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Comparison of Cloudless Sky Parameterizations of Solar Irradiance at Various Spanish Midlatitude Locations

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With 6 Figures

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Summary

We have developed a comparison among several cloudless sky parameterization schemes of the solar irradiance incoming at surface level. The data set was recorded at various Spanish mid-latitude radiometric stations, covering different climatic regimes. It consists of hourly values of the relevant quantities covering periods greater than one year at each radiometric station. Diffuse irradiance data have been corrected for shadowband effect using a model developed by the authors and successfully tested at various radiometric stations. At a first stage, the models were run using all the available local information. After that, we have run the models that present the better performance and, considering that under some circumstances not all the input parameters are available replacing some parameters by their monthly values. As the study reveals, the Gueymard and the Iqbal C model, which require the availability of appropriate information on aerosols, perform best. The influence of precipitable water is of second order thus allowing for the use of estimates based on monthly mean values obtained from climatological records. On the other hand, the study performed on the influence of solar elevation angle on models performance reveals that the worst results correspond to lower solar elevations. This could be a result of limitations in the transmittance parameterization for these elevations.

1. Introduction

Solar radiation at surface level is an important parameter for studies in agriculture, atmospheric science, building design, engineering, forestry, horticulture and hydrology. This radiometric flux is greatly influenced by the presence of clouds. Nevertheless, many applications of solar energy, such as system design and simulation, peak-cooling load of buildings and calibration of radiometers need a correct modeling of the clear sky irradiance components. On the other hand, the first step in the estimation of solar irradiance at surface level requires the evaluation of those radiometric fluxes under cloudless conditions. A variety of models of varying complexity have been proposed, ranging from simple empirical formulae to sophisticated spectral codes (ASHRAE, 1976; Bird and Hulstrom, 1981; Iqbal, 1983; Page, 1986; Bird and Riordan, 1986; Gueymard, 1989, 1993a). Many applications require an estimate of the broadband solar irradiance. This could be obtained by means of broadband models, which could be either empirically derived or physically based. These last models use broadband transmittances, obtained by means of a parametric approach, of the extinction process that takes place in the atmosphere.

At a first stage, 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. These models have been designed to evaluate all the components of the solar radiation, global and diffuse irradiances on a horizontal plane and direct beam irradiance, and use commonly available input parameters. The selected models are: CPCR2 model by Gueymard (1989), EEC model (described in Page (1986)), Josefsson model (submitted by its author to the IEA Task IX (Davies et al., 1988)), MAC model (which latest versions are described in Davies et al. (1988) and Davies and McKay (1989)) and the parametrics models A, B and C, described by Iqbal (1983), the last being a modified version of the one proposed by Bird and Hulstrom (1981). A complete description of the models is included in the preceding references. Following previous results reported by Gueymard (1993b), we have selected those models that present a better performance due to their more convenient parameterization of the extinction processes.

The number of studies that report extensive assessment of clear sky models is rather small. A great number of these studies include only a limited number of models tested against limited sets of data (i.e., Louche et al., 1988; Davies, 1987; Davies et al., 1988). We have compared these parametric models with carefully measured data at four Spanish mid-latitude radiometric stations characterized by different climatic regimes, using in situ information including all the required inputs on an hourly basis. The overall performance of all the models has been evaluated with the same standard statistics. We have evaluated the models considering 5° solar elevation angle bins. As an alternative, some simplifications have been made in order to test the model performance when not all the inputs required are measured. In this sense we tested the models using climatological information concerning two input parameters characterized by their high variability, water vapor and aerosols. Davis (1996) has developed a similar study using data recorded at Seattle-Tacoma airport, concerning the global irradiance estimates by means of spectral model (Bird and Riordan, 1986). In this study, we also analyze model performance in the direct beam and diffuse solar irradiance estimations.

Gueymard (1993b) has emphasized the internal consistency of the models. In our case we try to provide evidence of the success and failures of the models when applied to real conditions. For this reason, we have tried two approaches. The first one assumed the availability of all the input parameters needed for running the models. The second one considers the use of climatological information concerning the most important inputs, as is the case of aerosol information. According to Gueymard (1993b) the modeling of water vapor and especially aerosol extinction conditions the overall model accuracy.

2. Data and Measurements

For this study, we have used data recorded at four Spanish radiometric stations. Table 1 presents the geographical locations and the date of the measurements used. The stations are located in areas characterized by different climatic conditions. Thus, there are coastal locations, such as Almería, and inland locations with different degrees of continentality. For the different locations, we found rather different cloud regimes.

The measurements include horizontal solar diffuse and global irradiance, by means of pairs of Kipp & Zonen pyranometers, one with a polar axis shadowband and another without it. At Granada and Almería stations, CM-11 pyranometers have been used, while the other radiometric stations use CM-5 pyranometers. Diffuse irradiance measurements obtained by means of the shadowband have been corrected following the method proposed by Batlles et al. (1995).

The Almería data set was recorded at a radiometric station located at the University of Almería, a seashore location (36.83° N, 2.41° W). The measurements were recorded at five second intervals and stored as one minute averages until early 1993, since then five minute average intervals have been selected. From this database,

Table 1. *Geographical Locations and the Time Period of the Measurements Used*

	Latitude	Longitude	Altitude (a.m.s.l)	YEAR
Almería	36.83° N	2.41° W	0 m	1994–1996
Granada	37.18° N	3.58° W	660 m	1994–1995
Oviedo	43.35° N	5.36° W	348 m	1991
Madrid	40.45° N	3.75° W	664 m	1983–1985

hourly values, covering the period from January 1994 to December 1996, have been generated for the present study by integration. Direct beam radiation values have been obtained from global and corrected diffuse irradiance measurements. Cloud cover data recorded at the Almería Airport, located about 1 km away from the radiometric station, at 30 minutes intervals have been added to the data base. This radiometric station is located at the Mediterranean coast in Southeastern Spain and is characterized by the great frequency of cloudless days, and the persistence of a high humidity regime.

A second station is located in the outskirts of Granada (37.18° N, 3.58° W, 660 m a.m.s.l), an inland location. Data recorded at five second intervals and stored as one-minute averages during 1994–1995 has been used in the present study. The radiometric sensors are similar to those used at Almería. Hourly values have been obtained for the radiometric and meteorological variables by integration. Granada is located in the Southeast of the Iberian Peninsula. Its continental location is responsible for a wider temperature range than that encountered at Almería. On the other hand, Granada presents a low humidity regime. Cloud observations have been recorded at the location of the radiometric station by the Spanish Meteorological Institute (I.N.M.) at 9, 12, 15 and 18 GMT.

The pyranometers utilized in the previous stations are compared yearly against a reference CM-11, reserved for this purpose, and exposed to solar radiation only during these intercomparison campaigns. Temporal degradation of pyranometers is about a few tenths of a percent per year.

Additionally we have used a data set recorded at Madrid (40.42° N, 2.75° W, 666m a.m.s.l.). This data set consists of hourly values of the relevant radiometric quantities, covering the period from January 1983 to December 1985. The normal direct beam radiation has been measured using an Eppley Normal Incidence Pyrheliometer, Model NIP. The global and diffuse horizontal irradiances have been measured with Kipp & Zonen pyranometers, model CM5. This station is maintained by the Spanish Meteorological Institute and is characterized by a continental climate. Cloud observations have been recorded at 9, 12, 15 and 18 GMT.

At Oviedo radiometric station (43° N, 5.85° W, 248 m a.m.s.l), hourly values of global and diffuse horizontal irradiance are available. This station, located in the Northwest of the Iberian Peninsula, is maintained by the Spanish Meteorological Institute. It is characterized by a temperate climate with rains present all over the year. As in Granada and Almería, direct beam radiation values have been obtained from global and corrected diffuse irradiance measurements. Cloud observations have been recorded at 9, 12, 15 and 18 GMT.

Other measurements included in the data sets are the air temperature and relative humidity at screen level. For all the variables, hourly values have been obtained. 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 used only cases at a solar elevation angle above 5°.

Measurements of global and diffuse solar irradiance have an estimated experimental error of about 2–3%. For the direct beam irradiance we have different experimental errors. At Madrid, where direct beam measurements are available, the errors could be estimated to about 3%. At all other stations, the indirect procedure used for the computation of this radiometric flux suggests errors of about 5%. Data of meteorological variables were obtained with an accuracy of 0.2 °C for temperature and 3% for relative humidity.

To provide a better characterization of the solar radiation conditions at the analyzed radiometric stations, Fig. 1 presents diagrams showing the frequency distribution in the $k - k_t$ space for each one of the locations. This diagram is based on hourly values used in this study. The index k is the hourly diffuse fraction that represents the ratio of diffuse solar horizontal irradiance to global solar horizontal irradiance. On the other hand, k_t is the ratio of global solar horizontal irradiance to extraterrestrial solar horizontal irradiance, the so-called clearness index. The different cloud and aerosol regimes are evident in these diagrams. At Oviedo, we found a high frequency of cloudy conditions, characterized by high k values and low k_t ratios. On the other hand, at Almería, Granada and Madrid there is a predominance of cloudless conditions. In any

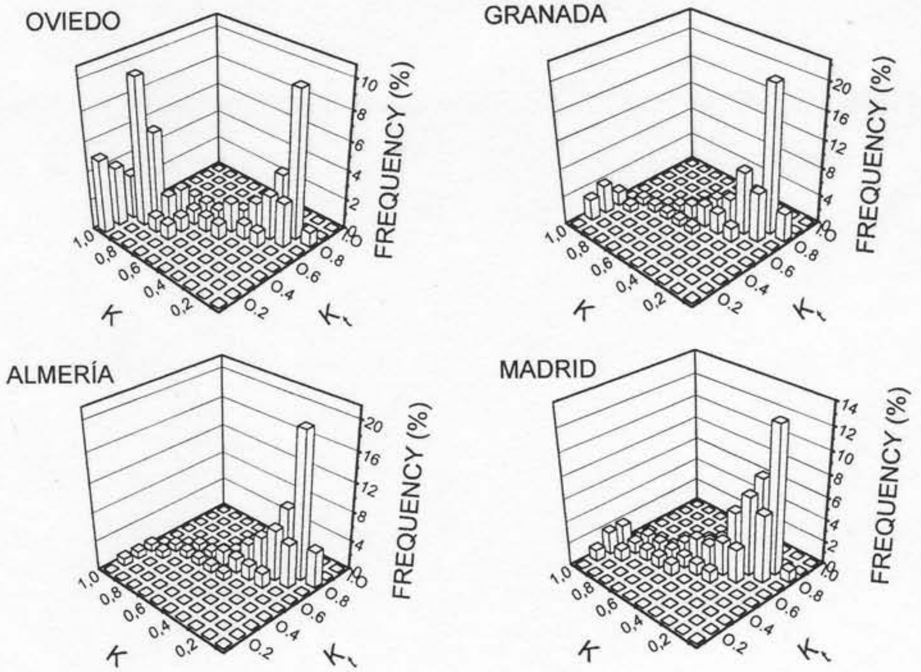


Fig. 1. Frequency distribution diagrams in the $k - k_t$ space for each one of the localities. $k =$ diffuse fraction, $k_t =$ clearness index

case, Almería presents the lowest frequency of overcast skies characterized by low values of k_t combined with high values of k.

3. Parametric Models Tested

The parametric models included in this study compute 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 scattering process. Finally, the global irradiance is obtained by combination of the direct irradiance projected onto the horizontal surface and the diffuse horizontal irradiance. A brief summary of the models analyzed is given in the following.

3.1 Iqbal Models A, B and C

These models are described in Iqbal (1983). The model A is based on the McMaster model (Davies et al., 1988; Davies and McKay, 1989). The ozone and water vapor transmittances are calculated by means of their respective absorptances (Lacis and Hansen, 1974), and the Rayleigh and aerosols transmittances following Iqbal (1983). For other parameters we use the values recommended by the author (Iqbal, 1983).

3.2 Gueymard Model (CPCR2)

This two-band radiation modeling technique, proposed for the clear sky case, is completely described in Gueymard (1989). The solar spectrum is divided into an UV/visible band (0.29–0.7 μm) and an infrared band (0.7–2.7 μm).

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

$$\tau_{A\lambda} = \exp(-m_A \beta \lambda^{-\alpha_i})$$

Thus, it follows

$$\tau_{Ai} = \exp(-m_\mathrm{A} \beta \lambda_{ei}^{-\alpha i})$$

where λ_{ei} are the effective wavelengths for each band that depends on aerosol optical mass, α and β are de Angström wavelength exponent and turbidity coefficient, respectively, and m_A is the aerosol optical mass.

3.3 MAC Model

This model has been proposed by Davies et al. (1988). The Rayleigh transmittance, τ_r, is

Table 2. *Values of Angström Wavelength Exponent, α, and Single Scattering Albedo, ω_0, Used at each Location. The Subscripts 1 and 2 refer to the Two-Band Model Proposed by Gueymard (1994)*

	α	α_1	α_2	ω_0	ω_{01}	ω_{02}	TYPE
Almería	1.20	1.10	1.30	0.883	0.931	0.932	Mean rural
Granada	0.85	0.70	1.00	0.740	0.800	0676	Urban
Madrid	1.10	0.90	1.30	0.883	0.931	0.832	Mean rual
Oveido	0.90	0.90	0.90	0.883	0.931	0.832	Mean rural

computed following the formula proposed by Davies (1987). Following Houghton (1954) the aerosol transmittance is computed by:

$$\tau_A = k^{mA}$$

where k is the aerosol transparency coefficient, which is difficult to obtain. For this reason we have computed the aerosol transmittance using the scheme used in Iqbal C model. The ozone transmittance, τ_0, and water vapor absortance, α_w, are computed using the expressions included in the parametric model Iqbal A (Iqbal, 1983).

3.4 Josefsson Model

This model (Davies et al., 1988) uses for the diffuse irradiance a procedure similar to that described for MAC model but under the hypothesis of a surface albedo equal to zero.

4. Models Performance

As indicated by Gueymard (1993b) a correct description of the transparency conditions is relevant for the kind of models analyzed in this study. To test the efficiency of these parameterizations with our data set, we have used the Linke turbidity factor as indicator of the transparency conditions:

$$I_n = I_o e^{-m_a \delta_r T_L}$$

where m_a is the optical air mass and δ_r is the Rayleigh optical depth obtained by the expression proposed by Kasten (1980).

The Angström turbidity coefficient, β, used in several parametric models is obtained from the Linke turbidity factor following the formula proposed by Dogniaux (also given in Page, 1986):

$$T_L = \frac{175 + \theta_z}{(39.5e^{-w} + 47.4)} + 0.1 + (16 + 0.22)\beta$$

where θ_z represents the solar zenith angle in degrees and w is the precipitable water in cm.

Following Gueymard (1994) and considering the features of each location, Table 2 includes the values selected for the Angström wavelength exponent, α, and the single scattering albedo, ω_0, for each station. The last column in this table indicates the type of atmosphere considered for each location. The subscript 1 and 2 refers to the values used in the two-band model by Gueymard (1989).

4.1 Global Performance of the Models

The performance of the models was evaluated using the root mean square deviation (RMSD) and the mean bias deviation (MBD), defined as follows:

$$\text{RMSD} = \left(\sum_{i=1}^{N} \frac{(X_{\text{estimated}} - X_{\text{measured}})^2}{N} \right)^{\frac{1}{2}}$$

$$\text{MBD} = \sum_{i=1}^{N} \frac{(X_{\text{estimated}} - X_{\text{measured}})}{N}$$

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. We have also analyzed the linear regression between estimated and measured values, providing information about the correlation coefficient, R, slope, a, and intercept, b. The first one gives an estimate of the experimental data variance exhibited by the model while the last two provide information on over- or underestimation tendency, in a particular range.

Separate results are presented for the hourly beam irradiance and the hourly diffuse irradiance values provided by the different models. For simplicity, some results concerning the statistics

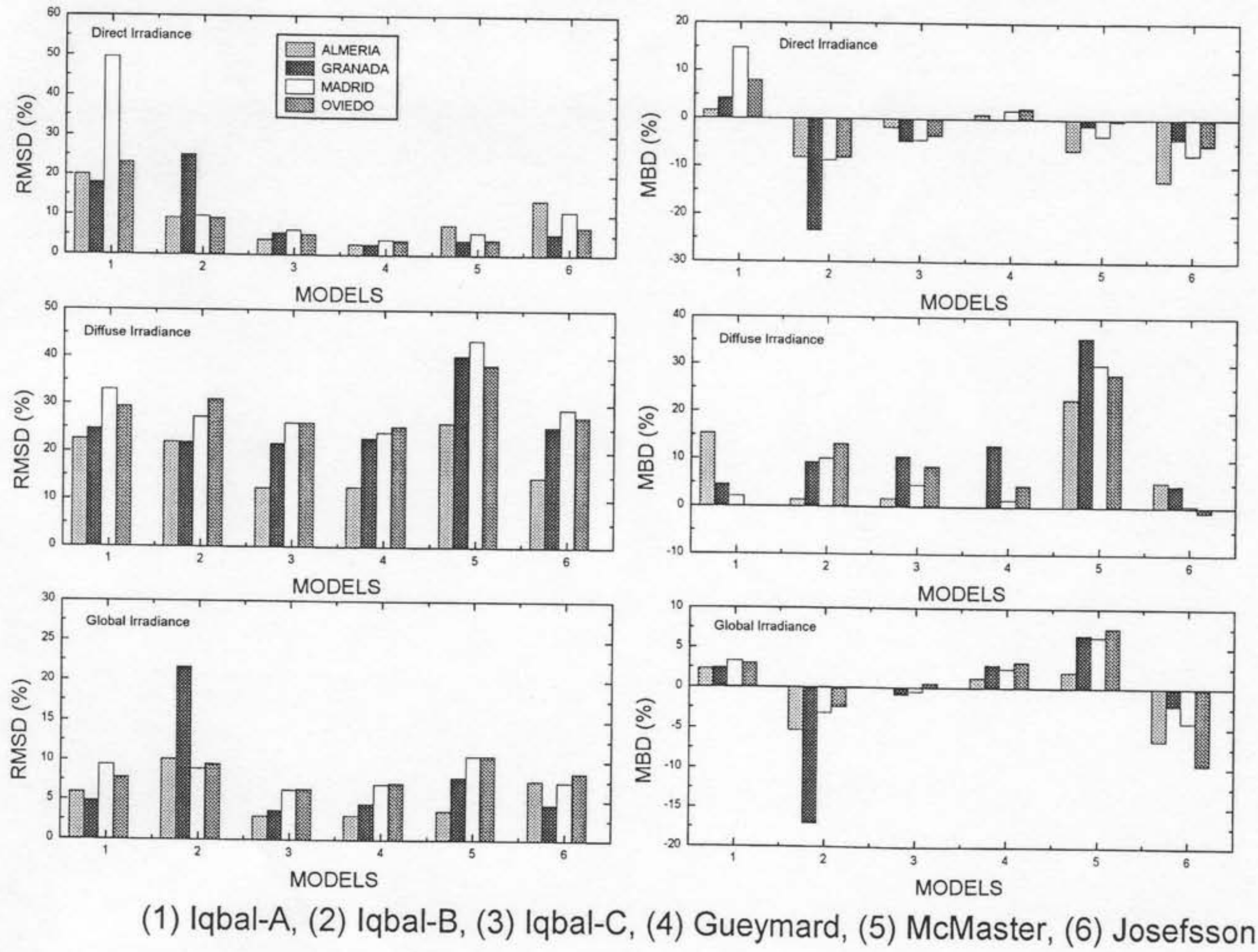


Fig. 2. Statistical results for the estimations of direct, diffuse and global irradiance by the selected models, for each one of the localities, using as input parameters all the required information for the corresponding model

mentioned above have been presented in a graphical way. Figure 2 shows, for each location, the results of the statistical analysis. In this case, we present the MBD and RMSD for the estimations of direct, diffuse and global irradiance by the selected models, using as input parameters all the required information for the corresponding model. For the selection of cloudless sky conditions we have used the meteorological observer criterion, that is total octas zero. For all the localities, considering the location of the radiometric stations we have selected a surface albedo of 0.2. Sensitivity tests show that for cloudless conditions and the natural surfaces present in the analyzed locations variations about 25% of this value provides similar results. For F_c, the factor of forward scatterance, we use the set of values proposed by Robinson (1962) as a function of the solar zenith angle.

As a first step, we discuss the results obtained in the study of the estimation of solar direct irradiance. As can be seen in Fig. 2, the model Iqbal A overestimates at all stations. On the other hand, the models Iqbal B and Iqbal C and McMaster underestimate at all the stations analyzed. The model proposed by Joseffson underestimates at all places except Granada. Finally, the Gueymard model presents a negligible mean bias deviation in each one of the localities. These performance differences are partially explained by the use of different expressions for the Rayleigh scattering. In fact, the Rayleigh transmittance expression used in the Josefsson model underestimates this term for low and medium solar elevations (Gueymard, 1993b). On the contrary, the expressions of Rayleigh transmittance used in the McMaster and Gueymard models overestimates for solar elevations angles greater than 70°. The models that present smaller RMSD are Iqbal C, Gueymard and McMaster. It is interesting to emphasize that the models Gueymard, Iqbal C and McMaster present similar values of RMSD and MBD in all the localities analyzed. To summarize, the models that provide better results for the estimate of the direct irradiance are Gueymard, Iqbal C and McMaster.

Concerning the diffuse irradiance estimation, both the RMSD and the MBD associated with each one of the models analyzed present a marked variability among the different localities. This variability is more significant for the McMaster model. The models that provide better results for the estimate of the diffuse irradiance are Iqbal C, Gueymard and Joseffson. A common feature of these models is that they split the transmittance due to aerosols into absorption and scattering contributions.

For the global solar horizontal irradiance, the models Iqbal B and Joseffson underestimate for all the stations. The models Iqbal A, Gueymard and McMaster overestimate, at all places, whilst the mean deviation for the model Iqbal C is practically zero. All the models present RMSD lower than 11% at all the analyzed locations, except Iqbal B model which presents a RMSD about 22% at Granada.

As a consequence of the previous analyses, we can assert that the models Gueymard and Iqbal C provide the better estimates of direct, diffuse and global solar irradiance. Concerning the location, the best results are achieved at Almería. In this case the RMSD associated with the estimation of direct, diffuse and global solar irradiance are less than 4%, 13% and 4% respectively, while the MBD values are negligible. The use of the two-band model proposed by Gueymard, CPCR2, provides slightly better estimates of direct and diffuse irradiances.

4.2 Influence of Solar Elevation Angle on Model Performance

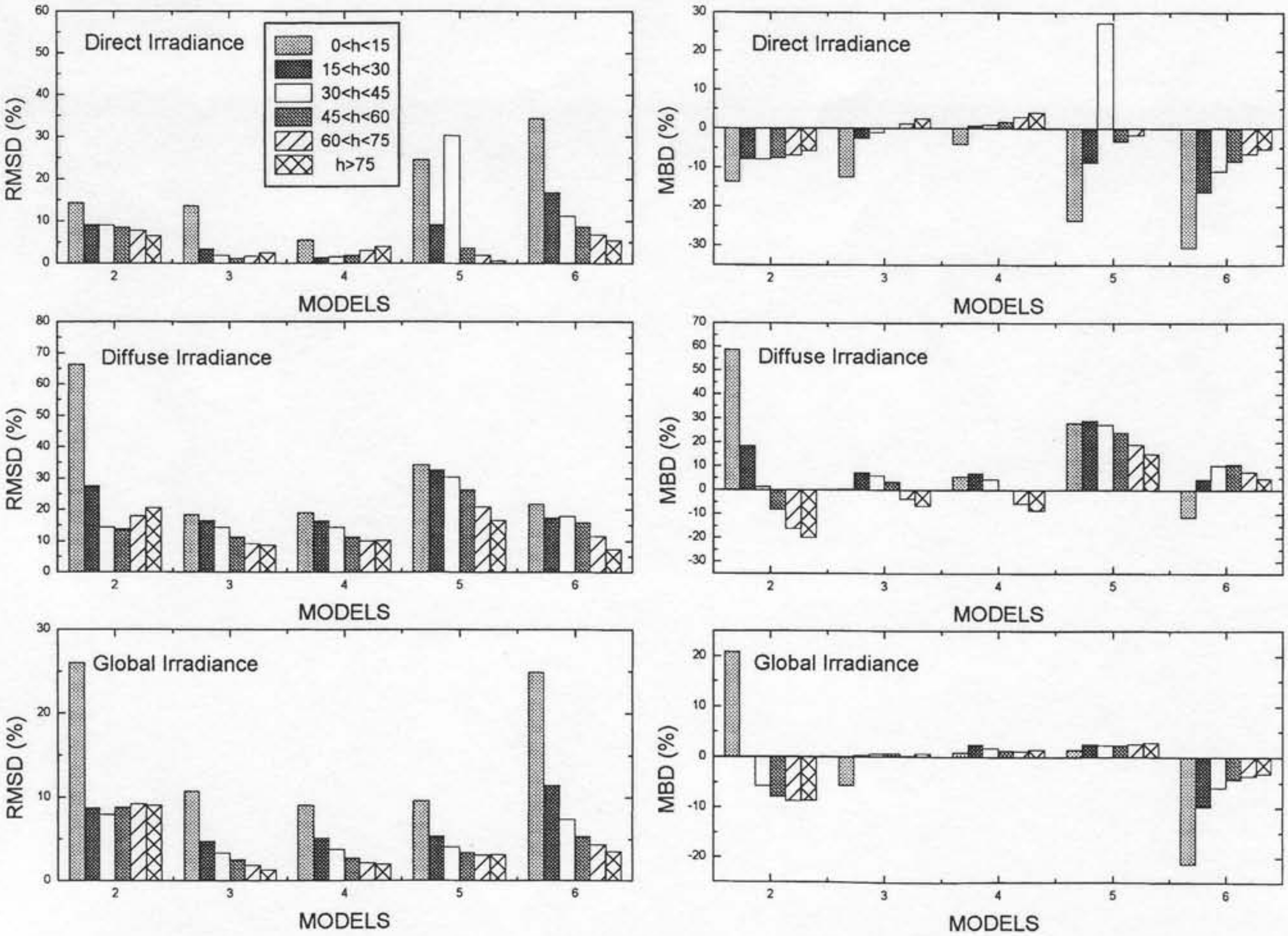
As indicated by Gueymard (1993b) the parameterizations included in the models present marked differences at some solar elevation angles. For this reason, we study the influence of solar elevation angle model performance. As shown above, the global performance of the models is better at Almería. Using this database, we have analyzed the model performance for different solar elevation angles. For this purpose, we have divided the complete data set recorded at Almería into bins of solar elevations angle 5° in width.

Figure 3 shows the results of the statistical analysis achieved for different solar elevations using the Almería data set. For solar elevation angles lower than 15° we found that the model Iqbal A (not included in Fig. 3) provides estimates of direct, diffuse and global solar irradiance with RMSD values of 129, 85 and 67%, respectively. Concerning the MBD, we obtain overestimation of 72, 37, and 43% for direct, diffuse and global irradiance respectively. As the solar elevation angle increases the RMSD diminishes and the MBD values approaches to zero. On the other hand, the performance of the models Gueymard and Iqbal C varies slightly with solar elevation angle. These two models provide the better results for solar elevation angles higher than 15°. In fact, these models estimate the direct, diffuse and global irradiances with negligible MBD and with RMSD smaller than 5, 16 and 5%, respectively. For solar elevation angles lower than 15° the models Gueymard and Iqbal C provides similar results concerning the estimate of the diffuse and global irradiances. On the other hand, the model Gueymard provides better results than the model Iqbal C for the estimation of the direct irradiance. In fact, the RMSD and MBD values achieved with Gueymard model are about 5% and −5%, while those associated to Iqbal C are about 13% and −12%. The models Iqbal B, McMaster and Josefsson present performance differences in the higher and medium range of solar elevation angles that can be explained as a result of the expressions used for the transmittances.

These results show that the use of a more complex parameterization, like that used in Gueymard two-bands model, provides a model with better performance for all the solar elevations considered. On the other hand, for the range of solar elevation angles important for solar energy applications the simpler model Iqbal C provides similar results.

4.3 Use of a Radiometric Criterion for the Selection of Cloudless Conditions Cases

The results presented above are obtained selecting the data that correspond to cloudless condi-



(2) Iqbal-B, (3) Iqbal-C, (4) Gueymard, (5) McMaster, (6) Josefsson

Fig. 3. Statistical results for the estimations of direct, diffuse and global irradiance, achieved for different solar elevations angles *h* using the Almería data set

tions by the use of the cloud information provided by a meteorological observer. In the following, we try to study the capability of classifying the sky conditions using a radiometric criterion. This could be of interest in absence of cloud observation. Different authors (Orgill and Hollands, 1977; Erbs et al., 1982; Reindl et al., 1990; Iqbal, 1980) have defined the sky conditions as a function of clearness index, k_t, and the diffuse fraction, k. High values of clearness index, k_t, and low values of diffuse fraction, k, correspond to cloudless conditions, while cloudy conditions present a combination of higher k and lower k_t. On the other hand, different authors (e.g., Iqbal, 1980; Vazquez et al., 1991; Soler, 1988) have provided evidence that for cloudless conditions there is a dependency of clearness index, k_t, and the diffuse fraction, k on solar elevation angle. Considering this we have developed a radiometric criterion to distinguish cloudless conditions from those characterized by the presence of clouds. The method is based on the definition of threshold values of k and k_t. For this purpose, we have studied the distribution of k and k_t values corresponding to cloudless conditions as defined by the zero octas criterion. This allows the definition of appropriate thresholds for k and k_t. These are not fixed thresholds; on the contrary, they depend on solar elevation angle, h. These solar elevation angle dependencies have been parameterized using the Almería database, where we have the more frequent cloud

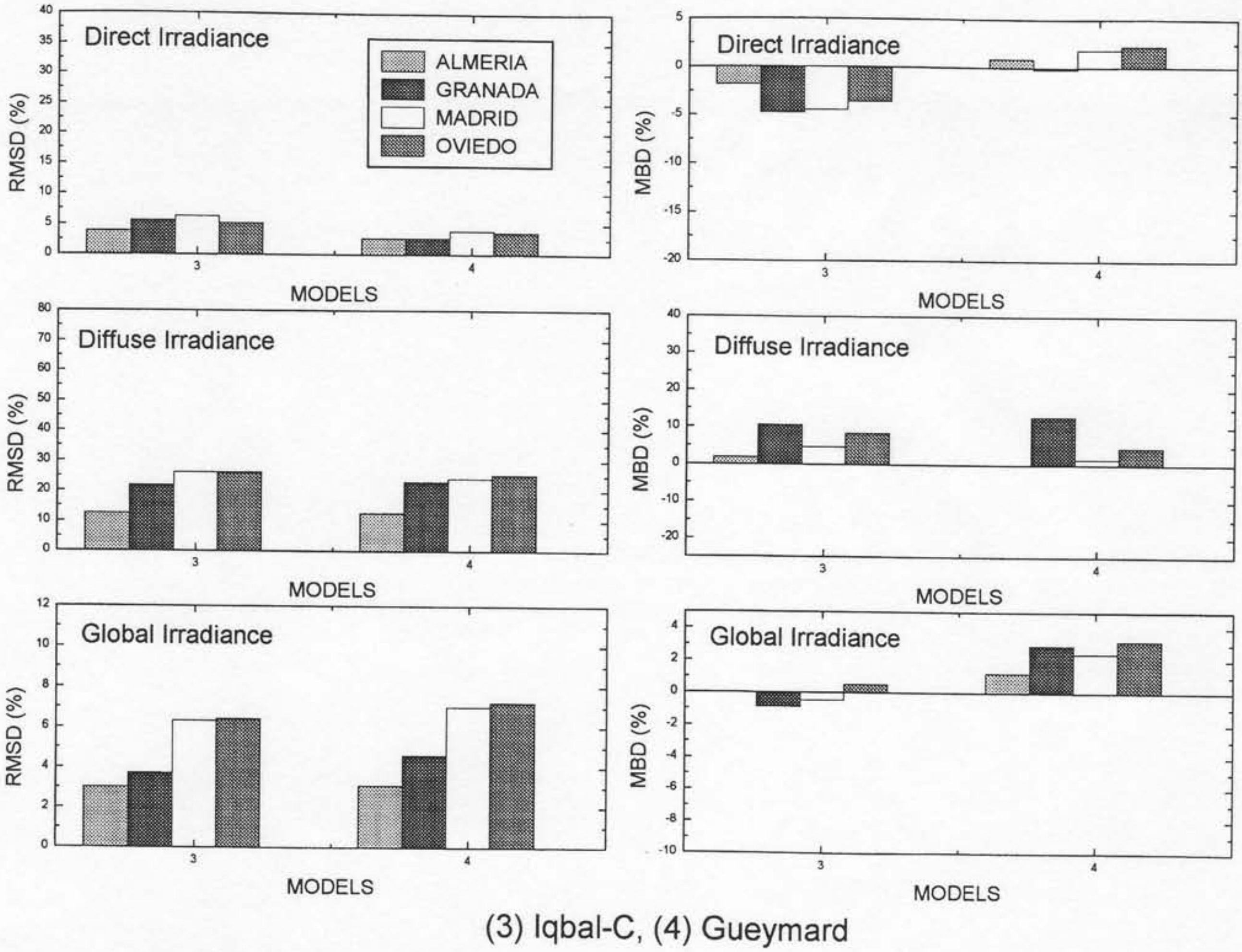


Fig. 4. Statistical results for the estimations of direct, diffuse and global irradiance by the Iqbal-C and Gueymard models, for each one of the localities, using the radiometric criterion

information. The expressions defining the minimum k_t, k_{tt}, and the maximum k, k_k, allowed for cloudless conditions, read as follows:

$$k_{tt} = -0.3262 - 0.0032\,h + 0.6843\log h \quad R^2 = 0.97$$

$$k_k = 1.0827 - 0.3893\log h \quad R^2 = 0.98$$

We have tested the validity of this criterion. For this purpose, we have evaluated the better models, Gueymard and Iqbal C, for the different localities selecting the cloudless cases with the radiometric criterion. Figure 4 shows the statistical results of this study. Concerning the direct and global solar irradiance, we obtain results similar to that achieved using the criterion zero octas for selecting cloudless conditions, compare Fig. 2. The results for the diffuse irradiance evidence a slight improvement. It is important to note that these results are obtained for all the locations analyzed, although the radiometric criterion for cloudless condition selection have been developed using data acquired at Almería only. The advantage of such cloud condition criterion is that it does not rely on meteorological observations, which are performed only in specific locations and at specified hours.

4.4 Analyzing the Use of the Parametric Models with Limited Input Data

As a final step in our analysis, we have considered that some of the input parameters required for the different models are difficult to obtain. For this reason, we have analyzed the effect on model performance using monthly values of some parameters. At a first stage, we analyze the performance of the Gueymard and

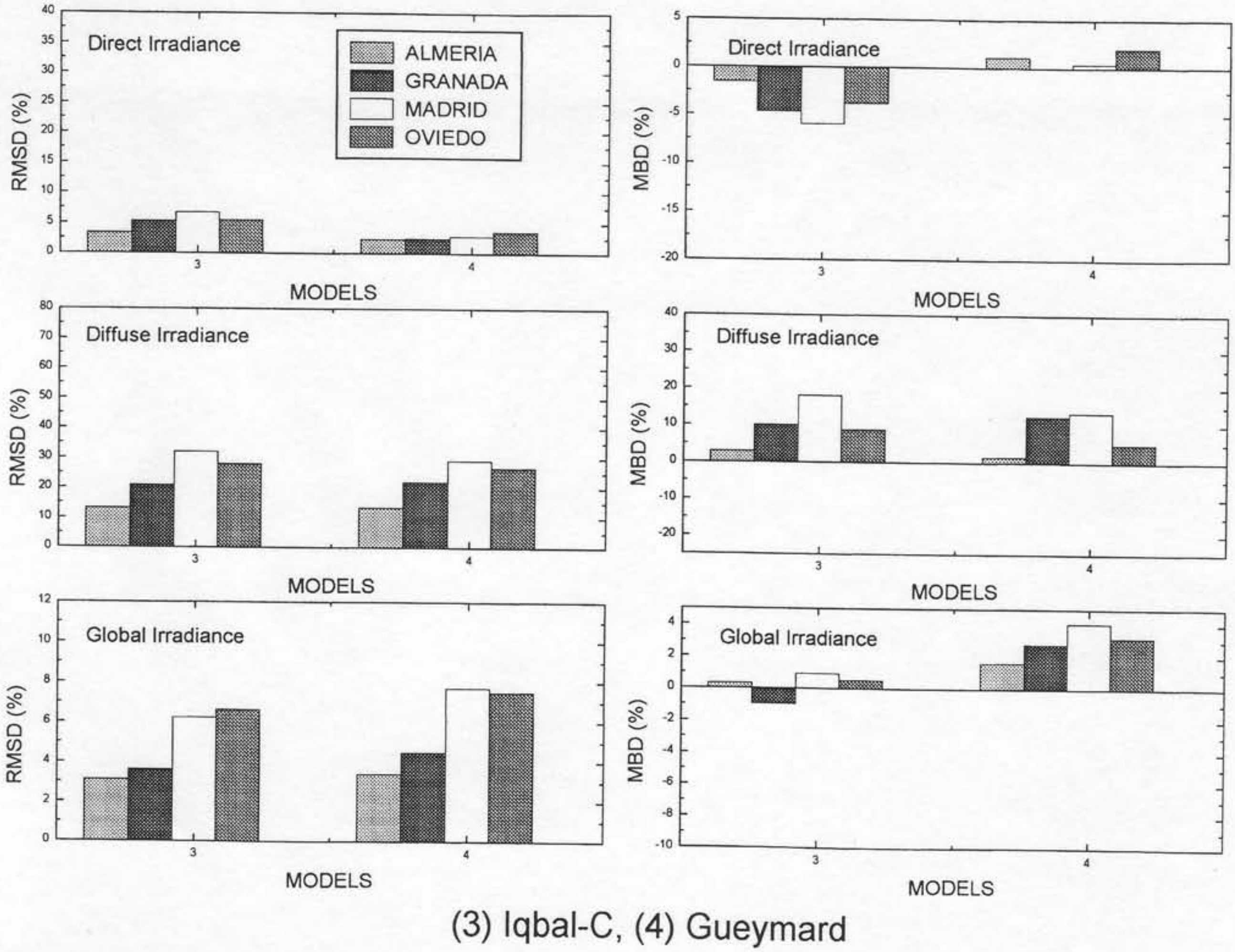


Fig. 5. Statistical results for the estimations of direct, diffuse and global irradiance by the Iqbal-C and Gueymard models, for each one of the localities, using monthly averages of precipitable water content as input variables

Iqbal C models, if monthly averages of precipitable water are used as a substitute of hourly values of this parameter. Figure 5 shows the results in terms of the RMSD and the MBD. We can see that the results are similar to those shown in Fig. 4, except for the estimation of the diffuse irradiance at Madrid. This shows that the influence of the precipitable water in models performance is of minor importance. Thus, one can obtain appropriate estimates of the radiometric fluxes by using a monthly average of precipitable water as input parameter for the parametric models.

In a second step, we have analyzed the performance of the Iqbal C and Gueymard models using monthly averages of both precipitable water content and Angström turbidity coefficient (β) as input variables. The mean monthly averages of Angström turbidity coefficient have been obtained by averaging the cloudless cases included in each month. Figure 6 shows the results achieved at each location. The deviations are greater than in Figs. 4 and 5. This finding shows the great importance of appropriate aerosol information for the accurate estimation of direct and diffuse irradiances. However, the use of monthly average values of turbidity for the global irradiance estimates provides results close to that obtained using hourly values of this parameter. The analysis of the differences between Figs. 5 and 6 reveals that the use of monthly values of the Angström turbidity coefficient leads to an increase in RMSD of 13% for the direct irradiance and 25% for the diffuse irradiance. On the other hand, the substitution of aerosol hourly informa-

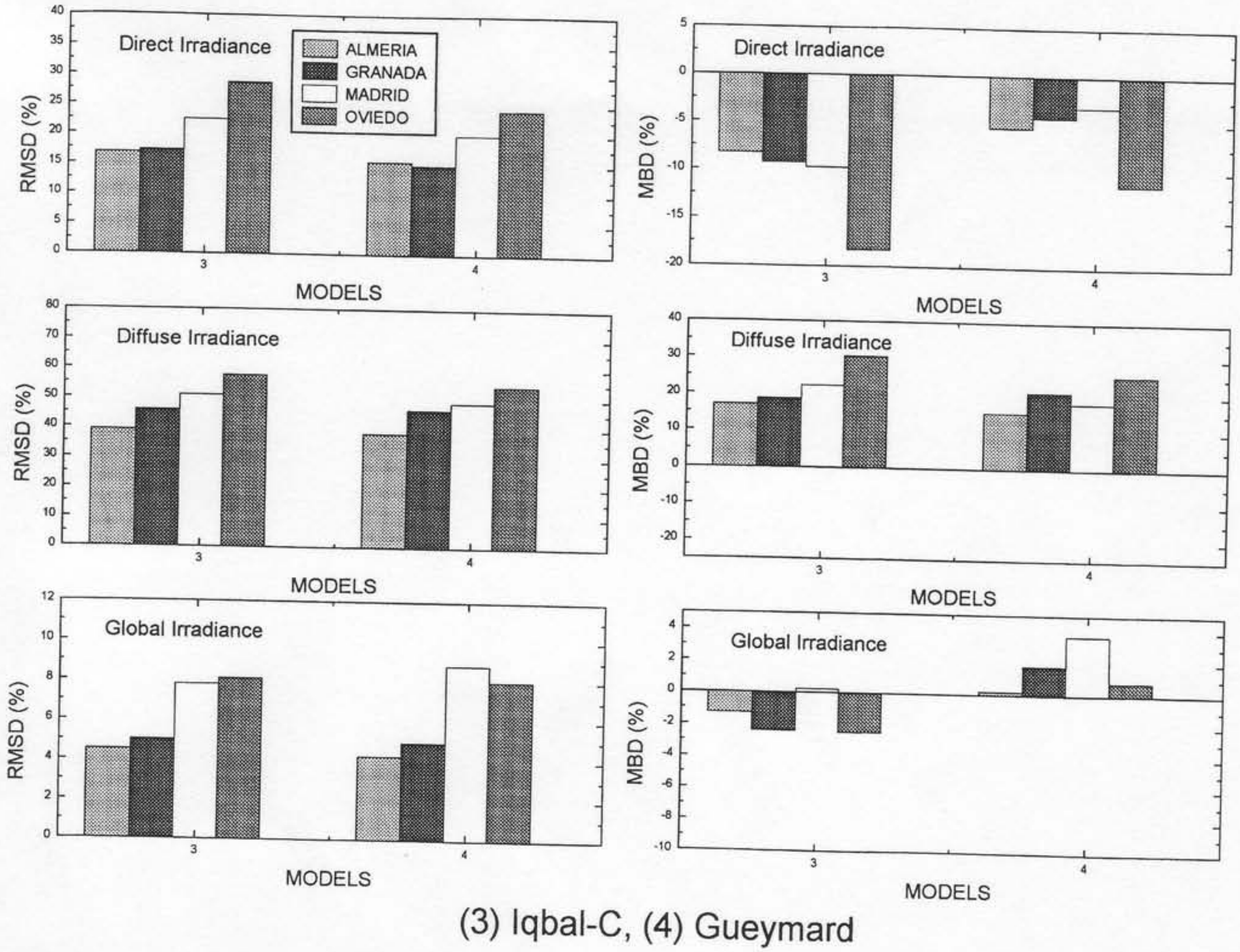


Fig. 6. Statistical results for the estimations of direct, diffuse and global irradiance by the Iqbal-C and Gueymard models, for each one of the localities, using monthly averages of both precipitable water content and Angström turbidity coefficient as input variables

tion by monthly averages leads to an increase in MBD by about 7% for the direct irradiance and 14% for the diffuse irradiance. Finally, the effect of this substitution on the performance of global solar irradiance estimates is less important. In fact, there is a slight increase of about 2% in RMSD and a negligible increase in MBD.

These previous results show that we could obtain appropriate estimates of global irradiance using an approximate value for the turbidity. This is particularly interesting for the estimation of global solar irradiance from remote sensing data. In this sense, the use of climatological values or the access to approximate estimations of the aerosol load via remote sensing data (Holben et al., 1992; Kaufman et al., 1997) could allow an appropriate mapping of global solar irradiance at regional or global scales.

5. Conclusions

The comparison of parametric models for the calculation of solar irradiances with data registered at various Spanish radiometric stations shows that the models that present smaller RMSD are Iqbal C, Gueymard and McMaster. It is interesting to note that the models Gueymard, Iqbal C and McMaster present similar values of RMSD and MBD for all the localities analyzed. Globally the models that provide better results for the estimate of the direct irradiance are Gueymard, Iqbal C and McMaster. Summarizing, we can assert that the models Gueymard and Iqbal C provide the better estimates of direct, diffuse and global solar irradiance. Concerning the location, the best results are achieved at Almería.

The solar elevation influence on the models performance reveals that for solar elevation angles lower than 15° the model Iqbal A provides unacceptable RMSD and MBD values. On the other hand, the performance of the models Gueymard and Iqbal C varies slightly with solar elevation angle. These two models provide the better results for solar elevation angles higher than 15°, with better results for the former. The model Iqbal B presents performance differences in the higher and medium range of solar elevation angles that can be explained as a consequence of the expression used for aerosols transmittance.

We have provided evidence for the existence of different cloud and aerosol regimes for the various locations analyzed. At Oviedo, we found a high frequency of cloudy conditions. On the other hand, at Almería, Granada and Madrid there is a predominance of cloudless conditions. In any case, Almería presents the lower frequency of overcast skies.

The new radiometric criterion to distinguish cloudless conditions from those characterized by the presence of clouds was tested with the help of the better models, Gueymard and Iqbal C. Our results suggest the convenience of this approach for the different locations analyzed.

Our study shows that the influence of precipitable water in model performance is of minor importance. Thus, one can obtain appropriate estimates of the radiometric fluxes using as input parameter for the parametric models, a monthly average of precipitable water. Also the use of monthly average values of turbidity information for the global irradiance estimates provides results close to that obtained using hourly values of this parameter. In contrast, the accuracy of the estimation of the direct and diffuse irradiances is reduced by the use of these monthly values of turbidity information.

The present work has shown the usefulness of the Iqbal-C and Gueymard parameterization of cloudless skies radiation. In this sense, these two formulations provide an important background for the estimate of solar radiation components under all sky conditions, once an appropriate cloud transmittance parameterization has been selected. Both models use an extensive parameterization of the atmospheric extinction processes, one by means of a two-band scheme and the other using a simpler one-band scheme. The transparency information plays an important role in both parameterizations, therefore appropriate information on turbidity conditions should be included. When hourly information of the Angström turbidity coefficients is not available, however, one can estimate the global irradiance with satisfactory accuracy by using a monthly value.

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References

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), 1976: Procedure for Determining Heating and Cooling Loads for Computerizing Energy Calculations, Algorithms for Building Heat Transfer Subroutines. New York, ASHARAE.

Batlles, F. J., Olmo, F. J., Alados-Arboledas, L., 1995: On shadowband correction methods for diffuse irradiance measurements. *Solar Energy,* **54**, 105–114.

Bird, R. E., Hulstrom, R. L., 1981: Review, evaluation and improvement of direct irradiance models. *Trans. ASME, J. Sol. Eng.,* **103**, 182–192.

Bird, R. E., Riordan, C., 1986: Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the Earth's surface for cloudless atmospheres. *J. Climate Appl. Meteorol.,* **25**(1), 87–97.

Davies, J. A., 1987: Parameterization for Rayleigh scattering. *Solar Energy,* **39**, 31–32.

Davies, J. A., McKay, D. C., Luciani, G., Abdel-Wahab, M., 1988: Validation of Models for Estimating Solar Radiation on Horizontal Surfaces. IEA Task IX Final Report, Vol. 1, Atmospheric Environment Service, Downsview.

Davies, J. A., McKay, D. C., 1989: Evaluation of selected models for estimating solar radiation on horizontal surfaces. *Solar Energy,* **43**, 153–168.

Davis, R. F., 1996: Comparison of modeled to observed global irradiance. *J. Appl. Meteorol.,* **35**, 192–201.

Erbs, D. G., Klein, S. A., Duffie, J. A., 1982: Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *Solar Energy,* **28**, 293–302.

Gueymard, C., 1989: A two-band model for the calculation of clear sky solar irradiance, illuminance and photosynthetically active radiation at the Earth's surface. *Solar Energy,* **43**, 253–265.

Gueymard, C., 1993a: Mathematically integrable parameterization of clear-sky beam and global irradiances and its use in daily irradiation applications. *Solar Energy,* **50**, 385–397.

Gueymard, C., 1993b: Critical Analysis and performance assessment of clear sky solar irradiance models using theoretical and measured data. *Solar Energy,* **51**, 121–138.

Gueymard, C., 1994: Updated Transmittance Functions for Use in fast Spectral Direct Beam Irradiance Models. Proceeding of the 23rd American Solar Energy Society Annual Conference, San Jose, CA.

Holben, B., Vermonte, E., Kaufman, Y. J., Tanré, D., Kalb, V., 1992: Aerosol retrieval over land from AVHRR data. Application for atmospheric correction. *IEEE Geos. Remote Sensing,* **30**, 212–222.

Houghton, H. G., 1954: On the heat balance of the Northern Hemisphere. *J. Meteorol.,* **11**, 1–9.

Iqbal, M., 1980: Prediction of hourly diffuse solar radiation from measured hourly global radiation on a horizontal surface. *Solar Energy,* **23**, 491–503.

Iqbal, M., 1983: An Introduction to Solar Radiation. Academic Press, Toronto.

Kaufman, Y. J., Tanré, D., Gordon, H. R., Nakajima, T., Lenoble, J., Frouin, R., Grassl, H., Herman, B. M., King, M. D., Teillet, P. M., 1997: Passive remote sensing of tropospheric aerosol and atmospheric correction for the aerosol effect. *J. Geophys. Res.,* **102**(D14), 16815–16830.

Kasten, F., 1980: A simple parameterization of the pyrheliometric formula for determining the Linke turbidity factor. *Meteorol. Rdsch.,* **33**, 124–127.

Lacis, A. A., Hansen, J. E., 1974: A parameterization for the absorption of solar radiation in the earth's atmosphere. *J. Atmos Sci.,* **31**, 118–132.

Louche, A., Simonnot, G., Iqbal, M., Mermier, M., 1988: Experimental verification of some clear-sky insolation models. *Solar Energy,* **41**, 273–279.

McClatchey, R. A., Selby, J. E., 1972: Atmospheric Transmittance from 0.25 to 38.5 μm: Computer Code LOWTRAN-2. Air Force Cambridge Research Laboratories, AFCRL-72-0745, *Environ. Res.* Paper 427.

Lacis, A. A., Hansen, J. E., 1974: A parameterization for the absorption os solar radiation at the Earth's surface. *J. Atmos. Sci.,* **31**, 118–133.

Orgill, J. F., Hollands, K. G. T., 1977: Correlation equation for hourly diffuse radiation on a horizontal surface. *Solar Energy,* **19**, 357–359.

Page, J. K., 1986: Prediction of Solar Radiation on Inclined Surfaces. (Series F. Solar radiation data, Vol. 3) Dordrecht: D. Reidel Publ.

Reindl, D. T., Beckman, W. A., Duffie, J. A., 1990: Diffuse fraction correlations. *Solar Energy,* **45**, 1–7.

Robinson, G. D., 1962: Absorption of solar radiation by atmospheric aerosol as revealed by measurements from the ground. *Arch. Meteorol. Geophys. Biokl. Ser. B,* **12**, 19–40.

Soler, A., 1988: The dependence on solar elevation of the correlation between monthly average hourly diffuse and global radiation. *Solar Energy,* **41**, 335–340.

Vazquez, M., Ruiz, V., Perez, R., 1991: The roles of scattering, absorption, and air mass on the diffuse-to-global correlations. *Solar Energy,* **47**(3), 181–188.

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