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A new simple parameterization of daily clear-sky global solar radiation including horizon effects

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Abstract

Estimation of clear-sky global solar radiation is usually an important previous stage for calculating global solar radiation under all sky conditions. This is, for instance, a common procedure to derive incoming solar radiation from remote sensing or by using digital elevation models. In this work, we present a new model to calculate daily values of clear-sky global solar irradiation. The main goal is the simple parameterization in terms of atmospheric temperature and relative humidity, Ångström's turbidity coefficient, ground albedo and site elevation, including a factor to take into account horizon obstructions. This allows us to obtain estimates even though a free horizon is not present as is the case of mountainous locations. Comparisons of calculated daily values with measured data show that this model is able to provide a good level of accurate estimates using either daily or mean monthly values of the input parameters. This new model has also been shown to improve daily estimates against those obtained using the clear-sky model from the European Solar Radiation Atlas and other accurate parameterized daily irradiation models. The introduction of Ångström's turbidity coefficient and ground albedo should allow us to use the increasing worldwide aerosol information available and to consider those sites affected by snow covers in an easy and fast way. In addition, the proposed model is intended to be a useful tool to select clear-sky conditions.

Keywords: Global solar irradiation; Clear-sky models; Atmospheric parameters

1. Introduction

Estimation of global solar radiation is vital to solar energy system design everywhere where adequate observations are missing. Values of clear-sky solar radiation are useful for determination of the maximum performances of solar heating and photovoltaic plants as well as for sizing air conditioning equipment in buildings or for determining their thermal loading, for instance. In fact, it has been recently shown that inverters of photovoltaic plants with similar efficiency present different performances (in the sense of the quality of the electricity supply) under clear-sky and partially cloudy conditions, showing minimum total harmonic distortion for clear skies [1].

Other scientific fields such as agriculture or hydrology also demand global solar radiation estimations as they need knowledge of insolation levels for studying ecosystem fluxes of materials and energy [2,3]. One methodology to achieve this task is to calculate global solar radiation under cloudless skies and then amend this estimation taking into account the effect of the cloud cover using an appropriate transmission function. This methodology is, for instance, widely used to calculate global solar radiation from satellite images.

Another important point to have modelled clear-sky global solar radiation values is related to the need of splitting all weather solar radiation data bases into two categories: clear-sky and non clear-sky conditions. This task

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could be achieved using meteorological information about the cloud cover of the sky, or employing sunshine duration measurements or even by visual inspection of instantaneous measurements of either global or direct components of solar radiation every day. However, these methods are not usually easy to apply because cloud cover observations are often either unavailable or with a low frequency in a day, sunshine duration records are not measured along with actinometric variables and the last case is time consuming. Several alternatives based on threshold values of the clearness index (defined as the ratio between global and extraterrestrial global solar radiation) or clearness index based functions have been used to this end [4,5]. However, these threshold values depend on the local climatology of the site as well as on the time of the year, and thus, they will not perform uniformly and accurately. An accurate clear-sky model would allow automatically comparing estimated against measured solar radiation values and selecting in this way the desired sky conditions.

The existence is known of numerous radiative transfer based models to estimate solar radiation [6–9], which need detailed information about atmospheric constituents as water vapour, ozone, carbon dioxide, nitrogen dioxide etc. However, for most practical purposes and users, most of them show to be unusable due to the large amount of atmospheric information required or present a difficult software implementation. On the other hand, many simple clear-sky models have been proposed in the literature for calculating instantaneous values of global solar irradiance I_g [10]. Among them, the most used types of empirical models are based on the following scheme:

$$I_g = A(\sin\alpha)^B, \tag{1}$$

where α is the solar elevation and A and B are constants to be determined. The local empirical determination of these coefficients constrains the accuracy and generality in the use of methods based on Eq. (1). This is the case of earlier versions of the Heliosat method [11,12]. In a previous study [13], we found that A and B can be expressed as functions depending on the precipitable water content, Ångström's turbidity coefficient, site elevation and ground albedo, avoiding in this sense the above noted locality. However, for many practical applications, daily insolation is required instead of instantaneous values [14,15]. If daily values of global irradiation are to be obtained from Eq. (1), a hard numerical integration must be performed because the analytical integration of the power function leads to a complex solution in terms of hypergeometric functions. On the other hand, daily values calculated from measured global irradiance data will depend on the temporal sampling frequency of these data. Temporal sampling frequency becomes an undesired source of error, which increases as the frequency diminishes [16].

To avoid the above limitations, in this work, we present a new simple parametric model to estimate daily values of horizontal global solar radiation under cloudless conditions and depending on the latitude, day of year, solar elevation at sunrise and sunset, Ångström's turbidity coefficient, precipitable water content and ground albedo. The two latter parameters are available everywhere since precipitable water content can be obtained from air temperature and relative humidity [17,18]. Ground albedo can be approximated to 0.8 if snow covers are present and 0.2 otherwise. Inclusion of atmospheric turbidity tries to benefit from the growing interest in the determination of atmospheric aerosol properties and the significant effort to establish a world wide, ground based aerosol monitoring network. On the other hand, recent advances in deriving this parameter from satellite images [19,20] open a new way to make available turbidity maps over wide areas and, thus, estimation of daily clear-sky global irradiation would be fast and easily achieved. Nevertheless, we will propose in the text a simple alternative method to avoid the lack of this information.

The model also includes a factor to take into account those sites where horizon obstructions are present and sunrise or sunset do not correspond to null solar elevations. This is a new important point introduced in this model and is absent in the majority of existing models. Solar radiation estimates over complex topographic surfaces, as mountain sites, require this facility to calculate the solar insolation levels properly.

After introducing this new simple model, estimates are compared to synthetic data obtained from the spectral code SMARTS [9] and the model performance is also evaluated using data from five radiometric stations without horizon obstruction. In addition, statistical results of the model performance are compared to those given by two clear-sky models: the parameterized daily irradiation model (DIM) by Gueymard [21] and the proposed one in the framework of the European solar radiation atlas, ESRA [12]. The last section is devoted to testing the new horizon factor using data measured in eleven radiometric stations located at a mountain region.

2. Experimental data

High-quality data from five different sites located in the US has been used to test the performance of the model developed without horizon obstructions. Table 1 lists their geographical locations and the recording period. All of them belong to the NOAA-SURFRAD network [22]. Stations are placed on disparate sites ranging in altitude from 98 to 1689 m above mean sea level. This allows solar irradiance measurements to be affected by different air masses. In addition, these sites present different annual cycles of atmospheric turbidity [23], precipitable water content and ground albedo. Monthly evolution of these two latter parameters can be seen in Fig. 1. This fact is very suitable for testing the models in a proper way.

Solar radiation measurements consisted of 3 min values of horizontal up welling and down welling global, horizontal diffuse and direct normal irradiances. Eppley pyranometers model PSP were employed to measure both global up and

Table 1
Characteristics of the radiometric stations

Station (State), Abbreviation	Latitude (°N)	Longitude (°W)	Altitude (m)	Years
Bondville (IL), BON	40.06	88.37	213	2000–2003
Desert rock (NV), DRA	36.63	116.02	1007	1998–2000
Fort peck (MT), FPK	48.31	105.10	634	1997–1999
Goodwin creek (MS), GWN	34.25	89.87	98	1999–2001
Table mountain (CO), TBL	40.13	105.24	1689	2000–2002
Huéneja (Spain) (11 stations)	37.20[a]	2.97[a]	1091–1659	2003

[a] Mean value.

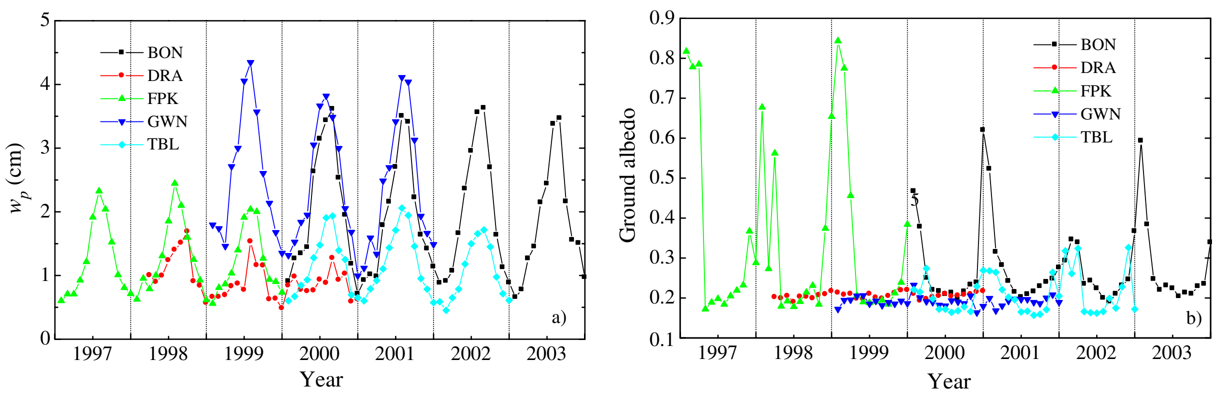

Fig. 1. Monthly values of precipitable water content and ground albedo for each location.

down welling irradiances, whereas Eppley model NIP pyrheliometers were utilized to record direct irradiance. Before 2001, diffuse irradiance was measured by means of Eppley ventilated pyranometers (model PSP) mounted on Eppley automatic solar trackers model SMT-3 equipped with shade disks model SDK. After 2001, these pyranometers were replaced by Eppley model 8-48 (black & white) pyranometers. Databases were completed with measurements of temperature and relative humidity obtained by means of standard sensors exposed in meteorological screens.

Because of cosine response problems of pyranometers to measure global irradiance, this was obtained from values of direct and horizontal diffuse irradiances. If one of these two components was missing or erroneous, then the corresponding pyranometric measurement was used. On the other hand, if either direct or diffuse irradiances were missing, they were derived from the other two available components of solar radiation. Values of precipitable water content, w_p, were calculated from the air temperature and relative humidity following the algorithm by Gueymard [17]. Local ground albedo, ρ, was obtained from up and down welling global irradiances. The Ångström turbidity coefficient β and the Linke turbidity coefficient T_L were also added to the databases. After that, daily values were obtained for all variables. Finally, visual inspection of the daily time evolution of the 3 min global, direct and diffuse irradiances was performed to discard those total or partly cloudy days. Notice that selected days are not totally free of clouds due to the impossibility to achieve this task from only broadband solar radiation data and some contamination by thin and/or little clouds may be present. For this reason, β was obtained using the method derived in Ref. [24], which was shown to be less dependent on cloud cover conditions than the more accurate algorithm by Gueymard and Vignola [25,23].

The dataset used for testing the model as horizon masking occurs consisted of global solar irradiance, air temperature and relative humidity, recorded at 11 radiometric stations located in the north face of the Sierra Nevada Natural Park, in the Hueneja municipal district (Granada, Spain). The surface covered by these stations is around 45 km^2 and corresponds to latitudes around 37.2° N and longitudes around 2.97° W. The stations altitude ranges from 1091 to 1659 m. Different horizon outlines due to the surrounding mountains are present. The measurements were obtained with LICOR 200-SZ photovoltaic pyranometers with 1 min frequency. The calibration constants of the pyranometers are checked yearly against reference Kipp and Zonen CM-11, reserved for this purpose, and exposed to solar radiation only during these intercomparison campaigns. The measures were integrated on a daily basis to obtain the daily global irradiation. Measurements used in this work correspond to clear-sky conditions in January 2003, which were selected following the previous method.

3. Model description

Under cloudless conditions, solar radiation reaching the earth surface is attenuated by absorption and scattering by the different atmospheric constituents. For monochromatic irradiances, these processes are assumed to be independent of each other in such a way that independent transmittance functions may be established for each attenuating process. This assumption is also reproduced to calculate broadband direct irradiance. Following this scheme, we investigated the availability of applying a similar procedure to estimate daily global irradiation. Based on Eq. (1), global irradiation H_g can be expressed as

$$H_g = \frac{D_l}{\pi} I_{SC} E_0 \int_0^{\omega_{sr}} A(\sin\alpha)^B \mathrm{d}\omega \tag{2}$$

where D_l is the day length, I_{SC} the solar constant, E_0 the eccentricity correction factor, ω the hourly angle and ω_{sr} the hourly angle at sunrise. In an atmosphere free of water vapour and aerosols, coefficients A and B were taken to be constants. Their values account for the attenuation due mainly to Rayleigh scattering and ozone, nitrogen dioxide and uniformly mixed gas absorption. Under these conditions, the power term can be approximated to a linear function as

$$A(\sin\alpha)^B \approx a + b\sin\alpha \tag{3}$$

such as can be derived from Fig. 2, where, without loss of generality and for illustration purposes, constants A and B were set corresponding to 0.7 and 1.15, respectively, following Ref. [26]. This simplification allows a straightforward analytical integration during a day:

$$H_g \approx \frac{D_l}{\pi} I_{SC} E_0 \int_0^{\omega_{sr}} (a\sin\alpha + b)\mathrm{d}\omega = \frac{D_l}{\pi} I_{SC} E_0 [a\cos\phi\cos\delta(\sin\omega_{sr} - \omega_{sr}\cos\omega_{sr}) + b\omega_{sr}] \tag{4}$$

where ϕ is the latitude in degrees, δ the declination, ω_{sr} the hourly angle at sunrise in radians and H_g is in [MJ m^{-2}] if $D_l = 0.0864$ s. For different latitudes, the coefficients a and b were obtained by fitting H_g to synthetic values of daily global irradiation given by the spectral code SMARTS

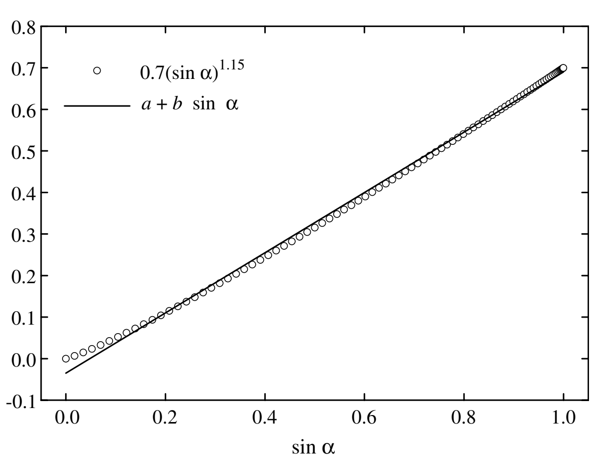

Fig. 2. Linear approximation of the power term given in Eq. (2) for particular values of coefficients A and B.

and using the US standard atmosphere, sea level and a ground albedo of 0.2. Also, we assumed that no horizon obstruction was present. The resulting daily global irradiation $H_{C\text{–}D}$, which corresponds to a clean and dry atmosphere, reads as

$$H_{C\text{–}D} = \frac{D_l}{\pi} I_{SC} E_0 (1.019 - 5.510^{-4}\phi) \times [0.965\cos\delta\cos\phi(\sin\omega_{sr} - \omega_{sr}\cos\omega_{sr}) - 0.0485\omega_{sr}] \tag{5}$$

In a general way, the effect of other attenuation or increasing processes on global radiation is collected by a pseudo daily clearness index K_t, leading to express H_g as

$$H_g = K_t(w_p, \beta, \rho, z) H_{C\text{–}D} \tag{6}$$

To calculate K_t, synthetic H_g^{SMARTS} values were obtained from several runs of SMARTS using different sets of input values, the US standard atmosphere and the rural aerosol model by Shettle and Fenn. Analysing the ratio $H_g^{SMARTS}/H_{C\text{–}D}$ against $H_{C\text{–}D}$ as one input parameter varies and the others are fixed, the following expression was derived for daily global irradiance:

$$H_g = 0.98 e^{0.07z/8345.3} e^{f_1(w_p,\beta)} H_{C\text{–}D}^{f_2(w_p,\beta)} f_3(\rho, \beta) \tag{7}$$

where f_1, f_2 and f_3 are given by the following equations:

$$f_1(w_p, \beta) = -0.249 w_p^{0.31225} + 2.81375\beta^2 - 2.5948\beta \tag{8}$$

$$f_2(w_p, \beta) = 1.00324 + 0.03483 w_p^{0.28073} - 0.97226\beta^2 + 0.64794\beta \tag{9}$$

$$f_3(\rho, \beta) = 0.98613 + 0.0705\rho - 0.15225\beta + 0.77513\rho\beta \tag{10}$$

It is interesting to note for simplicity purposes that the function f_3 can be omitted from Eq. (7) if it is known or assumed that the ground albedo is near 0.2.

Finally, in order to incorporate the effect of the different horizon obstructions from the environment of the specific site where solar radiation needs to be estimated, we firstly generated synthetic global irradiation values from SMARTS, $H_g^{SMARTS}(\alpha_{sr})$ by integrating the corresponding instantaneous irradiance values between solar elevations at sunrise, α_{sr}, ranging from 0° to 20° and noon. Integration is not performed between sunrise and sunset because different horizon obstructions can be present. To analyse the relationship between these synthetic irradiation values and those given by the model without horizon obstruction, we then set $H'_{g0} = H_g/2$. The following simple expression:

$$H_g^{SMARTS}(\alpha_{sr}) = a_\alpha + b_\alpha H'_{g0} \tag{11}$$

was found to be suitable to reproduce the existing relationship between both mid-daily global irradiations, where a_α and b_α are coefficients depending on α_{sr}. These coefficients have been shown to be independent of the remaining input parameters. By means of a least square fitting technique, coefficients a_α and b_α were obtained for several α_{sr}-values. Fig. 3 shows the dependence of these coefficients on solar elevation and the corresponding fitted curves. The

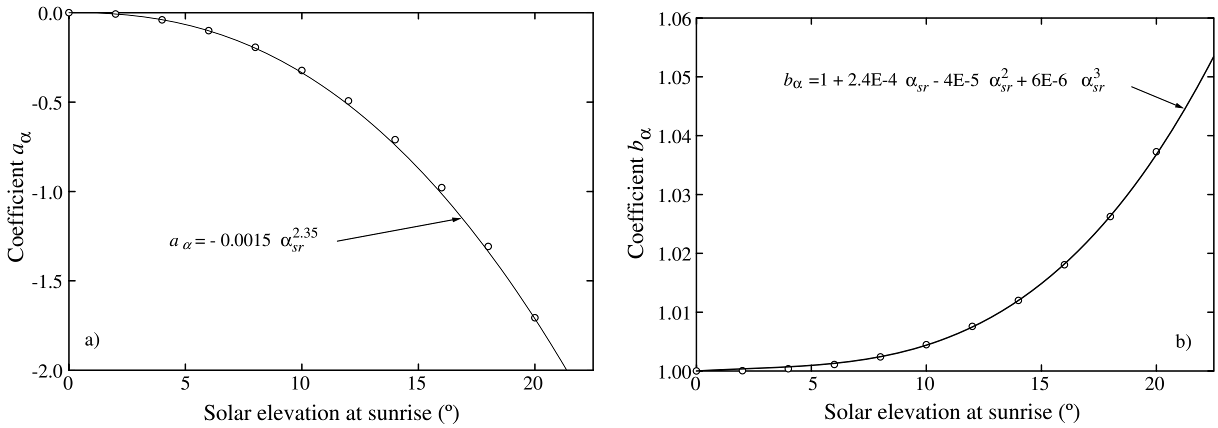

Fig. 3. Dependence of coefficients a_α and b_α from Eq. (11) on solar elevation.

mid-daily global irradiation including horizon dependence, $H'_{\mathrm{g}}(\alpha_{\mathrm{sr}})$, is then expressed as

$$H'_{\mathrm{g}}(\alpha_{\mathrm{sr}}) = -0.0015\alpha_{\mathrm{sr}}^{2.35} + (1 + 2.4E\text{-}4\alpha_{\mathrm{sr}} - 4E\text{-}5\alpha_{\mathrm{sr}}^2 + 6E\text{-}6\alpha_{\mathrm{sr}}^3)H'_{\mathrm{g0}} \tag{12}$$

Assuming that the atmospheric conditions are constant during the day, the evolution of instantaneous global irradiance is symmetric with regard to midday, and the total daily global irradiation, taking into account the horizon factor, is

$$H_{\mathrm{g}}(\alpha_{\mathrm{sr}}, \alpha_{\mathrm{ss}}) = H'_{\mathrm{g}}(\alpha_{\mathrm{sr}}) + H'_{\mathrm{g}}(\alpha_{\mathrm{ss}}) \tag{13}$$

where α_{ss} is the solar elevation at sunset.

If values of Ångström's turbidity coefficient are not available, the following rough approximation as a function of the day of the year, d_{j}, can be used

$$\beta = 0.015 + 0.0005d_{\mathrm{j}} - 1.3810^{-6}d_{\mathrm{j}}^2 \tag{14}$$

This expression is only intended to reproduce in the Northern Hemisphere the mean annual evolution of this parameter with the known increasing and decreasing trend in the summer and winter months, respectively, as reported in many studies, but not to describe its real local trend at one specific site.

On the other hand, if monthly values of w_{p} are to be used, they should correspond to clear-sky conditions. Since measurements of air temperature and relative humidity are available for every day and corresponding to all weather conditions, estimates of mean monthly values of w_{p} will usually be higher, leading to underestimation of clear-sky global solar radiation. We have investigated the possibility to derive the precipitable water content under clear-sky conditions, $w_{\mathrm{p}}^{(\text{clear-sky})}$, from values corresponding to all weather conditions. Fig. 4 shows that a linear relationship exists between both estimates regardless of the different local annual trend of w_{p} for each site and climatology. This is given by

$$w_{\mathrm{p}}^{(\text{clear-sky})} = 0.76w_{\mathrm{p}} \tag{15}$$

Nevertheless, this relationship should be further analysed using more sites to assure its validity.

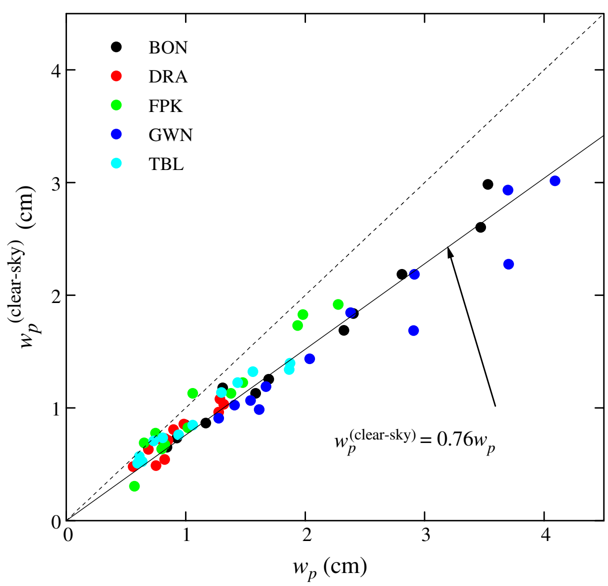

Fig. 4. Comparison between mean monthly values of w_{p} calculated from data corresponding to all sky conditions and from data corresponding to clear-sky days, respectively.

4. Model performance

4.1. Comparison with SMARTS

Comparisons of the model estimates with those given by the spectral code SMARTS show that for very different atmospheric and climatic conditions, the relative errors are lower than ±1% for almost any day of the year and for latitudes lower than about 40°N (see Fig. 5). We note the accurate estimates for high values of ground albedo and altitude. If the correction for ground albedo were not taken into account, underestimates of global irradiation ranging from −2% to − 18% would be obtained. As latitude increases, the relative differences also increase. For a latitude of 55°N, the model presents underestimations between 2% and 12% for very clear winter days. This result is partly affected by the low values of global irradiation of about 2–3 MJ m^{-2} at these high latitudes and, on the other

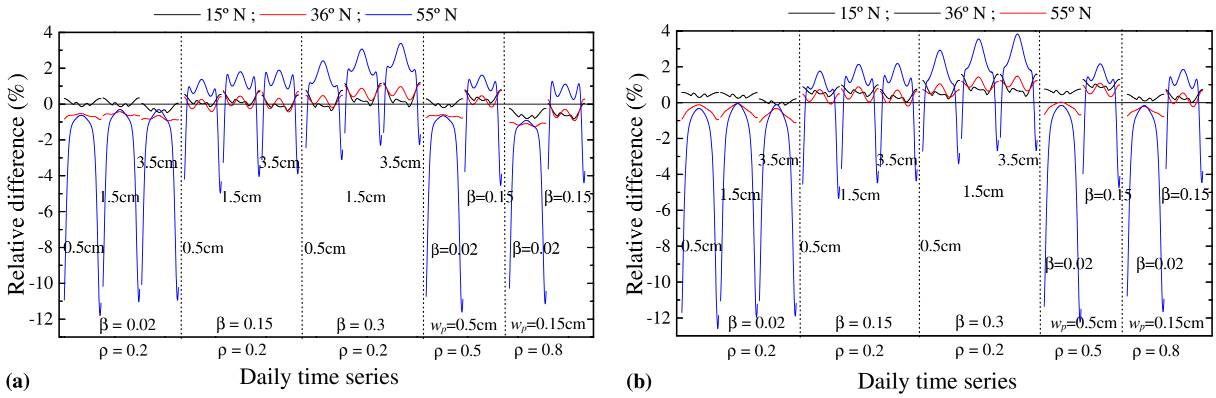

Fig. 5. Relative errors between estimated and synthetic values by SMARTS of H_g for different combinations of input variables and for site altitudes of: (a) 0 m and (b) 1200 m. Time series of 365 days are displayed for each input set.

hand, by the deviation of the approximation assumed in Eq. (3) at low solar elevations. For summer months, the deviations can range from −1% to 3%, depending on the atmospheric conditions. These errors are lower than experimental errors.

4.2. Model evaluation using data without horizon obstruction

In this section, we assess the model performance using experimental data that are not affected by horizon obstruction at sunrise or sunset. In addition, we compare the model performance with two other well established clear-sky models: the DIM model by Gueymard [21] and the ESRA model [12]. The first one was developed using a methodology similar to that used in this work for estimating both direct and global irradiations but using the two band physical irradiance model CPCR2 [27]. Inputs to the DIM model are the same ones used by the developed model but without the horizon effect term. The ESRA model estimates both direct and diffuse irradiations, and global irradiation is computed from their sum. Inputs to the model are latitude, day of the year, site altitude and the Linke turbidity factor for air mass 2 (which is derived from measurements of the direct solar radiation).

Table 2 displays the statistical results (expressed as a percentage of the corresponding mean measured daily global irradiation) of the three models considered. The new model presents root mean square errors (RMSE) and deviations lower than 3.1% and 1.1%, respectively, for each location other than Table Mountain, where the RMSE increases up to 4.0% and mean bias error (MBE) is −2.5%. The reason for this deterioration is due to a higher underestimation in the winter months as a consequence of the high site altitude (1689 m), which leads to very low values of turbidity ($\beta < 0.01$) and precipitable water content ($w_p \sim 0.5$ cm). Fig. 5(b) shows that for these input values, the model underestimates around −1% for a latitude of 36°N in regard to SMARTS. Since the Table Mountain's latitude is 40.13°N, a higher underestimation is expected for these months, which agrees with the MBE found.

On the other hand, estimates are improved in regard to those by the ESRA model at all stations, as the reduction to around 1.4% in the RMSE and 1.3% in the MBE proves. Similarly, the new model improves in regard to the DIM

Table 2
Statistical results from the comparison between estimated and measured daily global irradiation for each site

	BON		DRA		FPK		GWN		TBL	
	rmse	mbe	rmse	mbe	rmse	mbe	rmse	mbe	rmse	mbe
Daily input values										
ESRA model	3.4	1.5	4.1	3.5	6.1	3.8	2.5	1.6	5.1	3.6
DIM[a]	3.2	2.3	3.6	2.8	5.2	3.6	3.9	3.4	3.3	0.2
New model[a]	2.3	−1.1	2.5	0.9	3.1	0.3	1.9	0.0	4.0	−2.5
DIM[b]	3.5	2.1	3.0	1.8	4.9	3.3	5.5	4.5	3.8	−0.8
New model[b]	2.9	−1.2	2.5	0.0	3.1	0.0	3.0	0.9	5.1	−3.4
Mean monthly input values ($w_p^{\text{clear-sky}} = 0.76 w_p$)										
ESRA model	4.3	1.5	4.6	3.4	5.6	3.1	3.8	1.5	5.6	3.6
DIM[a]	4.2	2.2	4.3	3.1	5.8	4.0	4.4	2.9	4.0	0.6
New model[a]	3.4	−1.1	3.2	1.1	3.9	0.8	3.4	−0.7	4.4	−2.1
DIM[b]	4.0	2.0	3.4	2.0	5.7	3.9	5.4	4.0	4.0	−0.6
New model[b]	3.6	−1.3	2.9	0.2	3.8	0.7	3.6	0.2	5.0	−3.1

Rmse and mbe are expressed as a percentage of the mean measured values.
[a] β estimated from radiometric data.
[b] β calculated from the day of the year.

estimates, which present MBE values around 3% at all stations but Table Mountain, where the DIM model presents the best statistical results. The performance of the new model using the approximation of β given by Eq. (14) is slightly deteriorated in regards to the above results, but it is still more accurate than those by the DIM and ESRA models. We can also see that this β approximation appears to be suitable for the DIM model, avoiding in this way the need of using experimental data in a first step.

If only mean monthly input values associated with clear days are available, the estimates by the three models are slightly deteriorated as could be expected, but the new model performs better again. In addition, if mean monthly values of w_p and ρ calculated from all available clear and cloudy days are employed, the new model performance is still satisfactory and superior to those by the DIM and ESRA models for almost all sites, even though using the β approximation.

4.3. Model evaluation using data with horizon obstruction

In the previous section, we have evaluated the new model using data without any horizon obstruction. To assess the horizon factor introduced in the model by Eqs. (12) and (13), we have used data recorded at 11 radiometric stations located in Sierra Nevada's Mountain (Spain). They are affected by a complex topography leading to solar elevations at sunrise and sunset ranging from 1° to 15° in January. Precipitable water content is calculated from the air temperature and relative humidity data, whereas Ångström's turbidity coefficient is given by the proposed β approximation (Eq. (14)). Site altitude is known, and ground albedo is set as 0.2 as no better information is available. This assumption is not real for every radiometric station, and snow covers can be present in this winter month.

Fig. 6 shows that estimates by the new model without the horizon factor are clustered above the line 1:1 as a consequence due to the shadowing effect by the surrounding mountains at sunrise and sunset. In fact, the RMSE and MBE values are respectively 7.9% and 4.3%. Considering the horizon effect term in the model, a significant improvement is achieved as the data points are moved to around the line 1:1. In this case, the RMSE and MBE are reduced to 5.0% and 0.3%, respectively. We also found that a proportion of the data points are underestimated. The presence of snow covers (with higher values of ground albedo) could be the reason for this increase in measured global solar irradiation. Nevertheless, the overall result proves the convenience in using this horizon effect term at those sites where shadowing at sunrise or sunset occurs. In addition, the modelling of this effect should allow the remaining spread to be analysed in terms of additional parameters accounting for the solar radiation modifications due to local topography and surface features, as during examination of the contribution of diffuse solar radiation coming from multiple reflexions between the surface and the atmosphere.

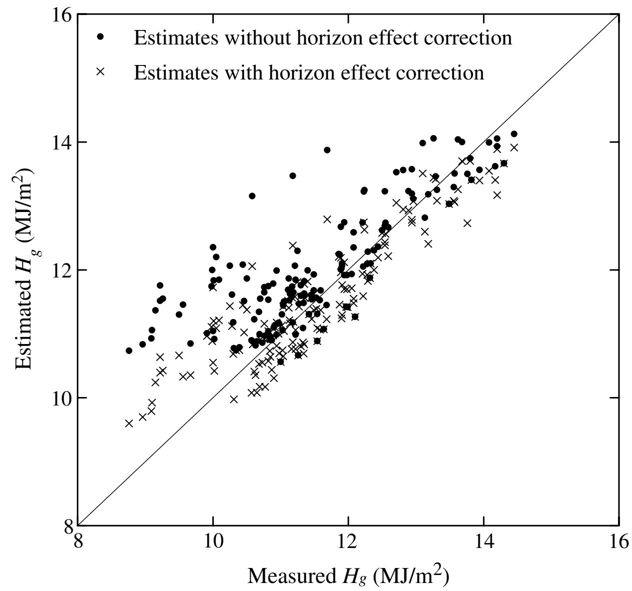

Fig. 6. Estimated without and with the horizon effect term versus measured daily global solar irradiation values for the eleven radiometric stations located in the mountain region of Huéneja (Spain).

5. Conclusions

In this work, a new simple physical model to estimate daily global irradiation under cloudless conditions is developed and tested. Input parameters consist of latitude, day of the year, air temperature, relative humidity, Ångström turbidity coefficient, ground albedo and site elevation along with the solar elevation at sunrise or sunset if horizon obstructions occur. These input variables allow the model to be site independent and to be used in locations where snow covers are present. Inclusion of a horizon factor allows estimating solar radiation in areas where shadowing at sunrise or sunset due to a complex topography takes place, as mountainous areas, and would be a first step to study the effect of diffuse solar radiation at these times.

The model is able to provide accurate estimates with errors similar to experimental errors, even if monthly mean input values are provided and turbidity information is not available. In any case, this new parameterization of daily clear-sky global irradiation has been shown to improve the estimates against those by both the DIM and ESRA models. This result, along with the ability of using the turbidity information everywhere it is available, can be very helpful to estimate daily clear global radiation from satellite images or to estimate clear-sky irradiation on tilted surfaces. The accurate estimations provided by this new model can be used as a test of the quality of measurements and to select clear-sky conditions in radiometric databases.

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