>
<td>388</td>
<td>0.944</td>
<td>0.892</td>
<td>-1.0</td>
<td>18.3</td>
</tr>
</tbody>
</table>

*a Almería data set. Total number of hourly data $N=1376$. Rest of symbols as in Table 1.
middle range, which includes the greater percentage of cases.

The study of the CPCR2 model can be summarized by the analysis of Tables 12 and 13, where we present results for the original and modified model. As in the analysis performed with data registered at Granada, the modification proposed leads to an improvement in the estimation of the different components. Nevertheless, for the diffuse component there persists an overestimation tendency. In this sense, at both locations, the PAR MODIFIED MODEL provides estimation better than that obtained by means of the CPCR2 MODIFIED MODEL, for all the components of the photosynthetic photon flux density.

5. Concluding remarks

In the present work, we have developed a comparison among two cloudless sky parameterization schemes of the photosynthetically active radiation. We have compared two parametric models against carefully measured data in two mid-latitude radiometric stations characterized by different climatic regimes. There is a coastal location, Almería, and an inland location. In a previous study (Alados and
Alados-Arboledas, 1999a), we have shown the evidence of the existence of different cloud and aerosol regimes in the locations analysed. This study shows the results obtained by analysing the database in an hourly basis.

We have developed a radiative criterion to distinguish cloudless conditions from those characterized by the presence of clouds. The method is based on the definition of threshold values of the hemispherical broadband transmittance, $k_t$. This criterion allows the extension of the data used with confidence level appropriate for the kind of radiative studies developed in this work.

The present work has shown the value of the MODEL PAR MODIFIED for the parameterization of cloudless skies photosynthetically active radiation. This model, based on the MODEL PAR developed by Gueymard, improves the estimation of the diffuse component, and through this of the global component. This improvement is obtained by introducing some modifications concerning the parameterization of the aerosol and molecules contribution to the diffuse component. Similar results are obtained by the introduction of the mentioned modifications in the CPCR2 model. In this sense, these two formulations provide an important background for the estimation of solar radiation components under all sky conditions, once an appropriate cloud transmittance parameterization was selected. Both models use an extensive parameterization of the atmospheric extinction processes. The transparency information plays an important role in both parameterizations, and in this sense, appropriate information on turbidity conditions has to be included. It seems that the Angstrom coefficient, $\beta$, can be obtained appropriately through solar radiation broadband measurements and meteorological variables. The selection of the Angstrom exponent, $\alpha$, and the single scattering albedo, $\omega_0$, requires some care. Tabulated values as a function of aerosol type could provide appropriate results. Nevertheless, in some circumstances the a priori choice is not a simple task. When available, direct information about the predominant aerosol properties can improve the estimation. This is especially true for the diffuse component. Obviously, the direct component does not depend on the single scattering albedo, $\omega_0$, and its dependence on the correct choice of the Angstrom exponent, $\alpha$, is not so crucial as for the diffuse component.

An interesting result of the precedent analyses is that the estimation of the direct and specially the diffuse components of the photosynthetically active radiation present more problems than the estimation of the global component. In fact, the estimation of the global component can be obtained with MBD close to the experimental error in cases where the error for the direct, and especially the diffuse components are obtained with errors higher than acceptable. This is a result of the compensation between underestimation and overestimation of the direct and diffuse components. Obviously, a good performance of the global components due to the compensation effects may be limited to similar situation to that analysed and one can not conclude that the algorithm would perform well in different circumstances.

6. List of Symbols

- $b$: slope of the linear fit between estimated and measured values forced through a zero intercept.
- $F_a$: forward scattering factor associated to aerosols scattering.
- $F_r$: forward scattering factor associated to Rayleigh scattering.
- $i$: subscript for wavebands. Subscript 1 is for waveband 290–700 nm, subscript 2 is for waveband 700–2700 nm.
- $k_t$: hemispherical broadband transmittance.
- $m_a$: optical air mass that can be computed from solar zenith angle, $\theta_z$, following the procedure described by Kasten (1965).
- $\beta$: slope of the linear fit between estimated and measured values forced through a zero intercept.
- $Q_p$: photosynthetically active radiation.
- $Q_{ph}$: global horizontal photosynthetically active photon flux density $\mu E m^{-2} s^{-1}$.
- $Q_{pd}$: diffuse horizontal photosynthetically active photon flux density $\mu E m^{-2} s^{-1}$.
- $Q_{ph}$: global horizontal photosynthetically active photon flux density $\mu E m^{-2} s^{-1}$.
- $R$: correlation coefficient of the linear relationship.
regression between estimated and measured values forced through a zero intercept.

\( R_b \) broadband solar direct irradiance (W m\(^{-2}\)).

\( R_c \) broadband extraterrestrial irradiance.

\( R_{ci} \) extraterrestrial irradiance for the \( i \) waveband.

\( R_d \) broadband solar diffuse horizontal irradiance (W m\(^{-2}\)).

\( R_{dal} \) broadband solar diffuse horizontal irradiance component due to aerosols in the waveband \( i \).

\( R_{dim} \) broadband solar diffuse horizontal irradiance component due to multiple reflections in the waveband \( i \).

\( R_{dr} \) broadband solar diffuse horizontal irradiance component due to Rayleigh scattering in the waveband \( i \).

\( R_{ni} \) normal beam irradiance for the waveband \( i \).

\( R_p \) global photosynthetically active radiation (W m\(^{-2}\)).

\( R_{pb} \) direct photosynthetically active radiation (W m\(^{-2}\)).

\( R_s \) broadband solar global horizontal irradiance (W m\(^{-2}\)).

RMSD Root Mean Square deviation expressed as a percentage of the mean experimental value of the corresponding photosynthetic photon flux density.

\( \alpha \) Angstrom exponent for the aerosol transmittance.

\( \alpha_1 \) Angstrom exponent for the aerosol transmittance for waveband 290–500 nm.

\( \alpha_2 \) Angstrom exponent for the aerosol transmittance for waveband 500–2700 nm.

\( \beta \) Angstrom coefficient for the aerosol transmittance.

\( \lambda \) wavelength.

\( \lambda_ei \) effective wavelength for each waveband.

\( \rho_g \) ground albedo.

\( \rho_{si} \) sky albedo.

\( \tau_{ai} \) integrated transmittance due to the absorption and scattering produced by aerosol particles in the waveband \( i \).

\( \tau_{aai} \) aerosol transmittance due to aerosol absorption.

\( \tau_{asi} \) aerosol transmittance due to pure scattering.

\( \tau_{gi} \) integrated transmittance due to mixed gases in the waveband \( i \).

\( \tau_{ji} \) integrated transmittance for the process \( j \) in the waveband \( i \).

\( \tau_{oi} \) integrated transmittance for ozone in the waveband \( i \).

\( \tau_{ri} \) integrated transmittance due to Rayleigh scattering by molecules in the waveband \( i \).

\( \tau_{wi} \) integrated transmittance due to water vapor in the waveband \( i \).

\( \omega_{oi} \) scattering single albedo.

\( \theta_z \) solar zenith angle.

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References


