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Empirical modeling of hourly direct irradiance by means of hourly global irradiance

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Abstract

A very important factor in the assessment of solar energy resources is the availability of direct irradiance data of high quality. Nevertheless, this quantity is seldom measured and thus must be estimated from measures of global solar irradiance, a quantity that is registered in most radiometric stations. In this work we analyze the results provided by different models in the estimation of hourly direct irradiance values. We have selected several models proposed by Orgill and Hollands, Erbs et al., Reindl et al., Skarveit and Olseth, Maxwell, and Louche et al. With the exception of the model from Louche et al. that estimates direct irradiance values from direct transmittance values, all of the models estimate direct irradiance from the diffuse fraction. The data set used in this study comprises 25 000 hourly values of global and diffuse irradiance. These values were registered in six Spanish locations with different climatic conditions. The results provided by the model depend on the clearness index, k_t, and the solar elevation. The best results are obtained for cloudless skies and higher solar elevation. In those conditions we can estimate the direct irradiance with a root square mean error close to 14% of the average measured value. We have estimated the direct irradiance under cloudless sky conditions using a parametric model proposed by Iqbal. In order to analyze the effect of turbidity on the estimation of direct irradiance we have compared the results obtained by the parametric model when using hourly values of the Angstrom turbidity parameter β with those obtained when using monthly means of hourly values of β. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Most solar energy applications such as the simulation of solar energy systems require, at the least, knowledge of hourly values of solar radiation on a tilted and arbitrarily oriented surface.

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Knowledge of direct irradiance is important in applications where the solar radiation is concentrated, either to raise the temperature of the system, as in solar thermal energy technologies, or to increase the intensity of the electric current in solar cells, as in solar photovoltaic systems. To evaluate the concentrating systems used in solar thermal electric systems, it is necessary to know the intensity of direct insolation as this is the only component of solar radiation that can be concentrated.

We can estimate direct irradiance with two different kinds of models, atmospheric transmittance models and models that calculate the decomposition of global irradiance in its components. Atmospheric transmittance models require detailed information of atmospheric parameters like atmospheric turbidity, precipitable water content and cloud cover [1,2]. On the other hand, decomposition models try to estimate direct and diffuse irradiance from global irradiance data [3–8].

Decomposition models are based on the correlations between the clearness index, k_t (global irradiance/horizontal extraterrestrial irradiance) and the diffuse fraction, k_d (diffuse irradiance/global irradiance) or the direct transmittance, k_b (direct irradiance/extraterrestrial irradiance). Orgill and Hollands [3], Erbst et al. [4], and Reindl et al. [6] have estimated the hourly diffuse fraction using the clearness index following the work by Liu and Jordan [9]. Some authors [5,6,10–12] have shown that the diffuse fraction depends also on other variables like the solar elevation, temperature and relative humidity. When we estimate the diffuse fraction from k–k_t correlations, the direct irradiance is obtained from the following equation:

$$I=G(1-k)/\sin\alpha \tag{1}$$

where G is the global radiation, α is the solar elevation angle, and k is the hourly diffuse fraction.

$$k=G/D \tag{2}$$

where D is the diffuse radiation.

Other authors [13,14] have estimated the direct irradiance by means of k_b–k_t correlations. They have found that the solar elevation is an important variable in this type of correlation. When working with these models direct irradiance is estimated with the following definition of direct transmittance:

$$I=k_bI_o \tag{3}$$

where I_o is the extraterrestrial irradiance.

In this work we will evaluate several models used to estimate hourly values of direct irradiance. We will estimate direct irradiance from diffuse fraction values [3–6] or from direct transmittance values [8] and we will use also a quasi-physical model [7]. These models will be evaluated under all sky conditions with different solar altitude values. Finally, the results obtained by these models will be compared with the results obtained under cloudless skies by a parametric model proposed by Iqbal [15]. Cloudless sky conditions are very important when estimating solar energy resources for solar concentrating systems, the type of system that usually requires information on direct radiation, as this is the only component of solar radiation that can be concentrated.

2. Data set

Table 1 shows the geographical locations and the date of the measurements used. In order to exclude data affected by the enhancement of stratospheric aerosols following volcanic eruptions like that of El Chichon and Mt. Pinatubo, we have limited the data used. In the case of Oviedo only the first semester of 1991 has been used. The stations are located in areas characterized by different climatic conditions; there are coastal locations, such as Almería, and inland locations with different climatic conditions. 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 and Zonenn 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. Other measurements included at Almería and Granada stations are the air temperature and relative humidity at screen level. Hourly values have been obtained for all the variables. Analytical checks for consistency of measurements were carried out to eliminate problems associated with shadowband misalignments and other questionable data. Due to cosine response problems, we have used only cases with solar elevation angles of more than 5°. A rough estimate of the cosine response of our pyranometer indicates that the error is below 2% for a solar elevation of 10°. The diffuse irradiance, measured by shadowband, has been corrected using the model developed by Batlles et al. [16]. Direct irradiance values used in this work have been obtained from hourly values of global and corrected diffuse irradiance.

3. Selected models

The models that we have selected cover the different methods available to estimate the direct irradiance. The models proposed by Orgill and Hollands [3], Erbs et al. [4], and Reindl et al. [6] estimate the direct irradiance using k–k_t correlations. The model developed by Reindl introduces the solar elevation angle as a new variable in the model. The model proposed by Skarveit and Olseth [5] estimates also the irradiance from k_t and the solar elevation, but the equations proposed are more complex than those proposed by Reindl. The model proposed by Louche [8] uses a k_b–k_t correlation and has been selected because it is the k_b–k_t model with the best performance [17]. The model proposed by Maxwell [7] combines a clear sky model with experimental fits in other

Table 1
Geographical locations and date of the measurements

	Latitude	Longitude	Altitude (m.a.s.l.)	N	Year
Almería	36.83°N	2.41°W	0	8117	1994–1996
Granada	37.18°N	3.58°W	660	7354	1994–1995
Logroño	42.47°N	2.69°W	373	1529	1991
Murcia	38.00°N	1.67°W	69	856	1987
Oviedo	43.35°N	5.36°W	348	3382	1991
Madrid	40.45°N	3.75°W	664	2267	1983–1985

conditions. We have also selected a parametric model that we will use to evaluate the performance of the empirical models under cloudless sky conditions. We have chosen the Iqbal C model. This model has been tested by Batlles et al. [18] and is among the best models for estimating the direct irradiance under cloudless skies. The models have been tested using data from six Spanish locations with different climatic conditions.

The different models read as follows:

3.1. *Orgill and Hollands*

Orgill and Hollands [3] estimated the diffuse fraction using k_t as the only variable. They used global and diffuse irradiance values registered in Toronto (Canada, 43.8°N) to validate the model. The correlation is given by the following equations:

$$k=1.0-0.249k_t \quad k_t<0.35 \tag{4}$$

$$k=1.577-1.84k_t \quad 0.35\le k_t\le 0.75 \tag{5}$$

$$k=0.177 \quad k_t>0.75 \tag{6}$$

3.2. *Erbs et al.*

As the correlation used by Orgill and Hollands to estimate the diffuse fraction k were derived from data registered at a high latitude station, Erbs et al. [4] studied the same kind of correlations with data from five stations in the USA with latitudes between 31° and 42°.

In each station hourly values of normal direct irradiance and global irradiance on a horizontal surface were registered. Diffuse irradiance was obtained as the difference of these quantities. The diffuse fraction is calculated using the following equations:

$$k=1-0.09k_t \quad k_t\le 0.22 \tag{7}$$

$$k=0.9511-0.1604k_t+4.388k_t^2-16.638k_t^3+12.336k_t^4 \quad 0.22<k_t\le 0.8 \tag{8}$$

$$k=0.165 \quad k_t>0.8 \tag{9}$$

3.3. *Reindl et al.*

Reindl et al. [6] estimated the diffuse fraction, k, using two different models developed with measurements of global and diffuse irradiance on a horizontal surface registered at five locations in the USA and Europe. The first model, that we have named Reindl-1, estimates the diffuse fraction using the clearness index as input data. The model is given by the following equations:

$$k=1.020-0.248k_t \quad k_t\le 0.30 \tag{10}$$

$$k=1.450-1.670k_t \quad 0.30<k_t<0.78 \tag{11}$$

$$k=0.147 \quad k_t \geq 0.78 \tag{12}$$

The second correlation, the Reindl-2 model, estimates the diffuse fraction in terms of the clearness index and the solar elevation. The equations obtained are the following:

$$k=1.020-0.254k_t+0.0123 \sin\alpha \quad k_t \leq 0.30 \tag{13}$$

$$k=1.400-1.749k_t+0.177 \sin\alpha \quad 0.30<k_t<0.78 \tag{14}$$

$$k=0.486k_t-0.182 \sin\alpha \quad k_t \geq 0.78 \tag{15}$$

3.4. Skartveit and Olseth

Skartveit and Olseth [5] estimated direct irradiance, I, from global irradiance, G, and from the solar elevation angle α with the following equation:

$$I=G(1-\Phi)/\sin\alpha \tag{16}$$

where Φ is a function of k_t and the solar elevation α in degrees. This function is detailed below:

If $k_t<k_o$

$$\Phi=1 \tag{17}$$

where

$$k_o=0.2$$

If $k_o \leq k_t \leq 1.09k_1$

$$\Phi=1-(1-d_1)(ak^{1/2}+(1-a)k^2) \tag{18}$$

where

$$k_1=0.87-0.56\exp(-0.06\alpha) \tag{19}$$

$$d_1=0.15+0.43\exp(-0.06\alpha) \tag{20}$$

$$a=0.27$$

$$k=0.5(1+\sin[\pi(a'/b'-0.5)]) \tag{21}$$

where

$$a'=k_t-k_o \tag{22}$$

$$b'=k_1-k_o \tag{23}$$

If $k_t>1.09k_1$ (24)

$$\Phi=1-(1.09k_1(1-\xi)/k_t) \tag{25}$$

where

$$\xi=1-(1-d_1)(ak'^{1/2}+(1-a)k'^2) \tag{26}$$

where

$$k'=0.5(1+\sin[\pi(a''/b'-0.5)]) \tag{27}$$

where

$$a''=1.09k_1-k_o \tag{28}$$

Note that the authors of this model indicate that some of the constants may have to be adjusted for conditions deviating from their validation domain. This task is not undertaken here.

3.5. Maxwell model

The Maxwell model [7] is termed as ‘quasi-physical’ as it combines a physical clear model with experimental fits for other conditions.

$$I=I_o\{K_{nc}-[A+B\exp(mC)]\} \tag{29}$$

where I_o is the extraterrestrial irradiance and K_{nc} is a function of the air mass, m, given by:

$$K_{nc}=0.866-0.122m+0.0121m^2-0.000653m^3+0.000014m^4 \tag{30}$$

and where A, B, and C are functions of the clearness index, k_t, given below:

$k_t\leq 0.6$

$$A=0.512-1.560k_t+2.286k_t^2-2.222k_t^3 \tag{31}$$

$$B=0.370+0.962k_t \tag{32}$$

$$C=-0.280+0.923k_t-2.048k_t^2 \tag{33}$$

$k_t>0.6$

$$A=-5.743+21.77k_t-27.49k_t^2+11.56k_t^3 \tag{34}$$

$$B=41.40-118.5k_t+66.05k_t^2+31.90k_t^3 \tag{35}$$

$$C=-47.01+184.2k_t-222.0k_t^2+73.81k_t^3 \tag{36}$$

3.6. Louche et al.

Louche et al. [8] used the clearness index k_t to estimate the direct transmittance. The correlation is given by the following equation:

$$k_b=-10.627k_t^5+15.307k_t^4-5.205k_t^3+0.994k_t^2-0.059k_t+0.002 \tag{37}$$

To develop the correlation they used global and direct irradiance data registered at Ajaccio (Corsica, France) between October 1983 and June 1985. They used a pirheliometer (model NIP, Eppley) to measure direct irradiance and a pyranometer (model CM-5, Kipp & Zonen) to measure global irradiance.

3.7. Iqbal model C

This model is described in Iqbal [16]. The beam irradiance for model C reads as follows:

$$I = 0.9751 I_o \tau_r \tau_o \tau_g \tau_w \tau_a \tag{38}$$

where the factor 0.9751 shows that the spectral interval considered is 300–3000 nm. I_o is the extraterrestrial irradiance at normal incidence, and τ_o, τ_g, τ_w, τ_r and τ_a are the ozone, gas, water, Rayleigh and aerosols scattering transmittances, respectively.

The horizontal diffuse irradiance at ground level (D) is a combination of three individual components corresponding to the Rayleigh scattering (D_r), the aerosols scattering (D_a) and the multiple reflection processes between ground and sky (D_m):

$$D_r = \frac{0.79 I_o \sin\alpha \tau_o \tau_g \tau_w \tau_{aa} 0.5(1-\tau_r)}{(1-m_a+m_a^{1.02})} \tag{39}$$

$$D_a = \frac{0.79 I_o \sin\alpha \tau_o \tau_g \tau_w \tau_{aa} F_c(1-\tau_{as})}{(1-m_a+m_a^{1.02})} \tag{40}$$

$$D_m = \frac{(I \sin\alpha + D_r + D_a)\rho_g \rho'_a}{1-\rho_g \rho'_a} \tag{41}$$

The aerosol transmittance is calculated from the visibility [19].

$$\tau_a = [0.97 - 1.265(\text{Vis})^{-0.66}]^{m_a^{0.9}} \tag{42}$$

As visibility was not measured at our meteorological stations we estimated it using the relationship proposed by Mächler and Iqbal [20]

$$\text{VIS} = 147.994 - 1740.523[\beta x - (\beta^2 x^2 - 0.17\beta x + 0.011758)^{0.5}] \tag{43}$$

where

$$x = 0.55^{-\alpha_A}$$

α_A and β are the Angstrom turbidity parameters. We have used 1.3 as the value of α_A, a value widely accepted. β is calculated using the Linke turbidity factor T_L following the equation proposed by Dogniaux (also given in Page [21])

$$T_L = \left(\frac{85+\alpha}{39.5e^{-w}+47.4} + 0.1\right) + (16 + 0.22w)\beta \tag{44}$$

where α is the solar elevation in degrees and w is the precipitable water content in cm.

The Linke turbidity factor, T_L, is defined as the number of Raleigh atmospheres (an atmosphere clear of aerosols and without water vapor) required to produce a determined attenuation of direct radiation. This is calculated using the following equation:

$$T_L = \frac{1}{\delta_R m_a} \ln\frac{I_o}{I} \tag{45}$$

where I is the beam irradiance, I_o is the extraterrestrial irradiance, m_a is the relative optical mass and δ_R is the Raleigh optical thickness, obtained using Kasten's formula [22].

The ozone and water vapor transmittances are calculated by means of their respective absorptances [23]. For other parameters we use the values recommended by the author [15]. The interested reader can consult the original text of the author [15] for a complete explanation of the model.

In order to analyze the effect of turbidity on the estimation of direct irradiance we have worked with two different versions of the Iqbal model. In the first version we use hourly values of the Angstrom turbidity parameter β (Iqbal C-1), in the second version we use monthly means of hourly values of β (Iqbal C-2).

4. Model performance

In Table 2, the database frequency distribution is given in terms of the clearness index, k_t, and the solar elevation. The models' performance was evaluated using the root mean square error (RMSE) and the mean bias error (MBE). These statistics allow for the detection of both the differences between experimental data and the model estimates and the existence of systematic over- or underestimation tendencies, respectively. Table 3 shows the statistical results of the different models as functions of the solar elevation and the clearness index, k_t. The results obtained in the range $k_t<0.24$ are not significant as this range comprises just 2% of the data.

For values of k_t over 0.24 and under 0.45 all the models estimate the direct irradiance with a RMSE over 60% for all solar elevations. Except the model from Louche and Reindl-1 the rest of the models overestimate the results in this interval for solar elevations over 50°. Globally, the model that gives the best results is the model proposed by Louche et al. [8]. In this interval all the models give quite poor results due to the fact that partially cloudy skies are the prevailing weather conditions in this category and the clearness index is not suitable to parameterize the effect of the clouds on direct irradiance.

In the range $0.45<k_t<0.75$ the models improve their RMSE and MBE. We have also found that the RMSE decreases with the increase of solar elevation. In the Louche and Reindl-2 models, the MBE increases with an increase of solar elevation, whereas in Maxwell's model the opposite happens. The models from Orgill and Holland and from Skartveit show no tendency. In this interval for solar elevations over 20°, the decomposition models estimate the direct irradiance with a RMSE of about 17% and with a MBE that depends on the model.

Table 2
Number of occurrences as a function of the clearness index, k_t, and solar elevation

k_t	<20°	20–30°	30–40°	40–50°	50–60°	>60°	All
0.00–0.24	374	144	84	29	11	11	653
0.24–0.45	1618	749	499	302	182	181	3531
0.45–0.75	2783	3777	3305	2547	2022	2107	16541
0.75>	92	161	322	418	729	1058	2780
All	4867	4831	4210	3296	2944	3357	23505

Table 3
Overall performance of selected algorithms as a function of insolation conditions and solar elevation

	MBE (%)							RMSE (%)						
$k_t \backslash \alpha$	<20	20–30	30–40	40–50	50–60	>60	0–85	<20	20–30	30–40	40–50	50–60	>60	0–85
Louche model														
0.00–0.24	−71	−62	−71	−53	−54	−68	−63	125	112	117	116	91	132	123
0.24–0.45	−39	−22	−6	−3	17	−27	−32	71	76	73	73	65	67	74
0.45–0.75	−13	−4	2	6	10	2	2	31	20	16	17	18	20	23
0.75>	28	15	7	6	3	7	5	39	24	14	14	10	9	19
Maxwell model														
0.00–0.24	−258	−195	−129	−92	−81	−216	−201	291	218	157	139	108	137	259
0.24–0.45	−10	−21	−23	−31	−25	−18	−21	62	76	75	76	78	77	71
0.45–0.75	10	6	4	1	−4	2	2	27	20	16	15	15	17	21
0.75>	−10	8	6	4	2	−2	−1	29	19	14	13	10	9	17
Orgill–Holland model														
0.00–0.24	−70	−60	−71	−53	−54	−63	−76	126	112	117	116	91	132	128
0.24–0.45	−51	−37	−25	−23	6	16	−30	78	82	76	74	76	72	75
0.45–0.75	20	1	5	1	−3	−6	7	34	17	17	16	16	16	22
0.75>	−23	−9	−2	0	3	3	−6	34	21	14	13	10	9	18
Erb model														
0.00–0.24	−89	−85	−89	−82	−83	−79	−88	141	133	135	113	141	83	139
0.24–0.45	−58	−44	−33	−31	−16	−24	−49	83	85	79	77	76	73	84
0.45–0.75	−20	−9	−3	1	5	8	−4	35	21	17	16	16	17	23
0.75>	25	10	2	0	−3	−2	0	35	21	15	13	10	9	17
Reindl-1 model														
0.00–0.24	−83	−78	−83	−72	−72	−78	−76	135	124	127	127	104	141	130
0.24–0.45	−44	−27	−12	−9	10	1	−42	73	78	75	73	78	70	76
0.45–0.75	−18	−11	−6	−2	1	5	−3	33	23	18	16	16	16	22
0.75>	27	11	3	1	−2	−2	−1	37	22	15	13	10	9	17
Reindl-2 model														
0.00–0.24	−84	−82	−87	−78	−79	−82	−77	136	126	129	131	110	146	133
0.24–0.45	−31	−24	−21	−28	−24	−30	−20	67	77	76	77	79	80	78
0.45–0.75	−10	−7	−6	−5	−4	−6	−6	30	21	18	17	16	16	24
0.75>	6	2	−2	−5	−8	−9	−4	28	20	13	13	12	12	18

(continued on next page)

Table 3 (*continued*)

$k_t \backslash \alpha$	MBE (%)							RMSE (%)						
	<20	20–30	30–40	40–50	50–60	>60	0–85	<20	20–30	30–40	40–50	50–60	>60	0–85
Skarveit model														
0.00–0.24	−94	−95	−95	−92	−91	−96	−94	144	138	137	141	120	154	143
0.24–0.45	−30	−43	−39	−40	−29	−37	−36	67	85	81	80	79	77	77
0.45–0.75	−7	−10	−9	−8	−6	−3	−9	27	21	19	17	16	15	22
0.75>	−28	−2	−3	−4	−8	−8	−9	39	18	14	14	13	12	19
Iqbal C-1														
0.75>	13	−7	−5	−4	−3	−1	−3	13	7	5	4	3	2	4
Iqbal C-2														
0.75>	−45	−19	−14	−12	−10	−9	−11	53	25	19	17	14	13	17

The models obtain their best results for values of k_t over 0.75 and solar elevations over 40°. In these intervals decomposition models estimate direct irradiance with a RMSE of about 10%, for the model Iqbal C-2 is about 14%, and for the model Iqbal C-1, about 3%. Most decomposition models have no significant MBE, with the exception of the model proposed by Skarveit and the Reindl-2 model that underestimate the results by 8%. The Iqbal C-2 model underestimates the results by 10% but the Iqbal C-1 model's MBE is almost zero. As expected, the Iqbal C-1 model gives the best results in cloudless conditions, probably because it has detailed information of the turbidity coefficient β. Nevertheless, when we use monthly values of the turbidity coefficient, the results worsen [24,25], a higher RMSE, 14% and MBE, −9%. These results show that if the precise information about turbidity is not available, decomposition models are a good choice to estimate direct irradiance under cloudless skies. In these conditions the results provided by both types of model are similar and decomposition models are much simpler.

The Maxwell, Reindl-2 and Louche models give the best results. Taking into account the complexity of the model proposed by Maxwell, and the fact that in the Reindl-2 model one has to take three k_t intervals to characterize the state of the sky, and these intervals depend on the location, we recommend the use of the model proposed by Louche to estimate the direct irradiance.

If we analyze the overall performance of the models we can observe that the RMSE has a minimum value of 20% and the RMSE is similar for all the models (Table 4). From this fact we can conclude that if we want to derive better models we should include more variables.

Fig. 1 shows the scatter plot of direct irradiance values estimated by the Louche model vs. measured direct irradiance values for different solar elevations. For lower solar elevations the model overestimates the measurements and the points are placed below the perfect fit line 1:1. When the solar elevation increases this deviation tends to disappear. For higher values of direct irradiance, values related to cloudless sky conditions, and for higher solar elevations there is a smaller dispersion of the points and they tend to be closer to the perfect fit line. We observe that for lower values of direct irradiance, values related to cloudy sky conditions, the points are very dispersed. This greater dispersion is due to the fact that the clearness index is not suitable to parameterize the effect of the clouds on direct irradiance.

Table 4
Statistical results for the different models

	MBE (%)	RMSE (%)
Louche model	1	21
Maxwell model	0	20
Orgill–Hollands model	−6	22
Erbs model	−4	22
Reindl-1 model	−5	22
Reindl-2 model	−1	20
Skarveit model	−9	21

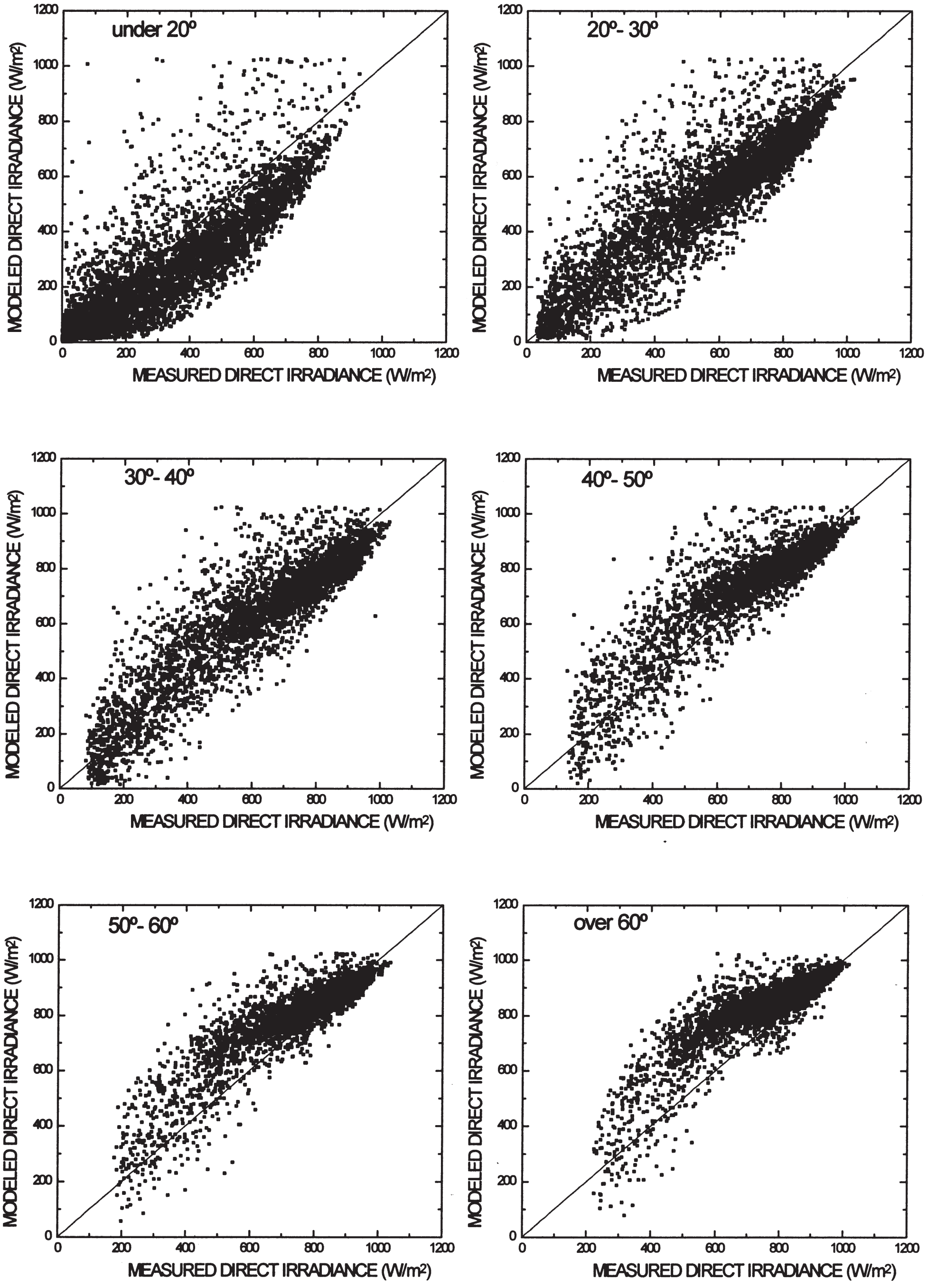

Fig. 1. Measured vs. modeled direct irradiance for different solar elevations using the Louche model.

5. Conclusions

In this work we have estimated hourly values of direct irradiance by means of decomposition models. The results provided by these models under cloudless skies have been compared with those provided by an atmospheric transmittance parametric model. The best results provided by the decomposition models are for high values of the clearness index, that is, cloudless skies and high solar elevations. These are the prevailing conditions for solar concentrating systems. In such conditions the model proposed by Louche et al. estimated the direct irradiance with a 10% root mean square error, the Iqbal C-1 RMSE was close to 4% and the Iqbal C-2 RMSE was 14%. The Louche and the Iqbal C-1 models had no significant mean bias error and the Iqbal C-2 model had a 10% underestimation of the measured direct irradiance. We can conclude that when we have precise information of the turbidity coefficient the best model is the parametric model. However, if there is no turbidity information available the decomposition models are a good choice.

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