

Estimating global solar radiation from common meteorological data in Aranjuez, Spain

Javier ALMOROX

*Universidad Politécnica de Madrid, School of Agricultural Engineers, Department of Soil Science and Climatology, Ciudad Universitaria s/n, 28040 Madrid-SPAIN
e-mail: javier.almorox@upm.es*

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Abstract

This study aimed to calibrate existing models and develop a new model for estimating global solar radiation data using commonly and available measured meteorological records such as precipitation or temperature.

Fifteen empirical global radiation models based on meteorological variables were generated and validated using daily data in 2003–2008 at the Aranjuez station (Community of Madrid, Spain). Validation criteria included coefficient of determination, root mean square error, mean bias error, mean absolute bias error, mean percentage error, and mean absolute percentage error. The best result was derived from the model proposed, which uses extraterrestrial solar radiation, saturation vapor pressures, transformed rainfall data and daily minimum relative humidity as predictors. The new multiple regression relation giving accurate estimates of daily global solar radiation was suggested. It has a high coefficient of determination $R^2 = 0.92$. The results showed that the suggested model can estimate the global solar radiation acceptable values of RMSE, MBE and MABE (2.378, 0.09767, 1.744 MJ m⁻² day⁻¹, respectively); and MPE and MAPE (-6.478%, 19.30%). Temperature based models provided less accurate results, of which the best one is the Bristow and Campbell model ($R^2 = 0.892$). The Hargreaves and Samani model is simple and are recommended to estimate the daily global radiation when only temperature data are available and when the coefficients cannot be determined. Based on overall results it was concluded that the meteorological based method provides reasonably accurate estimates of global solar radiation, for the site where coefficients of the model were developed.

Key Words: Daily global solar radiation, meteorological models, model comparison, solar radiation models

1. Introduction

Knowledge of the local global solar radiation is required by most models that simulate crop growth, and is also essential for many applications, including evapotranspiration estimates, architectural design, and solar energy systems. Design of a solar energy conversion system requires precise knowledge regarding the availability of global solar radiation at the location of interest. Since the global solar radiation reaching the earth's surface

depends upon the local meteorological conditions, a study of solar radiation under local climatic conditions is essential [1]. For locations where measured values are not available, solar irradiance can be estimated using empirical models.

Therefore various methods have been explored by many researchers to estimate, with reasonable accuracy, the solar radiation from other available meteorological data. Parameters used as inputs in the relationships include astronomical factors (solar constant, world-sun distance, solar declination and hour angle); geographical factors (latitude, longitude and altitude); geometrical factors (surface azimuth, surface tilt angle, solar altitude, solar azimuth); physical factors (albedo, scattering of air molecules, water vapor content, scattering of dust and other atmospheric constituents); and meteorological factors (atmospheric pressure, cloudiness, temperature, sunshine duration, air temperature, soil temperature, relative humidity, evaporation, precipitation, number of rainy days, total precipitable water, etc.) [2–5].

Parameters that have been most frequently investigated are sunshine, cloud cover; temperature and/or precipitation variables. Solar radiation can be easily estimated from sunshine duration; the Angström-Preseott models are sunshine-based and have widely applied to estimate global solar radiation [6, 7]. However, sunshine and cloud observations are data that are not available at most of the meteorological stations. In this context, global solar radiation estimation models based on air temperature and precipitation are attractive and viable options. It is necessary to develop a precise solar radiation model which utilizes commonly available parameters such as maximum and minimum temperatures, precipitation and geographical location. These parameters are the only daily variables available at a great majority of meteorological stations. Some of these approaches make use of basic meteorological data only [8–21].

This paper presents analysis of the relationship between daily global solar radiation and some geographical and meteorological factors. The reason for this approach comes from the fact that the air temperature and precipitation are worldwide measured meteorological parameters, and is used by several authors in solar radiation estimation techniques. The objectives of this study were to compare, calibrate and validate existing solar radiation models to predict solar global radiation from available meteorological data. It is a goal of this author to find a model in daily scale based on meteorological variables without sunshine hours will provide a significant and new contribution to the methodology.

2. Methodology

Daily data were taken from the Aranjuez agrometeorological station (Community of Madrid, Spain, latitude $40^{\circ} 04' 12''$ N and longitude $3^{\circ} 37' 45''$ W) and were provided by the SIAR (Agro-climatic Information System for Irrigation) covering the period from 10 December 2003 to 31 January 2008. The Community of Madrid, Spain, is a semi-arid region with a temperate Continental Mediterranean climate, and a total area of 8028 km^2 and with a cultivated area of 2206.3 km^2 . It is located at the centre of the country.

The SIAR is coordinated by the Regional Department of Agriculture (Community of Madrid) and the Ministry of the Environment and Rural and Marine Affairs. The following meteorological variables are currently recorded in the SIAR daily database: actual global solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), maximum relative humidity (%), minimum relative humidity (%), precipitation (mm), mean air temperature ($^{\circ}\text{C}$), maximum air temperature ($^{\circ}\text{C}$), minimum air temperature, and wind speed (km/h). Measurements of global solar irradiance were taken by pyranometer (SKYE SP1110). For quality control, all parameters were checked; the sensors were periodically maintained and calibrated. All data being recorded and hourly averaged on a data logger.

A number of methods have been reported using empirical relationships to estimate global solar radiation from commonly measured meteorological variables. Daily total extraterrestrial radiation H_o is often included in the relationships. H_o values were calculated using standard geometric procedures.

2.1. Extraterrestrial radiation

The only input required to calculate these daily values, for a specific day of the year, is the latitude of the location, in degrees [2]. Extraterrestrial radiation H_o , eccentricity correction factor of the Earth's orbit E_0 , solar declination δ (in degrees), day angle Γ (in radians), and hour angle of the Sun w_s (in degrees) are calculated through the formula

$$H_o = (1/\pi)I_{sc}E_0(\cos \lambda \cos \delta \sin w_s + (\pi/180) \sin \lambda \sin \delta w_s), \quad (1)$$

where

$$E_0 = 1.00011 + 0.034221 \cos \Gamma + 0.00128 \sin \Gamma + 0.000719 \cos(2\Gamma) + 0.000077 \sin(2\Gamma) \quad (2)$$

$$\delta = (180/\pi).(0.006918 - 0.399912 \cos \Gamma + 0.070257 \sin \Gamma - 0.006758 \cos(2\Gamma) + 0.000907 \sin 2\Gamma - 0.002697 \cos 3\Gamma + 0.00148 \sin(3\Gamma)) \quad (3)$$

$$\Gamma = 2\pi(n_{day} - 1)/365 \quad (4)$$

$$w_s = \cos^{-1}[-\sin \lambda \sin \delta / (\cos \lambda \sin \delta)] \quad (5)$$

2.2. Equations used

When solar radiation data is unavailable, it is possible to get reasonably accurate radiation estimates using the proposed models. A widely used method is based on empirical relations between solar radiation and commonly measured meteorological variables. In the literature, there are several empirical methods used to evaluate the global solar radiation. In this study, daily solar radiation was estimated using 14 solar radiation estimation models. These models were chosen as representative of the existing models that utilize extraterrestrial irradiation and readily available weather data.

2.2.1. Estimation of solar radiation using daily temperature only

Air temperature based estimation models use maximum and minimum air temperature to estimate atmospheric transmissivity. These models assume that maximum temperature will decrease with reduced transmissivity, whilst minimum temperature will increase due to the cloud emissivity. Clear skies will increase maximum temperature due to higher short wave radiation, and minimum temperature will decrease due to higher transmissivity.

Hargreaves and Samani model (Model 1) Hargreaves and Samani were the first to suggest that global radiation could be evaluated from the difference between daily maximum and daily minimum temperature. The equation form introduced by Hargreaves and Samani [8] is

$$H = H_o[A_{Model1}(T_{\max} - T_{\min})^{1/2}], \quad (6)$$

where, A_{Model1} is an empirical coefficient. Initially, A_{Model1} ($^{\circ}C^{-0.5}$) was set to 0.17 for arid and semiarid regions. Hargreaves [22] later recommended using $A_{Model1} = 0.16$ for interior regions and $A_{Model1} = 0.17$ for coastal regions.

Annandale model (Model 2) The modified Hargreaves-Samani model developed by Annandale et al. [9] includes a correction for altitudes:

$$H = H_o[A_{Model2}(1 + 2.7 \times 10^{-5}Z).(T_{\max} - T_{\min})^{1/2}], \quad (7)$$

where A_{Model2} is an empirical coefficient.

Bristow and Campbell method (Model 3) The model of Bristow and Campbell [10] describes daily solar radiation as an exponential asymptotic function of daily temperature range. In this model, daily solar radiation H and the temperature term difference ΔT are computed as

$$H = H_o \times A_{Model3} \times [1 - \exp(-B_{Model3} \times \Delta T^{C_{Model3}})] \quad (8)$$

$$\Delta T(^{\circ}C) = T_{\max i} - (T_{\min(i)} + T_{\min(i+1)})/2 \quad (9)$$

The empirical coefficients A_{Model3} , B_{Model3} and C_{Model3} have some physical explanation. The coefficient A_{Model3} represents the maximum value of atmospheric transmission coefficient, is characteristic of a study area, and depends on pollution content of the air and elevation. The coefficients B_{Model3} and C_{Model3} determine the effect of increments in the temperature term difference on the maximum value of atmospheric transmission. They will differ, for example, from humid to arid environments.

Model 3 has been used in numerous studies, and improvements have been developed. The accuracy and simplicity of data requirements appear to make this model an ideal tool for estimating solar irradiance at sites where measured solar radiation values are unavailable. It is obvious that the limiting factor in this model is the reliability of the coefficients used; these coefficients can be determined using available solar radiation data [23].

Donatelli and Campbell model (Model 4) The model proposed by Donatelli and Campbell [11] is similar in structure to model 3. The model has the following form:

$$H = H_o A_{Model4} [1 - \exp(-B_{Model4} f(T_{avg}) \Delta T^2 \exp(T_{\min}/C_{Model4}))] \quad (10)$$

where

$$\Delta T(^{\circ}C) = T_{\max i} - (T_{\min(i)} + T_{\min(i+1)})/2 \quad (9)$$

$$f(T_{avg}) = 0.017 \exp(\exp(-0.053T_{avg(i)})) \quad (11)$$

$$T_{avg(i)}(^{\circ}C) = (T_{\max(i)} + T_{\min(i)})/2. \quad (12)$$

Parameters A_{Model4} stands for the clear sky transmissivity, and B_{Model4} and C_{Model4} were calibrated by using all the data available at each location. Models 3–4 are part of a suite of models contained within the RadEst global solar radiation estimation tool [24].

Goodin model (Model 5) Goodin et al. [12] evaluated one form of model 3:

$$H = H_o A_{Model5} [1 - \exp(-B_{Model5} (\Delta T^{C_{Model5}} / H_o))] \quad (13)$$

The results suggest that model 5 provides reasonably accurate estimates of irradiance at non-instrumented sites and that the model can successfully be used at sites away from the calibration site.

Winslow model (Model 6) Winslow et al. [13] developed a model for estimation of H with inputs of daily maximum and minimum air temperature, mean annual temperature, mean annual temperature range, site latitude and site elevation. The prediction equation is:

$$H = H_o \zeta_{cf} Dl [1 - [A_{Model6} (e_s(T_{\min}) / e_s(T_{\max}))]], \quad (14)$$

where A_{Model6} is an empirical coefficient and Dl corrects the effect of site differences in day length:

$$Dl = [1 - (1/2)(H_{day} - (\pi/4))^2 H_{day}^2] - 1, \quad (15)$$

where H_{day} is the half-day length; and variable ζ_{cf} accounts for atmospheric transmittance and is estimated from site latitude, elevation and mean annual temperature. It is divided into three parts:

$$\zeta_{cf} = [\zeta_o \zeta_a \zeta_v]^{P/P_o} \quad (16)$$

$$P/P_o = [1 - (2.2569 \times 10^{-5})Z]^{5.2553} \quad (17)$$

$$\zeta_o = 0.947 - (1.033 \times 10^{-5}) \cdot |\lambda|^{2.22} \text{ for } |\lambda| \leq 80^\circ \quad (18)$$

and

$$\zeta_o = 0.774 \text{ for } |\lambda| > 80^\circ \quad (19)$$

$$\zeta_v = 0.9636 - 9.092 \times 10^{-5} [(T_{mean} + 30)^{1.8232}]. \quad (20)$$

The absorption of radiation by aerosols is extremely variable and inherently unpredictable; therefore we set ζ_a equal to 1.0.

Mahmood and Hubbard model (Model 7) Mahmood and Hubbard [14] used a different approach. In their model, transmissivity is a function of the day of the year, the daily range of temperature and the corrected clear sky solar irradiation H_{cc} and is computed

$$H = A_{Model7} (T_{\max} - T_{\min})^{B_{Model7}} H_{cc}^{C_{Model7}}, \quad (21)$$

where A_{Model7} , B_{Model7} , and C_{Model7} are empirical coefficients,

$$H_{cc} = I_s Tr, \quad (22)$$

$$Tr = 0.8 + 0.12c^{1.5}, \quad (23)$$

$$c = |182 - DOY/183|, \quad (24)$$

and

$$I_s = 0.04188(A_c + B_c \sin[(2\pi(DOY + 10.5)/365) - (\pi/2)]). \quad (25)$$

Here, A_c and B_c are constants. These can be estimated as follows [25]:

$$A_c = (0.29 \cos \lambda + 0.52) \{ \sin \lambda (46.355LD - 574.388) + (816.41 \cos \lambda \sin[(LD\pi/24)]) \}, \quad (26)$$

$$B_c = (0.29 \cos \lambda + 0.52) \{ (574.3885 - 1.509LD) \sin \lambda - (29.59 \cos \lambda \times \sin[(LD.\pi/24)]) \}, \quad (27)$$

$$LD = 0.267 \sin^{-1} \{ 0.5 + (0.007895 / \cos \lambda) + (0.2168875 \tan \lambda) \}^{1/2}. \quad (28)$$

LD is the longest day of the year (DOY, in hours). The expression presented is obtained from the Tables of Sunrise, Sunset and Twilight [26].

Mahmood and Hubbard proposed to locally debias the model to account for local scale advection and frontal movements by means of the following linear regression:

$$H = A_{Model\ 7} \left[(T_{\max} - T_{\min})^{B_{Model\ 7}} H_{cc}^{C_{Model\ 7}} - 2.4999 \right] / 0.8023 \quad (29)$$

2.2.2. Estimation of solar radiation using both temperature and other variables

In the estimation of solar radiation using temperature and other variables, the temperature based models were improved by adding other variables: precipitation, dew point temperature, relative humidity or averaged saturation deficit.

McCaskill (Model 8) McCaskill [15] related H and H_o and rain information as

$$H = A_{Model8} H_o + B_{Model8} R_{Tj-1} + C_{Model8} R_{Tj} + D_{Model8} R_{Tj+1}, \quad (30)$$

where A_{Model8} , B_{Model8} , C_{Model8} and D_{Model8} are coefficients determined by regression; and R_T is the transformed rainfall data and its subscripts ($j-1$, j and $j+1$) refer to the previous, current and successive days. The transformed rainfall data is calculated using the decision relation

$$R_T = \begin{cases} 0, & \text{if } PP = 0 \\ 1, & \text{if } PP > 0, \end{cases}$$

where PP is the measured daily total precipitation. The coefficient $A_{Model\ 9}$ is the atmospheric transmittance with no rainfall to the previous, current and next days, and $B_{Model\ 9}$, $C_{Model\ 9}$, and $D_{Model\ 9}$ are the amounts of radiation reduction when it rained on the day before, on the day and on the day after, respectively.

Hunt model (Model 9) Hunt et al. [16] has shown that calculation of solar radiation using the basic daily meteorological data of temperature maximum, temperature minimum, and precipitation, along with radiation above the atmosphere, is quite feasible using a simple equation:

$$H = A_{Model10} + B_{Model\ 10} H_o (T_{\max} - T_{\min})^{1/2} + C_{Model10} T_{\max} + D_{Model\ 10} PP + E_{Model\ 10} PP^2, \quad (31)$$

where $A_{Model\ 10}$, $B_{Model\ 10}$, $C_{Model\ 10}$, $D_{Model10}$ and $E_{Model\ 10}$ are empirical coefficients.

Liu and Scott (Model 10) Liu and Scott [17] developed a model that included temperatures and rain information:

$$H = A_{Model10} H_o (1 - \exp(-B_{Model10} \Delta T^{C_{Model10}})) \times (1 + D_{Model10} R_{Tj-1} + E_{Model10} R_{Tj} + F_{Model10} R_{Tj+1}) + G_{Model10}, \quad (32)$$

where, $A_{Model10}$, $B_{Model10}$, $C_{Model10}$, $D_{Model10}$, $E_{Model10}$, $F_{Model10}$ and $G_{Model10}$, are coefficients.

Richardson and Reddy model (Model 11) Richardson and Reddy [18] introduced a new solar radiation model:

$$H = A_{Model11} + B_{Model11}T_{min} + C_{Model11}T_{max} + D_{Model11}PP + E_{Model11}Wind. \quad (33)$$

In calibrating the model, empirical coefficients ($A_{Model11}$, $B_{Model11}$, $C_{Model11}$, $D_{Model11}$ and $E_{Model11}$) were derived from weather data.

Chen model (Model 12) Chen et al. [19] using meteorological variables such as precipitation, air temperature, maximum temperature, minimum temperature to estimate the global solar radiation, when the sunshine hours are unavailable, developed a new correlation:

$$H = H_o[A_{Model12}(T_{max} - T_{min})^{1/2} + B_{Model12}] + C_{Model12}PP + D_{Model12}D_{as} + E_{Model12}, \quad (34)$$

where $A_{Model12}$, $B_{Model12}$, $C_{Model12}$, $D_{Model12}$ and $E_{Model12}$ are empirical constants.

Skeiker model (Model 13) Skeiker [20] investigated the effect of geographical and meteorological parameters on the mean daily global solar radiation and found the following relationship:

$$H = A_{Model13} + B_{Model13} \sin \delta - C_{Model13}RH_{mean} - D_{Model13}T_{max} + E_{Model13}dew_{max} \quad (35)$$

Wu model (Model 14) Wu et al. [21] introduced this model based on commonly measured variables:

$$H = H_o(A_{Model14} + B_{Model14}(T_{max} - T_{min})^{1/2} + C_{Model14}T_{avg} + D_{Model14}R_T) \quad (36)$$

where $A_{Model14}$, $B_{Model14}$, $C_{Model14}$, and $D_{Model14}$ are empirical constants.

Proposed method (Model 15) In this study we present a new model for daily solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$). The new formula is a function of extraterrestrial solar radiation, saturation vapour pressures at temperature T_{min} , saturation vapor pressures at temperature T_{max} , transformed rainfall data, and daily minimum relative humidity:

$$H = 0.7345H_o(1 - \exp(-0.2549(e_s(T_{min})/e_s(T_{max}))^{-2.6518})) \times (1 - 0.1233R_T - 0.00428RH_{min}) \quad (37)$$

The proposed new model requires measured maximum and minimum air temperatures, minimum relative humidity and precipitation data. As saturation vapour pressure is related to air temperature, it can be calculated from the air temperature. The relationship is expressed by [27]

$$e_s(T_x) = 0.6108 \exp[17.27(T_x)/(T_x + 237.3)] \quad (38)$$

3. Statistical evaluation

In the literature, researchers investigate the goodness of the estimation of global solar radiation based on a set of statistical parameters such as R^2 , RMSE, MBE, MABE, MPE and MAPE. The performance of the models was evaluated by comparing the calculated daily solar radiation with the measured daily solar radiation data [28]. In this study, the accuracy of the estimated values was tested by calculating the R^2 (coefficient

of determination), RMSE (Root Mean Square Error), MBE (Mean Bias Error), MABE (Mean Absolute Bias Error), MPE (Mean Percentage Error), and MAPE (Mean Absolute Percentage Error). These tests are defined by the relations

$$R^2 = 1 - \left[\frac{\sum (H_{im} - H_{ic})^2}{\sum (H_{im} - H_{avgm})^2} \right], \quad (39)$$

$$RMSE = \left[\frac{1}{N_{obs}} \sum (H_{im} - H_{ic})^2 \right]^{0.5} (MJm^{-2}day^{-1}), \quad (40)$$

$$MBE = \frac{1}{N_{obs}} \sum H_{im} - H_{ic} (MJm^{-2}day^{-1}), \quad (41)$$

$$MABE = \frac{1}{N_{obs}} \sum |H_{im} - H_{ic}| (MJm^{-2}day^{-1}), \quad (42)$$

$$MPE = \frac{100}{N_{obs}} \sum \frac{H_{im} - H_{ic}}{H_{im}} (\text{percentage}), \quad (43)$$

$$MAPE = \frac{100}{N_{obs}} \sum \left| \frac{H_{im} - H_{ic}}{H_{im}} \right| (\text{percentage}). \quad (44)$$

Here, N_{obs} is the number of data pairs, H_{im} is the measured solar radiation, H_{ic} is the calculated solar radiation and H_{avgm} is the mean measure radiation.

A model is more efficient when R^2 is closer to 1. The RMSE provides information on the short-term performance of the correlations by allowing a term-by-term comparison of the deviation between the calculated and measured values. The values of the MBE represent the systematic error or bias, a positive value of MBE shows an over-estimate while a negative value an under-estimate by the model. The MABE gives the absolute value of bias error and it is a measure of the correlation goodness. The MPE is an overall measure of forecast bias, computed from the actual differences between a series of forecasts and actual data point observed; each difference is expressed as a percentage of each observed data point, then summed and averaged. The MAPE is an overall measure of forecast accuracy, computed from the absolute differences between a series of forecasts and actual observed data. The disadvantage associated with MBE and MPE is that errors of different signs may cancel each other, the smaller the value, the better the model performs, but some few values in the sum can produce a significant increase in the parameter. The MBE and MPE offering information regarding overestimation or underestimation of estimated data; low values of these mean errors are desirable, though it should be noted that overestimation of an individual data element will cancel underestimation in a separate observation.

4. Results and discussions

Empirical models to estimate solar radiation are a suitable tool. These models have the advantage of using meteorological data that are commonly available. The studied empirical models require calibration, for that reason it was necessary to change the model coefficients to obtain a better fit. The empirical coefficients of the equations can be determined using available solar radiation data (Table 1). Coefficients for all of the formulae were estimated using the Stat Graphics Plus (v.5.0).

Table 1. Calibration model parameters (Aranjuez weather station).

Method	A	B	C	D	E	F	G
Model 1	0.1459						
Model 2	0.1439						
Model 3	0.7025	0.0101	1.9034				
Model 4	0.7107	0.2481	67.4299				
Model 5	0.6849	0.3337	1.9442				
Model 6	1.0134						
Model 7	0.1076	0.5858	1.1882				
Model 8	0.6520	-1.1961	-4.0620	-1.7364			
Model 9	0.1349	0.1596	-0.0621	-0.8142	0.02640		
Model 10	0.6857	0.0149	1.8265	-0.0047	-0.1751	-0.0362	0.4442
Model 11	-4.570	0.9752	-0.3964	-0.2522	0.4776		
Model 12	0.1526	0.0405	-0.3548	-0.0623	-0.61891		
Model 13	14.903	-0.6831	-0.1672	0.5618	-0.26431		
Model 14	0.0695	0.1407	-0.0013	-0.1208			
Model 15	0.7345	- 0.2549	-2.6518	-0.1233	-0.00428		

The models were validated by comparing calculated and measured solar radiation in Aranjuez. The statistical results of different models are given in Table 2. The first conclusion coming from Table 2 is that the estimation of global solar radiation can be performed with an acceptable accuracy using all the tested calibrated models.

Obtained results show that estimation of solar radiation using temperature and precipitation data explained the highest portion of the solar radiation variance out of all the tested models. In general, temperature based models were less accurate in contrast to the meteorological based model. The temperature based models could be improved by adding other variables (Model 15), to the point where 92% of the solar radiation variance could be explained by adding successively the saturation vapour pressures at minimum and maximum temperatures, transformed rainfall data, and daily minimum relative humidity. Model 15 is considered the best relation for estimating the global solar radiation intensity for the Aranjuez station with an acceptable error. The R^2 , RMSE, MBE, MABE, MPE and MAPE values are 0.92, 2.37 MJ. m⁻²day⁻¹, 0.09 MJ. m⁻²day⁻¹, 1.74 MJ. m⁻²day⁻¹, -6.48% and 19.30%, respectively.

The regression analysis shows that in the models based on data of temperatures, the model 3 gives consistently a good estimate when applied to daily data. The model 3 model had the best overall results for the R^2 and in general, it produced small residuals compared to the other temperature based models with overall RMSE of 2.75 MJ. m⁻² day⁻¹. Model 1 performed better than the models 8, 11 and 13, considering the simplicity of the model and relative ease of deriving the coefficient compared to the other models, performed very well in the overall ranking. Generally, at locations where no solar radiation data (and no sunshine data) are available for site-specific estimation of coefficients, the nominal value of 0.16 appears to be well suited [29].

The results demonstrated that most of the tested models used were able to adequately estimate daily global solar radiation from daily temperature and/or precipitation. Using meteorological variables such as precipitation, mean air temperature, maximum and minimum air temperature, relative humidity, and saturation deficit to estimate the solar global radiation could get good results at most conditions. The new proposed method (model 15) in this work to estimate global solar radiation from more commonly and reliably measured meteorological data can be useful to provide radiation data which would otherwise be unavailable. This method

is applicable for estimating the daily global solar radiation on a horizontal surface at any site in the Community of Madrid, Spain. Nevertheless, the inability of the model 15 to be extended to other locations without coefficient calibration is clearly evident. Although these calibrated or developed methods were based on the meteorological data of one specific station, we hope, they could be applicable in other locations which are climatically similar.

Table 2. Statistical results of different models. R^2 , RMSE, MBE, MABE, MPE and MAPE computed in the comparison between observed and estimated daily solar radiation.

Model	R^2	RMSE	MBE	MABE	MPE	MAPE
1	0.87	3.00	-0.18	2.21	-16.49	27.50
2	0.87	3.00	-0.18	2.21	-16.49	27.50
3	0.89	2.75	0.04	1.93	-7.91	21.36
4	0.89	2.76	-0.05	1.93	-9.69	21.86
5	0.86	3.08	-0.41	2.26	-20.39	29.18
6	0.88	2.87	0.02	2.08	-12.39	24.12
7	0.87	2.96	-0.06	2.19	-13.59	25.54
8	0.82	3.48	0.08	2.61	-13.74	32.48
9	0.89	2.68	0.00	1.97	-8.79	22.69
10	0.90	2.52	0.00	1.81	-8.45	20.33
11	0.72	4.36	0.00	3.41	-15.08	32.96
12	0.89	2.74	0.00	2.02	-8.88	23.31
13	0.76	4.02	0.00	3.05	-15.59	30.59
14	0.89	2.67	-0.07	2.01	-12.15	23.58
15	0.92	2.37	0.09	1.74	-6.48	19.30

5. Conclusion

In the absence of global solar radiation data, reliable estimates can be made from easily available meteorological observations of temperature, precipitation and/or relative humidity along with extraterrestrial solar radiation using different models. In this study, using the Aranjuez station (Community of Madrid, Spain) as a case study, fourteen existing and one proposed models were calibrated and evaluated using the daily meteorological data from December 2003 to January 2008 for estimating global solar radiation.

We propose a strategy for selecting an optimal method, for estimating daily global solar radiation in Aranjuez: when temperature, precipitation and relative humidity are available, use Model 15; when only temperature and precipitation are available, use Model 10; and when only temperature data are available, use Model 3. The models 15, 10 and 3 were slightly superior to Model 1, but are considerably more complicated to use (and calibrate) than Model 1.

The model 1 is simple and could estimate the solar global radiation with relatively high accuracy. Are recommended to estimate the daily global radiation when the solar radiation and sunshine hours are unavailable, when only temperature data are available and when the model coefficients cannot be determined directly from available data (or extrapolation). Model 3 is the temperature based model that estimate the global radiation with relative accuracy, but they are more complex, and these equations could be used when there are measured data for calibration of coefficients. When there are meteorological variables the estimation of solar radiation using temperature and precipitation data could estimate the daily solar radiation with higher accuracy than

the temperature based models, this models are more complex and need calibration. The proposed Model 15 is recommended to estimate the global radiation in Aranjuez. The validity of the global solar radiation regression relation needs to be tested and calibrated on other sites.

Nomenclature

D_{as}	averaged saturation deficit (hPa)	RH_{min}	daily minimum relative humidity (in percent)
dew_{max}	daily maximum dew point temperature	R_T	transformed rainfall
[.5ex] DI	effect of site differences in day length	T_{avg}	daily range of air temperature ($^{\circ}C$)
DOY	day of year	T_{mean}	mean annual temperature ($^{\circ}C$)
$e_s(T_{max})$	saturation vapour pressures at T_{max} (hPa)	T_{max}	daily maximum temperature ($^{\circ}C$)
$e_s(T_{min})$	saturation vapour pressures at T_{min} (hPa)	T_{min}	daily minimum temperature ($^{\circ}C$)
$e_s(T_x)$	saturation vapour pressure at the air temperature T_x [kPa]	Tr	empirical transmissivity
E_0	eccentricity correction factor of the Earth's orbit	w_s	hour angle of the Sun (degrees)
H	daily solar radiation ($MJ\ m^{-2}\ day^{-1}$)	$Wind$	wind speed (km per hour)
H_{cc}	corrected clear sky solar irradiation ($MJ\ m^{-2}\ day^{-1}$)	Z	elevation (m)
H_{day}	half-day length (radians)		
H_o	daily solar radiation above the atmosphere ($MJ\ m^{-2}\ day^{-1}$),		
I_{sc}	solar constant ($118.11\ MJ\cdot m^{-2}\cdot day^{-1}$)		
LD	longest day of the year		
n_{day}	day number (starting 1 January)		
N_{obs}	number of data pairs		
P	atmospheric pressure (kPa)		
P_o	standard pressure (kPa)		
PP	daily total precipitation ($L\ m^{-2}$)		
RH_{mean}	mean daily relative humidity (in percent)		

Greek symbols

δ	solar declination (degrees)
λ	latitude of the site (degrees)
π	number π
ΔT	temperature term difference ($^{\circ}C$)
ζ_{cf}	accounts for atmospheric transmittance
ζ_a	transmittance affected by atmospheric aerosols and ozone
ζ_o	transmittance of clean dry air
ζ_v	transmittance affected by atmospheric water vapour
Γ	day angle (radians)

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