Estimation of daily global solar radiation from measured temperatures at Cañada de Luque, Córdoba, Argentina

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ABSTRACT

Solar radiation is the most important source of renewable energy in the planet; it's important to solar engineers, designers and architects, and it's also fundamental for efficiently determining irrigation water needs and potential yield of crops, among others. Complete and accurate solar radiation data at a specific region are indispensable. For locations where measured values are not available, several models have been developed to estimate solar radiation. The objective of this paper was to calibrate, validate and compare five representative models to predict global solar radiation, adjusting the empirical coefficients to increase the local applicability and to develop a linear model. All models were based on easily available meteorological variables, without sunshine hours as input, and were used to estimate the daily solar radiation at Cañada de Luque (Córdoba, Argentina).

As validation, measured and estimated solar radiation data were analyzed using several statistic coefficients. The results showed that all the analyzed models were robust and accurate (R^2 and RMSE values between 0.87 to 0.89 and 2.05 to 2.14, respectively), so global radiation can be estimated properly with easily available meteorological variables when only temperature data are available.

Hargreaves-Samani, Allen and Bristow-Campbell models could be used with typical values to estimate solar radiation while Samani and Almorox models should be applied with calibrated coefficients. Although a new linear model presented the smallest R^2 value ($R^2 = 0.87$), it could be considered useful for its easy application. The daily global solar radiation values produced for these models can be used to estimate missing daily values, when only temperature data are available, and in hydrologic or agricultural applications.

1. Introduction

Solar radiation is the most important source of renewable energy in the planet; it's important to solar engineers, designers and architects, and it is also fundamental for efficiently determining irrigation water needs and potential yield of crops, among others [1–3]. Despite the recognized importance of the solar radiation data, it is only recorded on a few meteorological stations, particularly in developing countries [4–6].

In the absence of measured solar radiation data, several models to estimate it, using more readily available data, have been developed. Some are the Ångström–Prescott equation and its modifications and other are linear, polynomial, exponential and logarithmic models; also stochastic, neural networks and genetic algorithm models, among others [7–11].

In the literature there are several empirical methods used to estimate the global solar radiation, in which it is expressed as an empirical function of one of the following parameters:

- Sunshine hours (Sunshine-based models).
- Cloudiness (Cloud-based models).
- Meteorological parameters (Meteorological data-based models).

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 tilts angle, solar altitude and solar azimuth.
- Physical factors: albedo, air molecules scattering, water vapor content, dust scattering and other atmospheric constituents.

- Meteorological factors: atmospheric pressure, cloudiness, sunshine duration, air temperature, soil temperature, relative humidity, evaporation, precipitation, number of rainy days, total precipitable water, etc.

Availability of weather data varies among locations, so the method to estimate the solar radiation has to be adapted to each situation. Parameters that have been most frequently investigated are sunshine duration, cloud cover and air temperature. Argentina's Solarimetric Network underwent a continuous decrease in the number of operational stations, in view of this situation, different alternatives were gradually considered in order to improve the available solar radiation data [12]. This situation was also observed by Will et al. [13], who stated that in Argentina there are many agricultural regions which lack on radiation data. For this country, diagnostic applications to characterize homogeneous regions of monthly average solar radiation were developed, with GOES-E satellite data. These models seem to be an efficient method for monitoring extended regions with high temporal and spatial resolution, nevertheless they need ground information as valuable reference for validation [14].

Solar radiation can be easily estimated from sunshine duration; the Ångström-Prescott models are sunshine-based and have been widely applied to estimate global solar radiation [15,16]. However, sunshine and cloud observations data are not available in most of the meteorological stations. In this context, daily solar radiation estimation models based on geographical location and air temperature, recorded at the great majority of the meteorological stations, are attractive and viable options; other authors [17–24] used air temperature measurements for estimating solar radiation data; Sayago [5] developed neural network models with air temperature, relative humidity, wind speed and rainfall as inputs to estimate hourly solar radiation.

Temperature based 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; so the difference between daily maximum and minimum air temperature becomes an indicator of cloudiness. Although cloud cover decreases maximum and increases minimum air temperature; clearly, many others factors, such as wind speed, air-vapor, precipitation, frontal weather systems, evaporation, etc., also affect temperature levels [25]. For this reason, models applied on daily time steps have substantially greater uncertainty and prediction error. Methods are recommended to use with five-day or longer time steps [3,21].

The objectives of this study were to calibrate, validate and compare five representative models to predict global solar radiation, adjusting the empirical coefficients of these models to increase the local applicability. In that sense a linear model was developed to include it in the comparison. The work essence was to develop models based on easily available meteorological variables, without sunshine hours as input.

2. Material and methods

2.1. Site of application and field data

Meteorological data used were acquired by an automatic weather station, Vantage Pro2 Stations (Davis Instruments, Hayward, California, USA), located in Cañada de Luque (30° 44′ 53″ S; 63° 43′ 50″ W), in Córdoba Province (Argentina). The study area was located in the central plains of Córdoba. The average annual rainfall is 770 mm concentrated in summer, and the average temperatures range between 25 °C and 35 °C during the summer and between 10 °C and 20 °C during the winter season; the climate in the study area is humid subtropical. This station provides data every half an hour and the solar radiation reading gives a measure of the amount of solar radiation hitting the sensor at any given time, expressed in Watts per square meter (W/m^2). The recorded value is the average solar radiation measured over the archive interval; the range is from 0 to 1800 W/m^2 with a ±5% precision. For quality control, all parameters were checked; the sensors were periodically maintained and calibrated [26]. The time period of the data comprised from 13/07/07 to 28/02/11. Half hourly data of solar radiation provided by the station were accumulated to daily values and units were converted from W/m^2 to MJ/m^2.

2.2. Extraterrestrial radiation

Daily total extraterrestrial radiation (H_0) is often included as an input to estimate incident solar radiation. H_0 values were calculated using standard geometric procedures, the only input that is required, for a specific day of the year, is the location's latitude.

$$H_0 = (1/\pi)\mathrm{Isc}\,E_0(\cos\lambda\cdot\cos\delta\cdot\sin ws + (\pi/180)\sin\lambda\cdot\sin\delta\cdot \mathrm{ws}) \tag{1}$$

Where Isc is the solar constant (118.108 MJ/m^{2}day), E_0 is the eccentricity correction factor of the Earth's orbit, λ is the latitude of the site (degrees), δ is the solar declination (degrees) and ws is the hour angle of the sun (degrees). These values can be computed by the following equations:

$$E_0 = 1.00011 + 0.034221\cos\Gamma + 0.00128\sin\Gamma + 0.000719\cos 2\Gamma + 0.000077\sin 2\Gamma \tag{2}$$

$$\delta = (180/\pi)(0.006918 - 0.399912\cos\Gamma + 0.070257\sin\Gamma - 0.006758\cos 2\Gamma + 0.000907\sin 2\Gamma - 0.002697\mathit{cos}\,3\Gamma + 0.00148\sin 3\Gamma) \tag{3}$$

$$\mathrm{ws} = \cos^{-1}[(-\sin\lambda\times\sin\delta)/(\cos\lambda\times\cos\delta)] \tag{4}$$

$$\Gamma = 2\pi\times(\mathrm{nday} - 1)/365 \tag{5}$$

Where Γ is the day angle (radians) and nday is the day number (starting 1st January).

2.3. Models

Six representative models were chosen to predict incident solar radiation:

M1: Hargreaves and Samani model.
M2: Allen model.
M3: Samani model.
M4: Bristow and Campbell model.
M5: Almorox model.
M6: a linear regression model.

Table 1 shows variables, which were used by all models.

M1: Hargreaves and Samani were the first to suggest that incident radiation could be evaluated from the difference between daily maximum and daily minimum temperature. The equation introduced by Hargreaves and Samani is [17]:

Table 1
Meteorological variables required for each model.

Models	M1	M2	M3	M4	M5	M6
H_o	X	X	X	X	X	X
$T_{\max}$	X	X	X	X	X	X
$T_{\min}$	X	X	X	X	X	X
P		X				
es($T_{\min}$)					X	
es($T_{\max}$)					X	

$$H_c = H_o \times \left[\mathrm{Kr} \times (T_{\max} - T_{\min})^{1/2}\right] \tag{6}$$

where, H_c (MJ/m^{2}day) is the estimated solar radiation, H_o (MJ/m^{2}day) is the extraterrestrial solar radiation, $T_{\max}$ (°C) is the maximum daily temperature, $T_{\min}$ (°C) is the minimum daily temperature and Kr (°C$^{-0.5}$) is an empirical coefficient. Initially, Kr was set to 0.17 for arid and semiarid regions. Hargreaves [19] recommended to use Kr = 0.16 for interior regions and Kr = 0.19 for coastal regions. The equation is based on the assumption that the difference between daily maximum and minimum temperatures provides a general indication of cloudiness.

M2: Allen [20,21] recommended a correction factor for Kr in Equation (6). He suggested a function of elevation as: $\mathrm{Kr} = A \times (P/1013)^{1/2}$

Where P (hPa) is the mean atmospheric pressure of the site, and A (°C$^{-0.5}$ hPa$^{-0.5}$) is an empirical coefficient equal to 0.17 for interior regions and equal to 0.2 for coastal regions. The introduction of the term (P/1013) was to account for elevation effects on the volumetric heat capacity of the atmosphere. The equation of this model is:

$$H_c = H_o \times \left[A \times (P/1013)^{1/2} \times (T_{\max} - T_{\min})^{1/2}\right] \tag{7}$$

M3: Using average monthly data for the entire year, Samani [22] developed the following relationship, which provides another modification of the empirical coefficient M1 Kr (Equation (6)).

$$\mathrm{Kr} = A(T_{\max} - T_{\min})^2 + B(T_{\max} - T_{\min}) + C \tag{8}$$

The relation suggests that Kr is a function of the daily temperature range.

This modification minimizes the error associated with the estimation of the solar radiation. Samani proposed, on data from 65 weather stations in the United States, the coefficients $A = 0.00185$ (°C^{-2}); $B = -0.04330$ (°C^{-1}) and $C = 0.40230$ (unitless).

The equation for this model is:

$$H_c = H_o\left[\left(A(T_{\max} - T_{\min})^2 + B(T_{\max} - T_{\min}) + C\right)(T_{\max} - T_{\min})^{1/2}\right] \tag{9}$$

M4: Bristow and Campbell [18] proposed a model that described daily solar radiation as an exponential asymptotic function of daily temperature range (ΔT) (°C)

$$H_c = H_o A\left[1 - \exp\left(-B\Delta T^C\right)\right] \tag{10}$$

Where $\Delta T = T_{\max(i)} - 0.5\,(T_{\min(i)} + T_{\min(i+1)})$, and i is current day and $(i+1)$ is next day. The empirical coefficients A, B and C have some physical explanation. The coefficient A represents the maximum value of the atmospheric transmission coefficient, is characteristic of a study area, and depends on pollution and elevation. The coefficients B (°C^{-1}) and C determine the effect of increments in ΔT on the maximum value of atmospheric transmission [27]. They will differ, for example, from humid to arid environments. Typical values are $A = 0.7$, and $C = 2.4$. The term B is calculated as follows:

$$B = 0.036\exp(-0.154\Delta T_1) \tag{11}$$

Where ΔT_1 is the monthly average ΔT; resulting for the site of application in the range of 0.001945–0.007846.

The Bristow and Campbell model has been used in numerous studies, and improvements have been developed. The model's accuracy and simplicity of data requirements appear to make it an ideal tool for estimating solar irradiance at sites where measured solar radiation values are unavailable. It is obvious that the limiting factor is the reliability of the coefficients used; which, for a specific site, can be determined using available solar radiation data.

For models M1 to M4 a comparative analysis, using typical and adjusted to the site of application values of the coefficients, was carried out, in order to determine the best option.

M5: Almorox et al. [23] developed a model that includes the daily temperature range, and the saturation vapor pressure at maximum and minimum temperatures. The following relationship is proposed:

$$H_c = H_o A(T_{\max} - T_{\min})^B\left(1 - \exp\left(-C(\mathrm{es}(T_{\min}))/(\mathrm{es}(T_{\max}))^D\right)\right) \tag{12}$$

Where A (°C^{-B}) and, B, C, and D are empirical coefficients (unitless) and es($T_{\max}$), es($T_{\min}$) are saturation vapor pressures at maximum and minimum temperatures respectively (kPa).

For derivation of the coefficients needed to the estimations, all models require measured data of incident daily global solar radiation. For M1 to M5 the regression analysis of the experimental data and the derivation of the coefficients involved simple and multiple-linear regression analysis that was carried out by Statgraphics (Plus Version 5.0). In Statgraphics, it is first defined the function that will be used to fit the data; then it is selected an iterative search algorithm to determine the estimates that minimize the residual sum of squares. The derived coefficients obtained (shown in Table 2) were then used to develop the solar radiation models.

M6: A correlation analysis between variables provided by the meteorological station (incident solar radiation, daily maximum air temperature, daily minimum air temperature, dew point, atmospheric pressure and relative humidity) and the extraterrestrial solar radiation (calculated for the model's application site) was performed. The general equation is:

$$H_c = AT\max + BT\min + \mathrm{CH}_o + D \tag{13}$$

Values for A (°C^{-1}), B (°C^{-1}), C (unitless) and D (MJ/m^{2}day) are shown in Table 2.

A comparative analysis with different time steps, since a daily basis to a monthly basis, was carried out for the Hargreaves and

Table 2
Adjusted and typical coefficients for models.

	M1	M2	M3	M4	M5	M6
Adjusted coefficients						
Kr	0.1463					
A		0.1486	−0.00016	0.7685	0.2939	0.62
B			0.00503	−0.0714	0.2655	−0.66
C			0.10968	1.0919	0.6331	0.62
D					−1.7751	−11.07
Typical coefficients						
Kr	0.16				There are not typical values	There are not typical values
A		0.17	0.00185	0.7000		
B			−0.04330	Between 0.00194 and 0.00784		
C			0.40230	2.4000		

Samani model (M1). The goal was to determine the time step that would be applied to the six models.

2.4. Statistical analysis

According to Yorukoglu and Celik [28], when the work's objective is to calculate the goodness of the estimation of global solar radiation, the statistical analysis should be based on measured daily solar radiation (H_m) versus calculated daily solar radiation (H_c). To assess the models predictive accuracy for daily solar radiation, various performance indicators were used: coefficient of determination (R^2), root mean-square error (RMSE), mean bias error (MBE), mean absolute bias error (MABE), mean percentage error (MPE) and mean absolute percentage error (MAPE); which are defined in the following equations:

Table 3
R^2 values for M1 to M4 with typical and adjusted empirical coefficients.

	M1	M2	M3	M4
Typical coefficients	0.8841	0.8843	0.4735	0.8732
Calibrated coefficients	0.8841	0.8844	0.887	0.8853

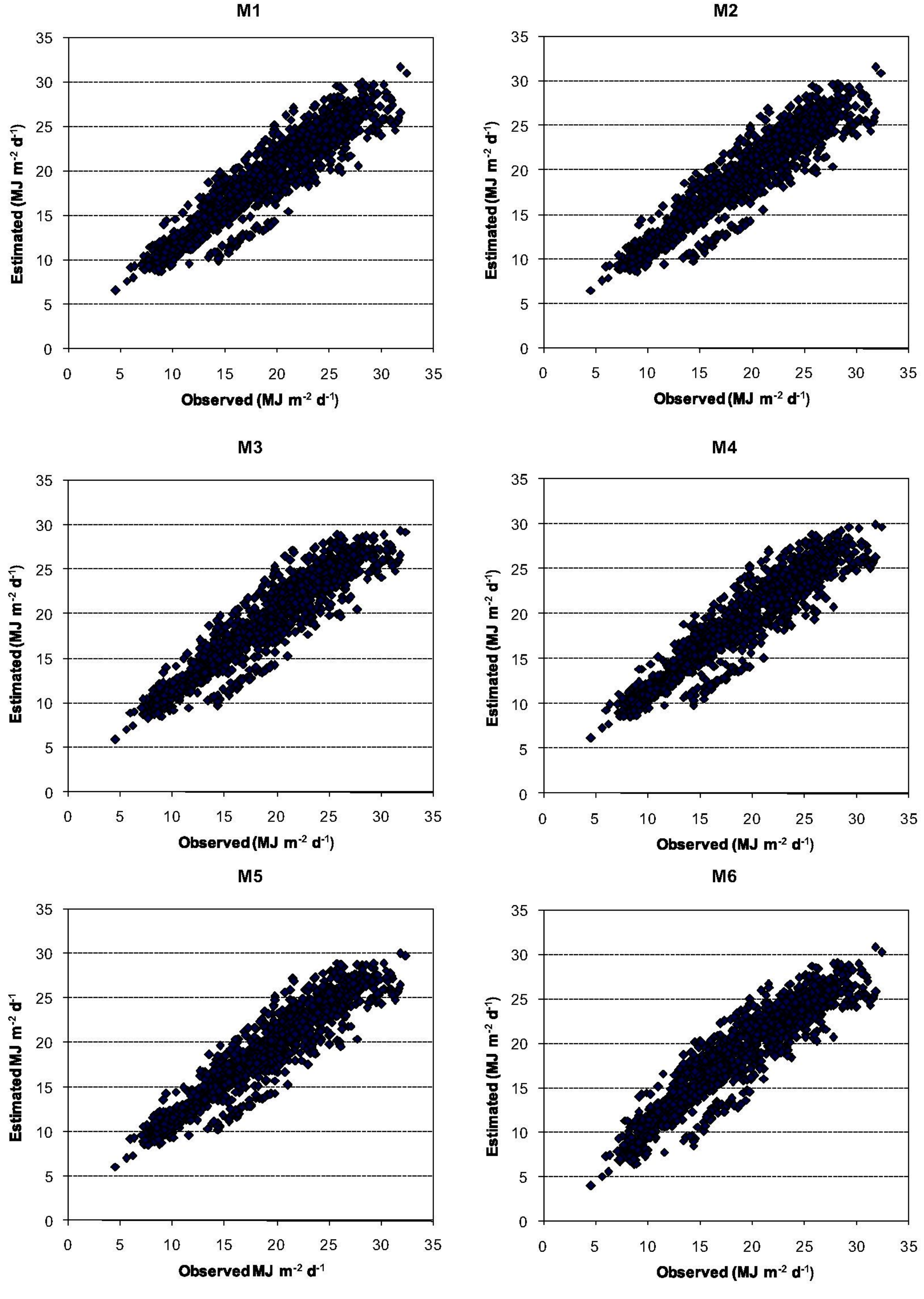

Fig. 1. Scatter plots between observed and estimated solar radiation in Cañada de Luque (Córdoba, Argentina) for M1to M6 models.

Table 4
Statistical for M1 considering different time steps.

Time steps (days)	R^2	RMSE MJ m^{-2} day^{-1}	MABE MJ m^{-2} day^{-1}	MAPE (%)	MBE MJ m^{-2} day^{-1}	MPE (%)	Kr (°$C^{-0.5}$)
1	76.15	3.67	2.74	22.62	−0.162503	−11.27	0.148
5	88.41	2.073	1.59	9.427	−0.083	−2.572	0.146
10	91.25	1.67	1.27	7.48	−0.06	−1.79	0.146
15	92.44	1.51	1.17	6.91	−0.05	−1.54	0.146
20	93.12	1.41	1.12	6.6	−0.05	−1.39	0.145
25	93.46	1.36	1.08	6.41	−0.047	−1.31	0.145
30	93.77	1.32	1.05	6.24	−0.04	−1.25	0.145

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(H_m - H_c)^2}{\sum_{i=1}^{n}(H_m - H_{mav})^2} \quad \text{unitless} \qquad (14)$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(H_m - H_c)^2} \quad \left(\text{MJ m}^{-2}\ \text{day}^{-1}\right) \qquad (15)$$

$$\text{MBE} = \frac{1}{n}\sum_{i=1}^{n}(H_m - H_c) \quad \left(\text{MJ m}^{-2}\ \text{day}^{-1}\right) \qquad (16)$$

$$\text{MABE} = \frac{1}{n}\sum_{i=1}^{n}(|H_m - H_c|) \quad \left(\text{MJ m}^{-2}\ \text{day}^{-1}\right) \qquad (17)$$

$$\text{MPE} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{H_m - H_c}{H_m}\right)100 \quad \% \qquad (18)$$

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left(\left|\frac{H_m - H_c}{H_m}\right|\right)100 \quad \% \qquad (19)$$

where *Hmav* is the mean measured solar radiation and *n* is the number of data.

3. Results and discussion

Table 2 shows the adjusted and typical coefficients required for models. In the literature there are not typical values for M5, therefore it was not included in this comparison; on the other hand M6 is a linear regression using local data, so there are not typical values for it.

In order to analyze the performance of the models (M1–M6) scatter plots considering observed and estimated solar radiation values were done (Fig. 1).

The R^2 values of the estimations for models M1 to M4, with typical and fitted values are shown in Table 3; concluding that only M3 has a significant improvement which would increase its local applicability.

Based on the results of the comparative analysis with different time steps for M1, all models were developed with a 5-days average time steps (the value adopted for each day corresponds to the average data of that day with the four later days). It can be observed (Table 4) that using a 5-days time step to reduce the amplitude of day-to-day variation was an effective way of improving the model's performances. From the five days average base, statistical values are acceptable, so this one was chosen in order to conserve accuracy on the estimations. Ball et al. [3] concluded that the performance of four models was improved by regressing a 7-days average time steps instead of a daily basis.

Table 5
R^2, RMSE, MBE, MABE, MPE and MAPE computed in the comparison between observed and estimated daily solar radiation.

	M1	M2	M3	M4	M5	M6
R^2	0.884	0.884	0.887	0.885	0.886	0.874
RMSE	2.073	2.075	2.046	2.064	2.076	2.141
MBE	−0.083	−0.092	−0.080	−0.081	−0.232	0.121
MABE	1.590	1.596	1.566	1.584	1.620	1.636
MPE	−2.572	−2.665	−2.481	−2.583	−3.567	−0.566
MAPE	9.427	9.484	9.268	9.414	9.835	9.406

Table 5 shows for all models, values of RMSE, which are low (between 2.046 MJ m^{-2} day^{-1} and 2.141 MJ m^{-2} day^{-1}), and the R^2 values indicate that models perform well. From M1 to M5, MBE values obtained are negative, which means overestimation; while M6 shows a positive value which indicates underestimation. Values of MPE are into the range of ±10%, which is considered acceptable.

Ball et al. [3] found, predicting daily solar radiation for 13 sites in North America, using a modified Hargreaves-Samani model, a site specific Hargreaves-Samani model and two forms of the Bristow and Campbell model, R^2 values between 0.53 and 0.97 and RMSE values in the range of 1.27 MJ m^{-2} day^{-1}–2.9 MJ m^{-2} day^{-1}. Álvarez et al. [29] estimated monthly global solar radiation for the south-central region of Chile using the r.sun, the Hargreaves-Samani and the Bristow-Campbell models, obtaining R^2 values equal to 0.9, 0.87 and 0.86 respectively, with RMSE values of 4.41, 3.81 and 3.29 for the mentioned models. Li et al. [24] obtained and proved in China a model using temperature variables with mean RMSE of 38.68%, and MBE of 0.38 MJ m^{-2} d^{-1}.

Considering the typical values for the coefficients, M3 had the lowest R^2 value, but when coefficients were locally adjusted M3 presented the highest value for R^2.

4. Conclusions

- Hargreaves and Samani (M1), Allen (M2) and Bristow and Campbell (M4) models could be used with typical values to estimate solar radiation at Cañada de Luque (Córdoba, Argentina). The Samani model (M3) should not be applied without calibration of its coefficients.
- Almorox model (M5), which considered the saturation vapor pressure and temperature range, can accurately estimate solar radiation once their coefficients are calibrated, showing a high R^2 value.
- Although a new linear model (M6) presented the smallest R^2 value, it could be taken into account for its easy application.
- Daily estimates of solar radiation by temperature based models are subject to errors caused by the temperature range, which is influenced by the movement of weather fronts, variations in wind speed and cloudiness, etc. Therefore, models are recommended to be used with five days or longer time steps.
- All models were robust and accurate over the evaluated site, so daily solar radiation can be estimated properly with temperature based models, which use easily available meteorological variables and can be used to estimate missing daily values of global solar radiation when only temperature data are available.

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