Direct and diffuse photosynthetically active radiation: measurements and modelling

Alados I.\textsuperscript{a}, Alados-Arboledas L.\textsuperscript{b,*}

\textsuperscript{a}Grupo de Física de la Atmosfera, Departamento de Física Aplicada, Universidad de Málaga, Málaga, Spain
\textsuperscript{b}Grupo de Física de la Atmosfera, Departamento de Física Aplicada, Facultad de Ciencias, Universidad de Granada, 18071, Granada, Spain

Received 6 April 1998; received in revised form 9 October 1998; accepted 9 October 1998

Abstract

Knowledge of photosynthetically active radiation is necessary in different applications dealing with plant physiology, biomass production and natural illumination in greenhouses. Nevertheless, due to the absence of widespread measurements of this radiometric flux it is often calculated as a constant ratio of broadband solar radiation. This ratio is affected by many parameters. In our previous work, we analysed the global horizontal component of this flux. This work describes the variations of the direct and diffuse ratios of photosynthetically active radiation to broadband solar radiation in sky conditions. The latter has been characterised by means of variables that could be accessible in common radiometric networks. For this purpose, data recorded at two radiometric stations are used. The first one is located at the University of Almería, a seashore location (36.83°N, 2.41°W), while the second one is located at Granada (37.18°N, 3.58°W, 660 m a.m.s.l.), an inland location. The database includes hourly values of the relevant variables that cover the years 1993–1994 in Almería and 1994–1995 in Granada. We have studied the variability of the ratios of photosynthetically active radiation to broadband solar radiation, both for the diffuse and direct components. We have explained this variability through the influence of sky conditions, represented by means of broadband solar radiation dimensionless ratios, solar zenith angle and dewpoint temperature. Additionally we have developed weather dependent functions of this ratio, to obtain an empirical model, which could be applied to estimate the photosynthetically active radiation in those radiometric networks that register solar broadband irradiance. The model validation shows that all the models estimate the experimental values with mean bias deviation (MBD), close to 1–2%. On the other hand the root mean square deviation (RMSD), presents values close to the experimental error. The regression analysis of measured versus estimated values of direct and diffuse photosynthetically active photon flux density, $Q_{pb}$ and $Q_{pd}$, indicates the absence of given ranges with special tendencies to over or underestimate the fluxes. The use of data sets from two different climatic conditions enables the verification of the local independence of the proposed technique. © 1999 Elsevier Science B.V. All rights reserved.

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

1. Introduction

Incident photosynthetically active radiation (400–700 nm) is required to model photosynthesis of single plant leaves or complex plant communities. Photo-
synthetically 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 $\hat{Q}_p$ from broadband global horizontal irradiance and meteorological parameters such as dewpoint temperature and sky conditions characterised by solar zenith angle $\theta$ and various alternative radiometric ratios evaluated from broadband flux measurements. 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, $Q_p$, is of fundamental importance. On the other hand, natural surfaces are rarely horizontal, in many circumstances one must deal with inclined surfaces, thus the actual radiometric 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; Feuermann and Zexel, 1992). These models require the 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. On the other hand, 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; McCree, 1966; Yocum et al., 1969; Britton and Dodd, 1976; McCartney, 1978; Ross, 1981; Varlet-Grancher et al., 1981; Stigter and Musabilha, 1982; Howell et al., 1983; Rodskjer, 1983; Papaioannou et al., 1993) 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 radiometric flux, $Q_{pd}$ and $Q_{pd}$. (Rao, 1984; Gueymard, 1989a, b; Karalis, 1989; Olseth and Skartveit, 1993).

In this paper, we present the analysis of direct and diffuse photosynthetic photon flux density, $Q_{pb}$ and $Q_{pd}$. measurements recorded in southeastern Spain, as part of a more extensive measurement program that also includes other radiometric and meteorological parameters. We study $Q_{pb}$ and $Q_{pd}$ hourly values, in terms of their respective ratios to the corresponding broadband solar radiometric fluxes. Different parameters are likely to affect this ratio, for example atmospheric pressure, solar elevation, turbidity and precipitable water. For these reasons, we have studied the variations of the direct and diffuse ratio photosynthetically active radiation to broadband solar radiation with the sky conditions to develop weather-dependent functions of these ratios. The goal is to provide a model transferable to those locations that routinely measure broadband solar radiation and the appropriate meteorological parameters. For this purpose, we have developed the empirical models using data collected at Granada and we have validated them by using both the dataset acquired at Granada and that collected at Almería.

1.1. Data and measurements

The dataset used in this study came from two radiometric stations. The first one is located at the University of Almería, a seashore location (36.83°N, 2.41°W). Measurements include 5 min values of various parameters. Solar global irradiance, $R_g$, was measured using a Kipp and Zonen model CM-11 (Delft, Netherlands), while another Kipp and 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 density flux 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 Batllles et al. (1995). This method has also been applied to
correct the diffuse photon flux density. From this database, hourly values have been generated covering 1993–1994. The corrected diffuse horizontal values of both radiometric 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, \( Q_{pb} \).

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

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

This radiometric station is located on the Mediterranean coast in southeastern Spain and is characterised by a greater frequency of cloudless days, and high humidity.

A second station is located on the outskirts of Granada (37.18°N, 3.58°W, 660 m a.m.s.l), an inland location. Data collected at 1 min intervals during 1994–1995 have been used in the present study. The radiometric sensors are similar to those used at Almería. The diffuse irradiance, measured by a radiometer equipped with a shadowband, has been corrected using the previously cited model developed by Batlles et al. (1995). Hourly values have been obtained for the radiometric and meteorological variables. Granada is located in the southeastern region of the Iberian peninsula. Cool winters and hot summers characterise its continental location. Their diurnal temperature range is rather wide with the possibility of freezing on winter nights. Most rainfalls occurs in spring and winter. The summer is very dry, with scarce rainfall in July and August.

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 percent 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%.

### 1.2. Analysis of hourly values

In our previous study (Alados et al., 1996) we have shown seasonal and daily variations of the ratio of global horizontal photosynthetically active photon density flux to broadband solar global horizontal irradiance hourly values, \( Q_{pb}/R_s \). A similar study performed on daily patterns of the ratio of direct photosynthetically active photon density flux to broadband solar direct irradiance hourly values \( (Q_{pd}/R_d) \), for the different months of the year reveals the variability of this ratio (Alados, 1997). This variability also characterises the hourly values of the ratio diffuse photosynthetically active photon density flux to broadband solar diffuse irradiance \( (Q_{pd}/R_d) \). Besides these temporal variations, we found local differences in both the ratios. In order to explain this behaviour we have considered a set of parameters that could describe appropriately the sky conditions influencing this ratio. Following the results of our previous study of the ratio of global horizontal photosynthetically active photon density flux to broadband solar global horizontal irradiance hourly values, \( Q_{pb}/R_s \), (Alados et al., 1996) we have used the sky clearness, \( \varepsilon \), and the brightness of skylight, \( \Delta \) (Perez et al., 1990).

\[
\varepsilon = \frac{(R_b + R_d)/R_d + 1.041 \theta^2}{1 + 1.041 \theta^2} \tag{3}
\]

\[
\Delta = R_d/(R_{no} \cos \theta) \tag{4}
\]

where \( R_d \) is diffuse irradiance, \( R_b \) is direct normal irradiance evaluated with diffuse and global values, \( R_{no} \) is the extraterrestrial solar irradiance in W/m². The sky clearness parameter, \( \varepsilon \), depends on cloud and aerosol amount. The skylight brightness parameter, \( \Delta \), depends on aerosol burden and the cloud thickness. It is important to note that the parameters \( \varepsilon \) and \( \Delta \) present a high degree of correlation for the higher range of \( \varepsilon \), that is cloudless conditions, while under overcast conditions, \( \varepsilon \approx 1.0 \), \( \Delta \) may vary by a factor of 10. The third parameter in the model is the solar zenith angle, \( \theta \). Finally, dewpoint temperature, \( T_d \), was
introduced to account for the effect of water vapour on the solar spectrum. The selection of dewpoint temperature, $T_d$, has been made because of its correlation with the amount of precipitable water (Reitan, 1963) and its ready availability. The water vapour absorption takes place in the infrared region of the spectrum and will therefore decrease the broadband solar irradiance, $R_s$, $R_b$, and $R_d$, more than the photosynthetically active photon density flux, $Q_p$, $Q_{pd}$ and $Q_{pb}$. On the other hand, scattering by aerosols that may be enhanced by atmospheric water vapour content, acts primarily visibly and will affect the photosynthetically active photon density flux, $Q_p$, $Q_{pd}$ and $Q_{pb}$, more than broadband solar irradiance, $R_s$, $R_b$ and $R_d$.

Figs. 1 and 2 show the hourly values of the ratio direct photosynthetically active photon density flux to broadband solar direct irradiance ($Q_{pb}/R_b$) using the database registered at Granada and Almería, respectively. To detect the influence of a particular parameter on the $Q_{pb}/R_b$ ratio, we have shown hourly values of this ratio versus the four sky parameters considered. To demonstrate more clearly the relationship between the radiometric ratios and the parameters, the ratios have been averaged over a range of values of the
parameter—each range of values being chosen so that it contains about 10% of the data. In the figures the average and the standard deviation are shown for each range. The degree of dispersion, around the mean values, suggests that the behaviour of the $Q_{pb}/R_b$ ratio must be modelled with more than one variable. The diagrams show some differences between both localities because of their different climatic conditions.

Concerning the dependence of the ratio of direct photosynthetically active photon density flux to broadband direct solar irradiance hourly values, $Q_{pb}/R_b$, vs. sky clearness, $\varepsilon$, brightness of skylight, $\Delta$, cosine of solar zenith angle, $\cos \theta$, and dew point temperature, $T_d$. Mean values and standard deviation intervals for 10% intervals of each independent parameter, using data from Almería.

For cloudless conditions the ratio $Q_{pb}/R_b$ depends mainly on this parameter. For lower values of clearness of the sky, $\varepsilon$, associated with cloudy conditions the ratio $Q_{pb}/R_b$ reaches the higher values. This is a result of the greater attenuation of a longer wavelength under cloudy conditions, that leads to greater reduction in the broadband direct irradiance, $R_b$, than in the direct photosynthetically active photon density flux, $Q_{pb}$. On the other hand, it is interesting to note that under cloudy conditions the direct components of both the radiometric fluxes show lower values. Perez et al. (1990) have encountered similar results in their study of luminous efficiency, defined as the ratio of lummi-
nance to broadband solar irradiance. On the other hand, as Figs. 1 and 2 show, that the ratio $Q_{pb}/R_b$ shows a linear dependence on the brightness of skylight, $\Delta$. For the medium and higher range of this parameter we found a greater spread of the $Q_{pb}/R_b$ values. For the lower range of $\Delta$, associated with clear skies, the $Q_{pb}/R_b$ values show a lower dispersion. Those situations characterised by lower values of $\Delta$ and higher values of $\varepsilon$, associated with cloudless and clean skies, show lower values of the ratio $Q_{pb}/R_b$. In these circumstances the Rayleigh scattering is responsible for greater extinction in the visible wavebands, thus contributing to a greater reduction in the direct photon flux density than in broadband direct irradiance. In contrast, for higher values of $\Delta$ and lower values of $\varepsilon$, which are representative of cloudy sky conditions with translucent clouds, we found higher values of the ratio $Q_{pb}/R_b$. This is a result of the enhancement of the extinction for near-infrared wavebands associated with these conditions, which are responsible for greater reduction of the broadband direct irradiance, $R_b$, than for the direct photosynthetically active photon density flux, $Q_{pb}$. For intermediate conditions, that is $1.5 < \varepsilon < 3$, we found lower

Fig. 3. Ratio of direct photosynthetically active photon density flux to broadband diffuse solar irradiance hourly values, $Q_{pd}/R_{d}$ vs.: (a) sky clearness, $\varepsilon$, (b) brightness of skylight, $\Delta$, (c) cosine of solar zenith angle, $\cos q$ and (d) dew point temperature, $T_d$. Mean values and standard deviation intervals for 10% intervals of each independent parameter, using data from Granada.
values of the $Q_{pb}/R_b$ ratio. These situations correspond to partially cloudy skies or very turbid skies, under these circumstances there is a greater extinction of the shorter wavelengths, due to the enhancement of scattering by aerosol particles.

We found a high degree of scattering in the dependence of the $Q_{pb}/R_b$ ratio for all the values of $\cos \theta$ and $T_d$. There are differences between Almería and Granada with reference to the dependence of the $Q_{pb}/R_b$ ratio on $\cos \theta$. In Granada we found a marked reduction of the ratio $Q_{pb}/R_b$ for lower values of $\cos \theta$ this was not found in Almería. This reveals different prevailing conditions for lower values of $\cos \theta$ in Almería and Granada. Under lower values of $\cos \theta$ there is an enhancement of the scattering process due to the greater optical air mass which has a greater effect on the shorter wavelengths. Nevertheless, the presence of morning mist could imply a reduction of longer wavelength. It seems that the scattering process dominates in Granada leading to a reduction in the $Q_{pb}/R_b$ ratio. On the other hand, in Almería we found frequent situations of morning mist throughout the year giving a reduction in both the longer and shorter wavelengths that leads to a slight increase in $Q_{pb}/R_b$ ratio. As Figs. 1 and 2 show the dependence of the ratio $Q_{pb}/R_b$ on $T_d$ is residual.

Fig. 4. Ratio of direct photosynthetically active photon density flux to broadband diffuse solar irradiance hourly values, $Q_{pol}/R_d$, vs.: (a) sky clearness, $\varepsilon$, (b) brightness of skylight, $\Delta$, (c) cosine of solar zenith angle, $\cos \theta$, and (d) dew point temperature, $T_d$. Mean values and standard deviation intervals for 10% intervals of each independent parameter, using data from Almeria.
Figs. 3 and 4 shows hourly values of the ratio $Q_{pd}/R_d$ versus the four parameters considered, for Granada and Almeria, respectively. The procedure used in the elaboration of these diagrams is similar to that followed in the $Q_{pb}/R_b$ ratio analysis. As in the analysis of the ratio of the direct components, the degree of dispersion, around the means’s values, suggests that the behaviour of the $Q_{pd}/R_d$ must be modelled using more than one variable.

Figs. 3 and 4 show that the degree of dispersion of the $Q_{pd}/R_d$ ratio around the mean value for the different classes considered for the sky conditions parameter is higher than that found for the direct ratio $Q_{pb}/R_b$. The standard deviation is high in all the cases. There are greater dependencies of the ratio $Q_{pd}/R_d$ on the sky clearness parameter, $\varepsilon$, and the brightness of skylight, $\Delta$. The behaviour of the ratio $Q_{pd}/R_d$ with respect to the sky clearness parameter, $\varepsilon$, is different to that encountered for the ratio $Q_{pb}/R_b$. For lower values of $\varepsilon$ there is an enhancement of the scattering process, for these reasons the lower wavelengths presents a marked extinction process, that leads to a reduction in the ratio $Q_{pd}/R_d$. On the other hand, the ratio $Q_{pd}/R_d$ decreases with the brightness of skylight, $\Delta$. Analysing the behaviour of the ratio $Q_{pd}/R_d$ for different combinations of the sky clearness parameter, $\varepsilon$, and the brightness of skylight, $\Delta$, we found the following. For the conjunction of higher values of $\varepsilon$ and lower values of $\Delta$, corresponding to cloudless conditions, the ratio $Q_{pd}/R_d$ reaches its highest values. On the other hand, the lowest values of the ratio $Q_{pd}/R_d$ correspond to the combination of lower values of $\varepsilon$ and higher values of $\Delta$, that is to cloudy conditions with translucent clouds. Concerning the $\cos \theta$ dependence it is evident that as the optical air mass increases, that is as there is a reduction in the relative contribution of photosynthetically active photon flux density in the whole solar spectrum. Finally, the increase of dewpoint temperature implies an increase of the ratio $Q_{pd}/R_d$ due to the enhancement of water vapour absorption in the longer wavelengths of the solar spectrum.

2. Model development

We have developed empirical models from the results of the previous section. The models use a multiple linear regression approach including appropriate functions of $\varepsilon$, $\Delta$, $\cos \theta$ and dew point temperature $T_d$. The forms of these functions have been selected by analysing the dependence of the $Q_{pb}/R_b$ and $Q_{pd}/R_d$ ratios on the corresponding parameter, shown in Figs. 1–4.

The empirical models presented in this work have been developed for the database from Granada. In the next Section 3, the performance of these models will be tested using the independent dataset from Almeria.

The multiple linear regression schemes goes on in a stepwise manner by entering or removing one variable at a time from a list of potential predictors. This procedure works entering the variable whose addition would increase $R^2$ most at each step, also checking variables already in the equation to ensure that they are still adding markedly to the strength of prediction (BMDP, 1991).

For each model, we have shown the corresponding correlation coefficient associated with the multiple linear expression.

For the ratio of direct photosynthetically active photon density flux to broadband solar direct irradiance at hourly values ($Q_{pb}/R_b$), the best results are obtained for the following expression:

$$Q_{pb}/R_b = 1.659 + 129 \exp(-5\varepsilon) - 0.29\Delta + 0.39\cos \theta \quad R = 0.610$$

(5)

The display of the model has been done to show the relative importance of each term. The degree of correlation between the $Q_{pb}/R_b$ ratio and each variable included in the model decreases with its position in the formula, from left to right. As an indicator of the goodness of this $Q_{pb}/R_b$ ratio parameterization, we have included the correlation coefficient $R$ of the multilinear regression model. The standard deviations of the coefficients are about 0.01, except the $\exp(-5\varepsilon)$ coefficient that has a standard deviation about 1. It is interesting to note that the inclusion of the dependence on $T_d$ does not improve the model. Thus, the best empirical model for this direct ratio implies only dependence on solar zenith angle, $\theta$, and sky conditions in terms of the indices $\varepsilon$ and $\Delta$. The inclusion of the dependence on $\cos \theta$ gives only a slight improvement in the estimation model and the linear dependence on this term seems the more appropriate.
Although Fig. 1(c) suggests non-linear dependence, the high degree of scattering around the mean values dictates the convenience of this single dependence.

For the ratio diffuse photosynthetically active photon density flux to broadband solar diffuse irradiance hourly values \( Q_{pd}/R_d \), the best results are obtained for the following expression, that we call Model 1:

\[
Q_{pd} = R_d \hat{a} + 0.067 \ln \varepsilon + 0.007T_d
\]

\[ R = 0.764 \] \( \text{(6)} \)

As in the direct ratio case, the display of the model has been done to show the relative importance of each term. The degree of correlation between the \( Q_{pd}/R_d \) ratio and each variable included in the model decreases with its position in the formula, from left to right. The standard deviations of the coefficients are about 0.001, except the \( \ln \varepsilon \) coefficient which has a standard deviation about 0.01. It is interesting to note that the inclusion of the dependence cannot improve the model. Thus, the best empirical model for this direct ratio only implies dependence on dewpoint temperature \( T_d \) and sky conditions in terms of the indices \( \varepsilon \) and \( \Delta \). In this case, we found that the parameter \( \Delta \) has more influence on the ratio \( Q_{pd}/R_d \).

As an alternative for those locations where dewpoint temperature data are not available, we have developed a simpler one, MODEL 2, with the exclusion of this parameter

\[
Q_{pd} = 2.35 - 0.81\Delta + 0.053\ln \varepsilon \quad R = 0.757 \] \( \text{(7)} \)

Although there is a slight decrease in the correlation coefficient, the simpler models provide a good estimate for the variations of the \( Q_{pd}/R_d \) ratio as a function of the sky conditions.

3. Model performance

We have analysed the performance of the different models. The procedure followed consists of testing each model using each one of the different sets of annual data. In this way, we use the years 1993–1994 in Almería as completely independent datasets. On the other hand, we also perform a check on the model using separately the years 1994 and 1995 obtained in Granada, the same as the dataset used for model development. The model has been evaluated to assess its capability to predict the photosynthetically active photon flux density. Linear regression analyses between measured and predicted values of the radiometric fluxes were carried out for each method. Table 1 shows the results obtained for the direct ratio model, including correlation coefficient \( R \), slope, \( b \), and intercept, \( a \), of the linear regression of measured versus estimated direct photosynthetically active photon flux density. Table 1 also shows the MBD, and RMSD, for each model. These statistics allow the detection of both the differences between experimental data and model estimates and the existence of systematic over- or under-estimation tendencies, respectively. Finally, we have included the confidence level for the hypothesis that the experimental and the synthetic data set have means not significantly different obtained by applying an ANOVA test to the data.

The statistical analysis has been done for the data set of Almería and Granada. There are about 3000 values at Almería and about 2800 at Granada. The mean values of the direct photosynthetically active photon flux density, \( Q_{ph} \), are 1014 and 986 \( \mu \text{E/m}^2\text{s} \), respectively, for the years 1993 and 1994 at Almería. On the other hand, at Granada we found mean values of 907 \( \mu \text{E/m}^2\text{s} \) for 1994 and 927 \( \mu \text{E/m}^2\text{s} \) for 1995. In

Table 1
Statistical results for the validation of the model of the ratio of direct photosynthetically active photon density flux to broadband solar direct irradiance, \( Q_{pd}/R_d \), in terms of its capability for estimating the direct photosynthetically active photon density flux, \( Q_{ph} \)

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>( a(\mu\text{E/m}^2\text{s}^{-1}) )</th>
<th>( b )</th>
<th>( R )</th>
<th>MBD (%)</th>
<th>RMSD (%)</th>
<th>p (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almería</td>
<td>1993</td>
<td>-6</td>
<td>1.010</td>
<td>0.991</td>
<td>1.2</td>
<td>7.3</td>
<td>54</td>
</tr>
<tr>
<td>Almería</td>
<td>1994</td>
<td>1</td>
<td>0.990</td>
<td>0.994</td>
<td>-0.9</td>
<td>6.0</td>
<td>61</td>
</tr>
<tr>
<td>Granada</td>
<td>1994</td>
<td>2</td>
<td>1.000</td>
<td>0.996</td>
<td>0.2</td>
<td>5.0</td>
<td>91</td>
</tr>
<tr>
<td>Granada</td>
<td>1995</td>
<td>-10</td>
<td>1.005</td>
<td>0.994</td>
<td>-0.6</td>
<td>6.2</td>
<td>78</td>
</tr>
</tbody>
</table>

\( R \) is the correlation coefficient of the linear regression of measured vs. estimated direct photosynthetically active photon flux density. 
\( p \) is the confidence level for the hypothesis that the experimental and the synthetic data set have means not significantly different obtained by applying an ANOVA test to the data.
any case, the MBD presents values slightly greater than 1%. For the RMSD, we found values close to the experimental error. Concerning the ANOVA test it is evident that the data set obtained at Granada has been used for model development. Nevertheless, the confidence level for the hypothesis that the experimental and the synthetic means are not significantly different is also greater than 50% in Almería. The regression analysis of measured versus estimated values of the direct photosynthetically active photon flux density, \( Q_{pb} \), indicates the absence of tendencies to over or underestimate the flux. Model and experimental values present a high degree of correlation in both localities. This is interesting considering the climatic differences between the two locations, and can be considered as a confirmation of the applicability of this model to other places different to the one considered for the model development.

For the diffuse ratio, Table 2 shows the results obtained for the different datasets. Separated results are presented for each model. Following the procedure described above the model analyses have been done in terms of their capability for estimating the diffuse photosynthetically active photon density flux, \( Q_{pd} \). The mean values of the diffuse photosynthetically active photon flux density, \( Q_{pd} \), are 449 and 436 \( \mu \text{E/m}^2\text{s} \), respectively, for 1993 and 1994 at Almería. On the other hand, at Granada we found mean values of 441 \( \mu \text{E/m}^2\text{s} \) for 1994 and 415 \( \mu \text{E/m}^2\text{s} \), for 1995. At Almería, we found that the RMSD reach values about 7%, with results slightly better for Model 1. Concerning the MBD we obtain values about 1% for Model 1 and close to 2% for Model 2. The greater differences between the two models are in terms of the confidence level, \( p \). It is evident that Model 1 provides better results. In relation to the results obtained at Granada, we obtain RMSD values about 4% and negligible MBD values. As in the direct component analysis, we found that model and experimental values present a high degree of correlation in both localities. Thus, we consider that the proposed models can be applied with a high confidence level in other places different to the one considered for the model development.

4. Concluding remarks

We have analysed data of photosynthetically active radiation and broadband solar radiation collected during 1993–1994 in Almería and 1994–1995 in Granada. We have shown that the ratios of photosynthetically active photon density flux to broadband solar irradiance calculated from hourly values of direct (\( Q_{pb}/R_b \)) and diffuse components (\( Q_{pd}/R_d \)) shows a dependence on the atmospheric conditions. We have analysed this dependence using a set of parameters developed in a

<table>
<thead>
<tr>
<th></th>
<th>( a(\mu \text{E/m}^2\text{s}) )</th>
<th>( b )</th>
<th>( R )</th>
<th>MBD (%)</th>
<th>RMSD (%)</th>
<th>( p ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Almería 1993</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1</td>
<td>3</td>
<td>0.995</td>
<td>0.994</td>
<td>0.2</td>
<td>5.1</td>
<td>92</td>
</tr>
<tr>
<td>Model 2</td>
<td>5</td>
<td>0.967</td>
<td>0.994</td>
<td>2.1</td>
<td>5.5</td>
<td>22</td>
</tr>
<tr>
<td><strong>Almería 1994</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1</td>
<td>12</td>
<td>0.973</td>
<td>0.993</td>
<td>0.0</td>
<td>5.7</td>
<td>96</td>
</tr>
<tr>
<td>Model 2</td>
<td>16</td>
<td>0.938</td>
<td>0.992</td>
<td>2.4</td>
<td>7.2</td>
<td>14</td>
</tr>
<tr>
<td><strong>Granada 1994</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1</td>
<td>−10</td>
<td>1.028</td>
<td>0.996</td>
<td>0.6</td>
<td>4.0</td>
<td>70</td>
</tr>
<tr>
<td>Model 2</td>
<td>−10</td>
<td>1.030</td>
<td>0.996</td>
<td>0.7</td>
<td>4.1</td>
<td>64</td>
</tr>
<tr>
<td><strong>Granada 1995</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1</td>
<td>−1</td>
<td>1.007</td>
<td>0.997</td>
<td>0.3</td>
<td>3.8</td>
<td>85</td>
</tr>
<tr>
<td>Model 2</td>
<td>2</td>
<td>0.998</td>
<td>0.996</td>
<td>0.1</td>
<td>4.2</td>
<td>93</td>
</tr>
</tbody>
</table>

\( R \) is the correlation coefficient of the linear regression of measured vs. estimated diffuse photosynthetically active photon flux density. \( p \) is the confidence level for the hypothesis that the experimental and the synthetic datasets have means not significantly different obtained by applying an ANOVA test to the data.
previous study of the global component of the ratio, \((Q_{ph}/R_s)\) (Alados et al., 1996). The study reveals that the variability of these ratios cannot be explained by a single parameter, several parameters are necessary to obtain an acceptable explanation of the behaviour of these radiometric ratios. The hourly values of the ratio of direct photosynthetically active photon density flux to broadband solar irradiance \((Q_{pd}/R_b)\) depend mainly on the sky clearness parameter, \(\varepsilon\). On the other hand, the ratio \((Q_{pd}/R_d)\), corresponding to the diffuse components, depends markedly both on the sky clearness parameter, \(\varepsilon\), and the brightness of skylight, \(\Delta\). It is interesting to note that the sky clearness parameter, \(\varepsilon\), depends on cloud and aerosol amount, and the skylight brightness parameter, \(\Delta\), depends on aerosol burden and cloud thickness. This indicates the influence of both aerosols and clouds in the spectral distribution of solar radiation at the surface level. The influence of solar zenith angle and dewpoint temperature, a measure of the precipitable water content, is of second order.

We have shown the convenience of an empirical modelling scheme, which uses a multilinear regression, including functions of various atmospheric parameters, to estimate the fraction of photosynthetically active radiation contained into broadband solar radiation. This applies for both the direct and diffuse components of these radiometric fluxes, thereby extending the results obtained with the global horizontal fluxes in the previous work. The input parameters necessary for this model are accessible in common radiometric and meteorological networks. As indicated, clouds and aerosols have most influence on the radiometric ratios analysed. In fact the model for the ratio \(Q_{ph}/R_b\) uses as input variables the sky clearness parameter, \(\varepsilon\), the brightness of skylight, \(\Delta\), and the solar zenith angle. The inclusion of dewpoint temperature dependence does not improve the model performance. On the contrary, for the ratio \(Q_{pd}/R_d\) the best model implies the use of dewpoint temperature and excludes the solar zenith angle.

The models have been developed using the dataset from Granada. The applicability of the developed models to other locations has been tested using an independent dataset obtained at Almería. Our results suggest that the parameters selected to characterise the sky conditions that influence the ratios of photosynthetically active photon density flux to solar broadband irradiances are appropriate. The use of the model developed provides estimates of the different photon density fluxes with errors close to the experimental ones. The use of these models in combination with some of the models proposed for the computation of solar radiation on inclined planes permit the estimation of the photosynthetically active photon density flux impinging on an arbitrarily oriented surface. This is interesting for the case of closed stands of plants located in hill slopes. On the other hand, the direct and diffuse components allow estimates of the photosynthetically active photon flux intercepted by isolated plants, which can be treated as cylinders, spheres, etc.

**Acknowledgements**

This work was supported by La Dirección General de Ciencia y Tecnología from the Spanish Ministry of Education and Research through the project No: CLI95-1840. We are very grateful to the Armilla Air Base Meteorological Office Staff and specially to Guillermo Ballester Valor, Chief Meteorologist of the Meteorological Office for the maintenance of the radiometric devices. Our colleague Dr. Batlles was responsible of the correct functioning of the Almería radiometric station. The authors are indebted to the Regional editor, Dr. J.B. Stewart and to Dr. Juhan Ross and the anonymous referee who read the manuscript and made valuable suggestions.

**References**


