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[1] Departamento de Física Aplicada, Universidad de Granada, Granada, Spain
[2] Departamento de Física Aplicada, Universidad de Jaén, Jaén, Spain

Performance reduction of solar irradiance parametric models due to limitations in required aerosol data: case of the CPCR2 model

F. J. Olmo[1], **J. Vida**[1], **I. Foyo-Moreno**[1], **J. Tovar**[2], and **L. Alados-Arboledas**[1]

With 2 Figures

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Summary

Knowledge of the partition of global solar irradiance in its diffuse and direct beam components is required in different areas of applied meteorology. In the absence of solar irradiance measurements parametric approaches have to be used instead. In the present work, the parametric CPCR2 model has been analysed at Granada (37.18° N, 3.58° W, 660 m a.m.s.l), an inland location, covering a period greater than three years. Only cloudless conditions are analysed. Angström's α and β coefficients have been computed from measurements carried out with a sunphotometer. As the study reveals, the best performance of the parametric model is conditioned to the availability of appropriate information on aerosols, especially when the interest is focused on the direct and diffuse irradiance.

1. Introduction

Solar radiation at the surface level is an important parameter in many areas of interest such as studies in agriculture, atmospheric science, building design, engineering, forestry, horticulture or hydrology. Measurement networks do not provide solar radiation data (direct, diffuse and global) with sufficient spatial resolution and temporal continuity to define the climatological potential for solar energy applications. As a first approach, the estimation of solar irradiance at the earth's surface requires the evaluation of these fluxes under cloudless skies. In the absence of experimental measurements, the estimation by models may be a good alternative if the necessary input data are available. Solar radiation is also highly influenced by the presence of clouds. Cloud amount data may come from surface observations or radiances measured from remote sensing platforms, like geostationary satellites. The cloudless sky estimation, combined with the appropriate algorithm to take into account the cloud effect, provides the complete estimation of solar irradiance. Two important questions are to be considered at this stage. The importance of the clear sky irradiance modelling in order to obtain a good estimation under all sky conditions, as pointed out by Foyo-Moreno et al. (1993), and the need of an appropriate but simple cloudless sky irradiance model for the estimation of solar irradiance from satellite measurements. As stated by Olmo et al. (1996), an accurate clear sky estimation is an important prerequisite in the algorithm for the computation of the solar irradiance over extended areas from satellite data. Moreover, a clear sky irradiance model can also be used to check the validity of measured data during the quality control process of data in radiation networks (i.e., Gueymard, 1989).

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 vapour, oxygen and carbon dioxide). The absorption takes place within selected lines and bands, while the scattering takes place over the whole solar spectrum, with more or less spectral variation depending on the aerosol characteristics. The phenomena are complex since the factors controlling the attenuation of solar radiation may differ from one place to another or vary as a function of time.

For clear sky conditions, aerosols are generally the main source of extinction in the atmosphere at wavelengths less than 0.7 μm (e.g., Iqbal, 1983; Gueymard, 1989, 1993b). To account for aerosols, their concentration and the size distribution as well as absorption and scattering properties are important quantities. Most aerosol parameters have to be estimated on the basis of a number of assumptions; some optical properties and the concentration of the aerosols can be estimated from measurements of the optical depth and from irradiance measurements.

In this study, only atmospheric conditions under cloudless skies will be considered. A variety of broadband or spectral cloudless sky models have been proposed, ranging from simple empirical formulae to more sophisticated spectral codes (ASHRAE, 1976; Bird and Hulstrom, 1981; Iqbal, 1983; Page, 1986; Bird and Riordan, 1986; Gueymard, 1989, 1993a, 1994a). The broadband models use broadband transmittances, obtained by means of a parametric approach to the extinction process that takes place in the atmosphere. To carry out this study we have selected the CPCR2 model (Code for Physical Computation of Radiation, 2 bands), which includes convenient parameterisations of the extinction processes and which requires commonly available input parameters (Gueymard, 1989). Previous studies have shown that this model provides better results than other parametric models applied to direct, diffuse and global irradiance estimations in a horizontal plane at different sun height and localities around the world (Gueymard, 1993b; Batlles et al., 2000). On the other hand, the CPCR2 model may predict radiation with an accuracy comparable to more sophisticated spectral codes, but with far less computational effort (Gueymard, 1993b). A complete description can be found in Gueymard (1989), and a summary revision of its main features will be given in the next section.

The CPCR2 cloudless sky parameterisation scheme has been tested by means of quality radiometric data measured at Granada (37.18° N, 3.58° W, 660 m a.m.s.l). Experimental broadband global solar irradiance data have been compared against CPCR2 estimations using aerosol measurements from a sunphotometer. CPCR2 model performances have also been tested concerning the direct beam and diffuse solar irradiance estimations. Having in mind that aerosol information is not routinely measured in extended networks, two different approaches have been tried. First, the availability of all the necessary input parameters for running the model is assumed. In a second study, aerosol climatological information has been considered. This second approach becomes interesting also in remote sensing applications, even though the processing of polar orbiting satellites information may provide the needed aerosol data (Holben et al., 1992; Kaufman et al., 1997).

A similar study to this was carried out by Davis (1996) by means of data registered at Seattle-Tacoma airport and the spectral model developed by Bird and Riordan (1986). Davis' study (Davis, 1996) focused on the solar global irradiance under all kind of sky conditions without any reference to the partition of the global solar irradiance into direct and diffuse components.

2. Data and measurements

Our radiometric station is installed in the outskirts of Granada (37.18° N, 3.58° W, 660 m a.m.s.l), an inland location. Granada is a medium size city located in the south-eastern part of Spain, a continental site with large temperature differences, cool winters and hot summers. The diurnal temperature range allows for the possibility of freezing in winter nights. Most rainfall occurs during spring and wintertime. Summer is normally very dry with few rainfalls in July and August. Granada also presents a low humidity regime.

Solar radiation data registered at five second intervals and stored as one-minute averages from the middle of 1994 to the end of 1998 have been used in the present study. The four year period covers a complete range of seasonal conditions among the samples. The measurements include horizontal solar diffuse and global irradiance, by means of two Kipp & Zonen pyranometers (CM-11) one of them with a polar axis shadowband and a second one without it. Diffuse irradiance measurements, obtained by means of the shadowband, have been corrected following the method proposed by Batlles et al. (1995). Direct beam radiation values have been obtained from global and corrected diffuse irradiance measurements. The pyranometers are intercompared yearly against a reference CM-11, reserved for this purpose, and exposed to solar radiation only during these intercomparison campaigns. It is a first class instrument according to the classification of pyranometers by the World Meteorological Organization. This reference pyranometer CM-11 has been calibrated by Kipp & Zonen with a standard pyranometer, having a non-linearity factor with irradiance of about 0.0% from 0–500 $\mathrm{Wm^{-2}}$ and about +0.7% at 100 $\mathrm{Wm^{-2}}$. The stability is about 1% per year, the dependence on ambient temperature is ±1% over at least a temperature range of −10 to +40 °C, and a combined cosine and azimuth error of ±3% at 10° sun's altitude can be estimated. Periodical on site calibration checks of the radiometric devices have been carried out. Temporal degradation of pyranometers is about a few tenths of a percent per year.

The aerosol optical depth at several wavelengths (368, 500, 675 and 778 nm) have been measured routinely since the end of 1994 until the middle of 1998 by an EKO sunphotometer (Model MS-120) at 9, 12, 15 and 18 h GMT. This sunphotometer has been designed following the WMO guidelines (WMO, 1971) with high spectral purity and stability against temperature changes. The accuracy of wavelength is ±2 nm, and the half bandwidth 5–6 nm. Periodical checks of the calibration constant for each wavelength were carried out by means of the Langley method under stable atmospheric conditions (Schmid et al., 1995). In spite of other error sources that may persist, it is possible to reach 4% accuracy in the sunphotometer calibration. The Angström exponent, α, and the atmospheric turbidity due to suspended aerosol particles, β, have been computed from this data set.

Other measurements also recorded at Granada station include air temperature and relative humidity at screen level. Analytical checks, for measurement consistency, were carried out in order to eliminate problems associated with shadowband misalignments, and other questionable data. Due to cosine response problems, we have used only cases at solar zenith angle less than 85°.

The radiometric and meteorological data have been completed with in situ observations of cloud cover up to three different levels, including cloud layer amount, type and height. These data have been provided by the Spanish Meteorological Institute following the WMO guidelines (WMO, 1981).

An experimental error of about 2–3% was estimated in the irradiance measurements and an accuracy of 0.2 °C and 3% considered in the temperature and relative humidity, respectively. The total data set includes nearly 2000 individual measurement values and covers a broad range of cloudless atmospheric conditions.

3. Parametric model tested

The CPCR2 model assumes that the direct rays entering the atmosphere encounter extinction processes limited to: ozone absorption, molecular scattering, absorption by uniformly mixed gases, water vapour absorption, aerosol scattering and aerosol absorption. Separated extinction layers are considered. The model computes broadband transmittances for the different atmospheric extinction processes. 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 consider the complexity of the scattering processes. Finally, the global irradiance is obtained by a combination of the horizontal projected direct irradiance and the diffuse horizontal irradiance. We summarise the CPCR2 model main features.

This two-band clear sky radiation modelling technique is described in detail elsewhere (Gueymard, 1989). The solar spectrum is divided into UV/visible band (0.29–0.7 μm) and an infrared band (0.7–2.7 μm). The model is based on the solar extraterrestrial spectrum proposed by the World Radiometric Centre (WRC), with a solar constant value of 1367 $\mathrm{Wm^{-2}}$. The UV/visible and infrared bands considered in the CPCR2 model account for 46.04% and a 50.57% of the solar constant, respectively. Thus, for each one of the two bands ($i = 1, 2$), the beam irradiance at normal incidence is given by:

$$I_{ni} = \tau_{oi}\tau_{ri}\tau_{gi}\tau_{wi}\tau_{ai}I_{oi} \tag{1}$$

where I_{oi} is the extraterrestrial irradiance at normal incidence, $\tau_{oi}, \tau_{ri}, \tau_{gi}, \tau_{wi}$ and τ_{ai} are the ozone, Rayleigh, uniformly mixed gases, water vapour and aerosol scattering transmittances.

The total beam irradiance at the ground level is obtained from the two bands:

$$I_n = I_{n1} + I_{n2} \tag{2}$$

The diffuse component is modelled as a combination of three individual components: molecules, aerosols and the backscattering process between ground and sky,

$$D = \sum_{i=1}^{i=2}(D_{ri} + D_{ai} + D_{mi}) \tag{3}$$

Each one of the diffuse components are obtained as follows:

$$D_{ri} = B_r \tau_{oi} \tau_{gi} \tau_{wi} \tau_{aai}(1 - \tau_{ri}) I_{oi} \cos\theta_z \tag{4}$$

$$D_{ai} = B_a \tau_{oi} \tau_{gi} \tau_{wi} \tau_{ri}(1 - \tau_{asi}) I_{oi} \cos\theta_z \tag{5}$$

$$D_{mi} = \frac{\rho_g \rho_{si}(I_{ni}\cos\theta_z + D_{ai} + D_{ri})}{1 - \rho_g \rho_{si}} \tag{6}$$

where ρ_g and ρ_{si} are the ground and sky albedo, respectively. τ's are the direct beam transmittances of each process. All the governing equations may be found in Gueymard (1989). For the aerosol contribution we have:

$$\tau_{ai} = \tau_{asi} \tau_{aai} \tag{7}$$

with

$$\ln\tau_{asi} = \omega_{oi} \ln\tau_{ai} \tag{8}$$

where ω_{oi} is the single-scattering albedo, a function of the aerosol optical characteristics that depends on the absorption features of the aerosol particles, and τ_{aai} and τ_{asi} represent the transmittance due to aerosol absorption and pure scattering, respectively.

The terms B_r and B_a represent the respective fractions of the fluxes scattered by molecules (Rayleigh) and aerosols that are directed downwards (forwardscatterance). Following the recommendation of the Gueymard model a fixed value of 0.5 has been considered for B_r, while the model assumes that B_a is independent of wavelength, and computed following Robinson (1962):

$$B_a = 1 - \exp(-0.6931 - 1.8326\cos\theta_z) \tag{9}$$

The diffuse irradiance due to multiple reflections between the Earth's surface and the atmosphere depends on the ground albedo, ρ_g, and on the sky albedo, ρ_{si}. These albedos have been considered wavelength independent. The expression for ρ_{si} proposed by Justus and Paris (1985) is used, according to the diffusion approximation (Kondratyev, 1969).

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

$$\tau_{a\lambda} = \exp(-m_a \beta \lambda^{-\alpha}) \tag{10}$$

where m_a is the optical air mass that can be computed from solar zenith angle following the procedure described by Gueymard (1993b), and α and β are the Angström's coefficient depending on the type and amount of aerosol particles. The exponent α is related to the aerosol size distribution. In this way, an α value close to zero indicates the predominance of big aerosol particles, while values close to 4 indicates very small particles. The coefficient β is associated with the amount of aerosol in the vertical. Considering the partitioning in spectral bands, it follows:

$$\tau_{ai} = \exp(-m_a \beta \lambda_{ei}^{-\alpha i}) \tag{11}$$

where λ_{ei} are the effective wavelength for each band that depends on optical air mass, m_a, α and β (Gueymard, 1989).

4. Model performance

4.1 Required CPCR2 model inputs

Considering that the model has been developed for clear sky conditions we have reduced our experimental data set to those recordings under cloudless skies. For the selection of cloudless sky conditions we have used the usual meteorological criterion, that is, zero octas. A qualified observer in the same radiometric station observed and registered cloud amount data in Granada at 9, 12, 15 and 18 h GMT.

The CPCR2 model requires a set of input parameters. Some of them are fixed for a given location, as is the case of surface albedo. Following precedent studies (Alados-Arboledas et al., 2000) an average zonal albedo value of 0.15 has been considered in this work.

The total ozone amount is another input parameter required by the model. We have used the latitudinal model proposed by Van Heuklon (1979), considering the minor influence of this component for the whole solar spectrum.

The precipitable water has been obtained from the meteorological data acquired at surface level following the model proposed by Paltridge and Platt (1976).

The radiative properties of aerosols play a fundamental role on the solar radiation spectrum. As previously indicated, the CPCR2 model parameterises the radiative effect of aerosol by means of the Angström model for the aerosol optical depth. The log-log scale least square fit of aerosol optical depth versus the wavelength for a given spectral range seems to be the most adequate method for the retrieval of the α and β parameters. However, the dependence on the selected spectral ranges is also evident. On the other hand, the amplitude of the spectral range is another limitation in the applicability of the Angström law. The linear behaviour of the Angström law in the log-log plot scale models represents quite well the general curvature shown by real aerosol particles, because of the multimodal nature of aerosol size distribution. Therefore, the Angström law is well suited when short spectral ranges are used. As demonstrated, the visible spectral range from 400 to 700 nm shows a good linear behaviour in the log-log scale for many different types of aerosols. On the other hand, the specific values of the α-β parameters are very dependent on the selected spectral range used in the estimation of the parameter (i.e., Cachorro et al., 2000). In our case, continuous measurements of optical depth at wavelengths 368, 500, 675 and 778 nm are available. From these optical depth measurements the corresponding aerosol optical depths have been computed by removing the Rayleigh scattering effects and the appropriate molecular absorption effects. Finally, as the increase of the optical depth with decreasing wavelength may well be described with the Angström formula, the Angström turbidity coefficients β and the wavelength exponents, α, which produced the best fit to the data were employed. To this end we have used a Chi-Square (χ^2) fitting procedure (Press et al., 1989), in which the parameters are adjusted by minimizing the value of χ^2 and the associated errors. In our case, the Angström law offers a good description of the data in about 90% of the cases. The other cases correspond to situations associated with the invasion of big particles due to agricultural and mineral activities. Because of actual knowledge limitations, it is necessary to assume that $\alpha_1 = \alpha_2 = \alpha$ in our model computations (Gueymard, 1989).

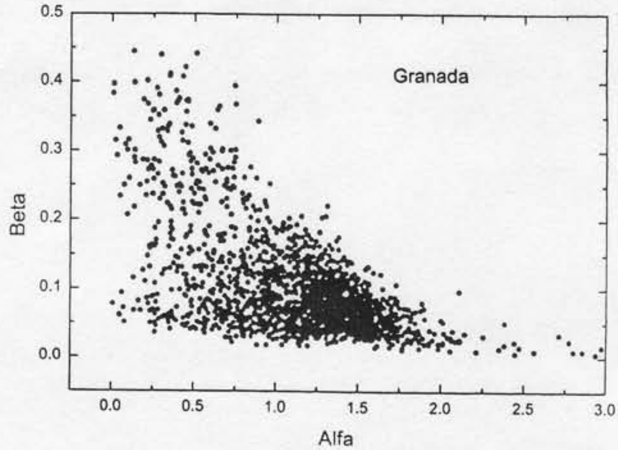

Fig. 1. Scatter plot of the α values versus β values of our data set

Figure 1 shows a scatter plot of α and β at Granada, for the considered period. It can be seen that it is possible to find very clean conditions, β close to zero, and rather turbid conditions, β around 0.4. Nevertheless, values lower than 0.1 are predominant, being the mean value close to 0.09 and the value with greater relative frequency 0.05. With respect to the wavelength exponent, α, there is also a wide range of values, ranging from situations with a predominance of big particles with α close to zero, to situations with a predominance of medium size particles with α close to 2. The mean value of α was estimated to be 1.14, and the value with the greatest relative frequency to be 1.3. The latter is normally considered as the climatological value if continental or rural aerosols are predominant. It seems clear from our data set that the lowest α values correspond to the highest β values and vice-versa, but this is not always a general behaviour as observed by us and other authors in other areas (i.e., Prodi et al., 1984; Cachorro et al., 2000). Single day variations of 40% have often been observed between the 4 spectra usually measured during a day. These facts show that the aerosol load may show a high variability at Granada. There is not, however, a clear correlation between both parameters, α and β.

The parameterisation of the diffuse component requires knowledge on the absorption capability of the aerosol. This is considered by means of the single-scattering albedo, ω_o. It may vary with the sources of the air masses and pollution levels. Gueymard (1989) proposes different values for different atmospheric conditions. At present, we have used a value of 0.750 (Alados-Arboledas et al., 2000), which lies between those of 0.800 and 0.690 proposed by Gueymard (1989) for the urban atmosphere. This is in accordance with several studies under development about the optical properties of the aerosol at Granada. These studies show that the amount of soot particles in the aerosols present at Granada is greater than that present in a typical urban atmosphere.

4.2 CPCR2 model performance

The model performance was evaluated by means of the root mean square deviation (RMSD) and the mean bias deviation (MBD). These are standard statistics in assessing the performance of solar radiation models and allow for the detection of both the differences between experimental data and model estimates and the existence of systematic over- or underestimation tendencies, respectively. The linear regression between estimated and measured values has also been analysed, 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 with the model.

Separated results, expressed as a percentage of the observed mean values, are presented for the beam, diffuse and global irradiance values provided by the model. Table 1 shows the statistical analysis results when all the required information is used. It is evident that the direct and global irradiances are obtained with MBD and RMSD close to experimental errors. The correlation coefficients are about 90% and 99%, respectively.

Table 1. Statistical results for the CPCR2 model using the Granada data set

	Mean Value (Wm^{-2})	b	R	M.B.D (%)	R.M.S.D (%)
Direct	822	0.958	0.903	−3.8	2.9
Diffuse	102	1.164	0.869	23.5	32.1
Global	660	1.008	0.995	0.01	3.2

These results are comparable with the best results obtained by the author of the CPCR2 model at different localities around the world using high quality data sets (Gueymard, 1989, 1993b).

Therefore, if the necessary input parameters are available, it appears possible to obtain the direct and global irradiance component with an accuracy comparable to routine measurements. In particular, good information on aerosol amount is necessary to obtain accurate predictions of direct irradiance. Nevertheless, the MBD associated with the direct and diffuse component reveals opposite trends of under- or overestimation, respectively, leading to compensation in the global component estimation. Obviously, the selection of ω_o influences the estimation of the diffuse component and, through this, it also affects the estimation of the global component. In selecting the ω_o value we had in mind the consideration that it must provide the best estimation of the diffuse component appropriate for the prevailing local atmospheric conditions.

Figure 2 shows the scatter plot for the three components estimated according to the selection used for the analysis as shown in Table 1. The good fit for the global and direct component are evident, with a slight underestimation for the direct component. These results reveal the absence of a definite tendency to over- or underestimation in a given range of the considered flux. For the diffuse component, a marked overestimation tendency of about 23.5% can be recognized. However, the diffuse component RMSD in Granada is about 32%, a relatively high deviation from the experimental value. The correlation coefficient, R, is quite acceptable for all irradiance components. Even if the errors associated to the diffuse irradiance appear large on a relative scale, they correspond to about $30\,Wm^{-2}$ on an absolute scale, i.e., the same magnitude as the errors associated to direct irradiance. This two-band model, however, offers extra-accuracy over more conventional one-band models, and may predict radiation with an accuracy comparable to more sophisticated spectral codes, but with far less computational effort (Gueymard, 1993; Batlles et al., 2000).

Taking into account the great number of individual measured values, covering a broad range of cloudless atmospheric conditions, these results may be considered as highly significant.

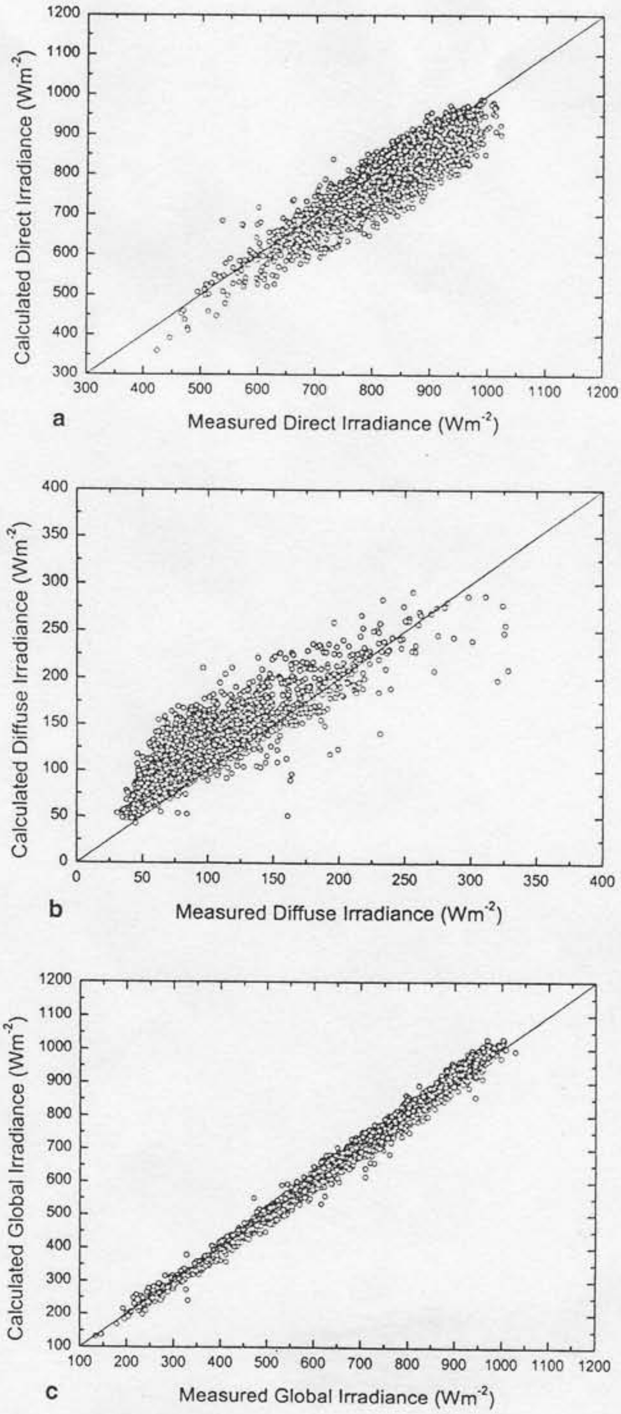

Fig. 2. Statistical results for the estimations of **a**) direct, **b**) diffuse and **c**) global irradiance by the CPCR2 model, using all the required input

4.3 Considerations about the uncertainty in aerosol input data

Precedent analysis was carried out with complete information on atmospheric aerosol properties available for our area of interest. Nevertheless, the aerosol optical depth is not routinely measured in extended networks for which the irradiance components may be needed. For this reason, it is usually necessary to acquire further information on α and β if parametric models are to be used. For instance, the value $\alpha = 1.3$ has been normally considered representative for a wide range of cases at continental locations. However, different methods have been proposed to estimate β coefficient from available measurements of solar broadband direct irradiance (Page, 1986; Fox et al., 1994; Grenier et al., 1994; Gueymard, 1998). Obviously, if direct irradiance values are not available, it is also possible to use climatic values from a close radiometric station. In this section we are going to analyse the influence that the limitation on the availability of aerosol input data could exert over the model performance.

It is evident that the estimation of the direct component can be improved using a different choice for the α parameter. In this sense, different authors (i.e., Gueymard, 1994b; Alados-Arboledas et al., 2000) have recently suggested the convenience of considering the relative humidity influence on the wavelength exponent α for different types of atmospheres

Many substances, which are part of aerosol particles, are deliquescent. This means that the substance takes up a certain quantity of water when a minimum humidity is exceeded. The amount of water uptake depends on the humidity and the substance. For a given humidity equilibrium is reached when the saturation vapour pressure over the solution equals the vapour pressure in the air. The atmospheric aerosol contains a mixture of several substances where no exact phase transition can be found. When the humidity increases from <50 to 90% the rural-continental aerosol takes up about its own mass of water, the urban aerosol about half and the maritime aerosol about twice its mass (Horvath, 1998). Granada shows a very variable mixture of rural-continental/urban aerosol particles, and their amounts depend on the atmospheric and seasonal conditions (Fig. 1). In this sense, we have tested the use of an exponent α depending on the humidity as proposed by Gueymard (1994a, b). We have computed the corresponding value of α for the Granada data set at four similar intervals to those proposed by Gueymard. The results obtained are

Table 2. α values as a function of relative humidity obtained from experimental values registered at Granada radiometric station

R. Humidity	0%	50%	70%	90%
α	0.76	1.05	1.09	0.98

Table 3. Statistical results for the CPCR2 model using α values tabulated in Table 2

	B	R	M.B.D (%)	R.M.S.D (%)
Direct	0.978	0.877	−2.0	6.4
Diffuse	1.113	0.861	17.0	29.5
Global	1.013	0.993	1.2	3.8

Table 4. Statistical results for the CPCR2 model using $\alpha = 1.3$

	B	R	M.B.D (%)	R.M.S.D (%)
Direct	0.945	0.869	−5.5	8.5
Diffuse	1.226	0.849	28.7	39.6
Global	1.000	0.992	0.0	3.8

in accordance with Gueymard's results and with the typical aerosol loads at Granada. Table 2 shows the values of the Angström's exponent as a function of relative humidity for Granada conditions. The different irradiance components have been estimated by applying the previously calculated β value and the α parameter as a function of the relative humidity. As it can be seen in Table 3, this choice provides an estimation of the global component with negligible MBD and RMSD. The slope of the estimated versus measured regression analysis evidences the proximity to the perfect fit 1:1 line. The direct irradiance is obtained with a MBD close to the experimental errors, showing a slight tendency to underestimation with respect to the experimental values. The RMSD is about 6.4%, which represents an increase by a factor 2 with respects to the corresponding value in Table 1. On the other hand, results for the diffuse irradiance improve when the α parameters dependency on humidity is considered. The MBD, the RMSD and the slope improve the results obtained for the diffuse irradiance with respect to the results shown in Table 1. An improvement of about 28% on MBD and 8% on RMSD is achieved. The variance explained by the model is about 86% or more, depending on the components. These results are interesting if we remember that the comparison is carried out involving instantaneous values, for which random errors are rather high, and that the α parameter could not be tuned to the conditions of each individual measurement. We think that this fact is a consequence of the Angström law, since it doesn't represent the mixture of small and big particles with enough accuracy, while this dependence of the α parameter with the relative humidity averages the situations and smoothes the extreme values of the parameter. Our analysis also shows that it is possible to obtain the global and direct irradiance components with an accuracy similar to routine measurements if the α parameter is considered as a function of relative humidity.

Table 4 shows the results when a constant value of the α parameter ($\alpha = 1.3$) is considered. This is a common choice in continental locations when some information about the α parameter is needed. As it can be observed (Table 4), the direct and diffuse deviations are higher. With respect to the direct irradiance, the underestimation is about −5.5% and the RMSD close to 8.5%. The estimated diffuse irradiance is about 28.7% greater than the measured values, with a RMSD about 39.6%. The results get worse for both irradiance components than those presented in Table 3. However, due to the compensation of deviations in the direct and diffuse components, the global irradiance may still be estimated with MBD and RMSD close to the experimental values.

Bearing in mind that the β turbidity coefficient is not either routinely measured in extended networks, a study with monthly mean values has been carried out. This is the case when diffuse and direct irradiance values are needed for applications and only global irradiance data and some spectral series not coincident in time, or data from some close station, are available. To this end, the whole data set of aerosol parameters has been used to define a set of twelve monthly values. In doing this, these values have been considered as representative of the local climatic conditions. Table 5 shows the statistical results for the CPCR2 model using monthly values of β and $\alpha = 1.3$.

Table 5. Statistical results for the CPCR2 model using monthly values of β and $\alpha = 1.3$

	B	R	M.B.D (%)	R.M.S.D (%)
Direct	0.934	0.607	−5.9	11.4
Diffuse	1.167	0.550	30.9	52.3
Global	1.000	0.993	0.0	3.5

The MBD and RMSD values for the direct and diffuse irradiance are not negligible in this case and the variance explained by the model gets worse. In contrast the use of monthly average values of turbidity information for the global irradiance estimates provides results close to those obtained by the use of the appropriate values (Table 1).

5. Conclusions

The CPCR2 model performance has been studied by means of radiometric data carefully recorded at Granada. Aerosol information has been introduced by means of the Angström turbidity coefficient, β, and the wavelength exponent, α, obtained from sunphotometer readings.

Our results show that global irradiance estimations with accuracy close to routine measurements can be obtained with an approximate value for the aerosol contribution. This is particularly interesting in the estimation of solar global irradiance from remote sensing data. In this sense, the use of climatological values or approximate estimations of the aerosol load from remote sensing data (Holben et al., 1992; Kaufman et al., 1997) would allow for an appropriate mapping of solar global irradiance at regional or global scales. Nevertheless, if the interest is focused in the partition of the solar global irradiance into its direct and diffuse components the use of accurate information on the aerosol characteristics is necessary.

From our results it is clear that the accurate estimations of solar diffuse irradiance presents the greatest difficulties. It is also important to point out the inherent difficulty associated to the measurement of this radiative flux. In this way, when measuring the diffuse component by means of shadowband it is necessary to account for the sky dome obstructed by the band, and when a shadow disk is used, the angle subtended by this device is about 5° instead of the 0.5° subtended by the sun. This means that part of the diffuse irradiance included in the circumsolar area is excluded in the measurements, which ultimately implies an underestimate of the actual radiative flux. Obviously, when the direct irradiance is measured with a pyrheliometer the opposite situation is true. The instantaneous field of view corresponds to an angle of 5°, thus the direct irradiance measurement includes the circumsolar diffuse contribution, giving measurements that exceed the actual direct beam flux. This consideration could explain the results obtained in the estimation of the direct beam component in the ideal situation, and obviously contributes to an explaination of the discrepancies between measurements and estimates that we have found.

Various authors (Kato et al., 1997; Halthore et al., 1997, 1998), however, have shown that radiative transfer models consistently overestimate the surface diffuse downward irradiance in cloud free atmospheres while the same models correctly compute the direct solar irradiance at the surface. At this point, one must consider that the direct solar irradiance depends only on atmospheric extinction of solar energy without regard to the details of extinction, while the diffuse irradiance depends on scattering by molecules and aerosols. In this sense, Kato et al. (1997) conjectured that the aerosol optical depth inferred by sunphotometers might be overestimated, thus leading to an overestimation of the diffuse irradiance. Thus, in order to improve the diffuse irradiance estimation the retrieved aerosol optical depth must be reduced. By the way, to obtain the appropriate estimate of solar direct irradiance a compensating increase in atmospheric absorption must be considered. Halthore et al. (1998) have checked this approach using data measured at two low altitude and two high altitude sites. Their results confirm the hypothesis by Kato et al. (1997). They determine that the excess absorption is related to the excess absorption under cloud-free conditions and, possibly, cloudy conditions as reported by Arking (1996).

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Authors's addresses: F. J. Olmo, J. Vida, I. Foyo-Moreno, L. Alaḍos-Arboledas, Departamento Física Aplicada, Universidad de Granada, Fuentenueva s/n, E-18071 Granada. J. Tovar, Departamento de Física Aplicada, Universidad de Jaén, E-23071 Jaén, Spain.

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