GLOBAL SOLAR RADIATION IN TWO TUNISIAN CITIES: COMPARISON OF PREDICTION AND MEASURED DATA

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Abstract - In this paper, we have studied the solar radiation data available at two meteorological stations located in the south of Tunisia. Measurements of global solar radiation on horizontal surface are compared to predictions made by different methods. The first method is based on Angström-Prescott formula which correlates relative global solar radiation H/H_0 to corresponding relative duration of bright sunshine SS/SS_0. The second method, a model due to Mechlouch et al., uses cloud cover N, the hours of the day t and the quantum of the year q. The third method, an empirical relation due to Sivkov, uses the monthly sunshine duration nm and the noon altitude of the sun h.
The models are compared and tested on the basis of statistical error tests (MBE, RMSE, MPE and R^2) and the results are presented.

Keywords: Solar energy, Global solar radiation, models, Tunisia

1. INTRODUCTION

Considering the measuring apparatus of solar irradiation is not always available and that receiving solar energy is essential for the dimensioning of the solar installations. The modeling of the solar irradiation will be the solution of this problem. In the solar energy literature, there have been numerous papers dealing with the evaluation and comparison of solar radiation estimation models.
Several empirical models have been developed to calculate global solar radiation using various parameters. These parameters include extraterrestrial radiation, sunshine hours, mean temperature, maximum temperature, soil temperature, relative humidity, number of rainy days, altitude, latitude, total precipitable water, albedo, cloudiness and evaporation [1-2].
More recent, the meteorological data for three cities; Awka, Enugu and Owerri in the south eastern Nigeria, for the period of 11 years (2000 – 2010) were used by Elekalachi et al [3] to derive Angstrom type regression equation used for estimation of global solar radiation incident on a horizontal surface in the cities studied. In other to evaluate the significance of the results, three statistical methods have been used for the purpose. The three error formulae are; Mean Bais Error (MBE), Mean Percentage Error (MPE) and Root Mean Square Error (RMSE). The results shows that sunshine based model can be used for estimating global solar radiation in south eastern Nigeria.
Maraj et al [4] In this paper, different solar radiation models (linear, exponential, power) for the city of Tirana-Albania, are built and tested. These models are used to estimate the monthly average total solar radiation on horizontal surface, based on measured data. Measured data include solar radiation on horizontal surface and sunshine duration data, which are used for the development of the models. Calculated and measured values are compared and evaluated by using statistical test methods. Calculated values obtained from the proposed solar radiation models show a good agreement with the measurements.
In Turkey, Hakan Okyay Menges [5] validates several models to predict the monthly average daily global radiation on a horizontal surface against an independent data set for Konya (Turkey) and, thus, to select the most accurate model.
To Yemen, Khogali et al. [6] tested interrelationships of Angström [7] and of Barbaro et al. [8] for the determination of global and diffuse solar flux densities. Viorel Badescu [9] had formulated the correlation to estimate the monthly mean daily global solar irradiation, with bright sunshine hour number or

fractional total cloud amount as input for Romania. Rehman and Halawani [10] had developed an empirical correlation for the estimation of global solar radiation in Saudi Arabia. Also, he had presented the comparison between the present correlation and other models developed under different geographical and varied meteorological conditions.

Mohandes et al [11] have compared radial basis function methods with regression models for Saudi stations and found the radial basis method models to be better than the regression models.

Islam et al. [12] compared measured solar energy radiation for a one complete year in Abu Dhabi with NASA SSE model and 10-year average data of Abdalla et al. [13]. They also compared the monthly mean daily values of global solar radiation and temperature of Abu Dhabi and other Arab State capitals.

Other researchers used different models to calculate the solar radiation received by a tilted plan. Desnica et al. [14] presented a method for the calculation of the received solar global flux to different slant. They used interrelationships of Liu-Jordan [15] and of Klein [16] modified while taking account of the atmospheric transmission, calculations have been made for two regions in Yugoslavia. Good results have been gotten for the different slants.

Ma and Iqbal [17] compared the three following models: Model isotropic [17], model of Hay [18] and model of Klucher [19] for the evaluation of the received solar radiation by a tilted plan in the region of Ontario (Canada). It is shown here that only models of Hay and Klucher could be used.

The objective of this study was to validate several models to predict the monthly average daily global solar radiation on a horizontal surface against an independent data set for two cities in the south of Tunisia; Medenine city and Gabes city and, thus, to select the most accurate model.

2. EXPERIMENTAL SETUP AND PROCEDURE

2.1. Experimental data

The sites of the measurement stations were located at two cities in the south of Tunisia; Medenine city (33°21'N latitude, 10°29'E longitude) and Gabes city (33°53'N latitude, 10°06'E longitude).

The experimental data are registered in a Degreane weather station located in the two cities for a period of six years (2002-2008). This data logger was used to collect meteorological data; the global solar radiation on horizontal surface is the principal measuring parameter. A Degreane weather station had a pyranometer Kipp & Zonen model CM-6B of accuracy ±2% for measuring global solar radiation. The meteorological data from the data logger will be transmitted to two computers in the two cities every hour using specified software.

2.1.2. Empirical models

Model 1:

The first relation which we shall use is an Angström [7] correlation based relationship and modified by Prescott (1940) [20]:

$$\frac{H}{H_o} = a + b.\frac{SS}{SS_0} \tag{1}$$

Where H is the monthly average of the daily global radiation on a horizontal surface, H_0 is the extraterrestrial solar irradiance on a horizontal surface, SS is the monthly average of daily hours of bright sunshine, SS_0 is the maximum daily hours of sunshine, and a and b are regression constants.

The ration SS/SS_0 is the fraction of maximum possible number of bright sunshine hours and H/H_0 is the atmospheric transmission coefficient.

Values of SS are computed from Cooper's formula

$$SS = \frac{2}{15}.\cos^{-1}(-\tan\varphi.\tan\delta) \tag{2}$$

Where φ is the latitude and δ is the solar declination, While H0 is obtained from [21]:

$$H_0 = \frac{24}{\pi}.I_s.f.(\cos\varphi.\cos\delta.\sin\omega + \frac{2\pi.\omega}{360}.\sin\varphi.\sin\delta) \tag{3}$$

Where Is is the solar constant (=1367 W/m^2), and ω is the sunrise hour angle.

$$f = (1 + 0.033\cos(\frac{360q}{365})) \tag{4}$$

Where *f* is the eccentricity correction factor and q is the day number.

Model 2:

In our model Mechlouch, the hourly global solar radiation can be expressed as [22]:

$$G_H = A_N.A_q.A_t \tag{5}$$

$$A_N = 0.1412N - 23.04 \qquad for\ N \le 0.5 \tag{6}$$

$$A_N = 3.7209N - 37.853 \qquad for\ 0.5 < N \le 1 \tag{7}$$

$$A_q = 0.01407\sin[\frac{360}{365}(284+q)] - 0.0357 \tag{8}$$

$$A_t = t^4 - 47.958t^3 + 795.68t^2 - 5291t + 12158 \tag{9}$$

Where GH is the hourly global solar radiation on a horizontal surface (W/m²), q is the Julian day of the year, t is the hour of the day and N is the daily average

of cloud cover.
To estimate the monthly global solar radiation, we use the following expressions:

$$G_d = \sum_{t_1}^{t_2} G_H = \sum_{t_1}^{t_2} A_N.A_q.A_t \qquad (10)$$

$$H = \sum G_d \qquad (11)$$

Where G_d and H are respectively the daily and the monthly global solar radiation.
t_1 is the sunset hour and t_2 is the sunrise hour.

<u>Model 3:</u>

This correlation was proposed by Sivkov [23–24]:

$$H=4.9(n_m)^{1.31}+10500(\sinh)^{2.1} \qquad (12)$$

Where H and n_m are respectively the monthly global solar radiation and the monthly sunshine hours and h is the noon altitude of the sun.
While sinh is obtained from:

$$\sinh = \sin\varphi.\sin\delta + \cos\varphi.\cos\delta.\cos\omega \qquad (13)$$

3. RESULTS AND DISCUSSION

In this part we are going to present the comparison of the predicted values of global solar radiation for the two Tunisian cities using three models and the measured values.

3.1. Estimation by model 1

The monthly average of the daily values of H/H_0 and SS/SS_0 are employed to compute the linear regression coefficients a and b of equation (1). The results of Medenine are presented in table 1, and the results of Gabes are presented in table 2.

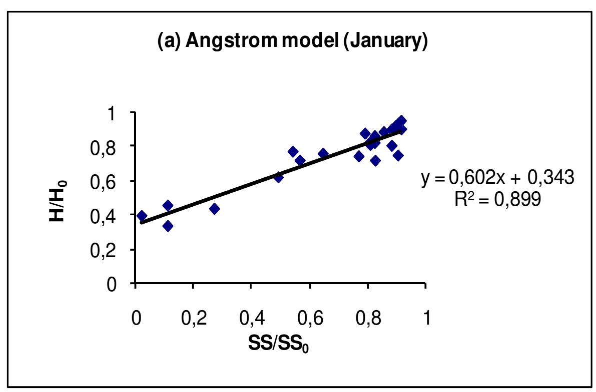
Table 1. Linear regression coefficients and coefficient of determination for Angström-Prescott model (Medenine city)

Months	a	b	R^2
1	0.60	0.34	0.90
2	0.72	0.29	0.90
3	0.61	0.38	0.91
4	0.32	0.55	0.95
5	0.46	0.48	0.92
6	0.31	0.62	0.94
7	0.46	0.44	0.93
8	0.38	0.50	0.92
9	0.70	0.27	0.95
10	0.58	0.40	0.93
11	0.69	0.30	0.90
12	0.62	0.31	0.94

Table 2. Linear regression coefficients and coefficient of determination for Angström-Prescott model (Gabes city)

Months	a	b	R^2
1	0.41	0.27	0.90
2	0.45	0.25	0.93
3	0.67	0.10	0.90
4	0.58	0.18	0.96
5	0.59	0.17	0.93
6	0.54	0.23	0.91
7	0.56	0.19	0.94
8	0.49	0.25	0.90
9	0.58	0.17	0.95
10	0.63	0.13	0.93
11	0.45	0.24	0.96
12	0.56	0.16	0.96

Linear regression coefficients a and b are employed in Angström-Prescott model to calculate monthly global solar radiation, the comparison with measured values is presented in Fig. 1 and 2, respectively for January and December.



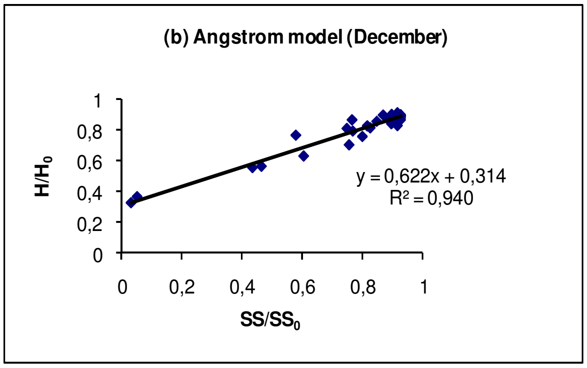


Fig. 1. H/H_0 versus corresponding SS/SS0 for January (a) and December (b) for Medenine city

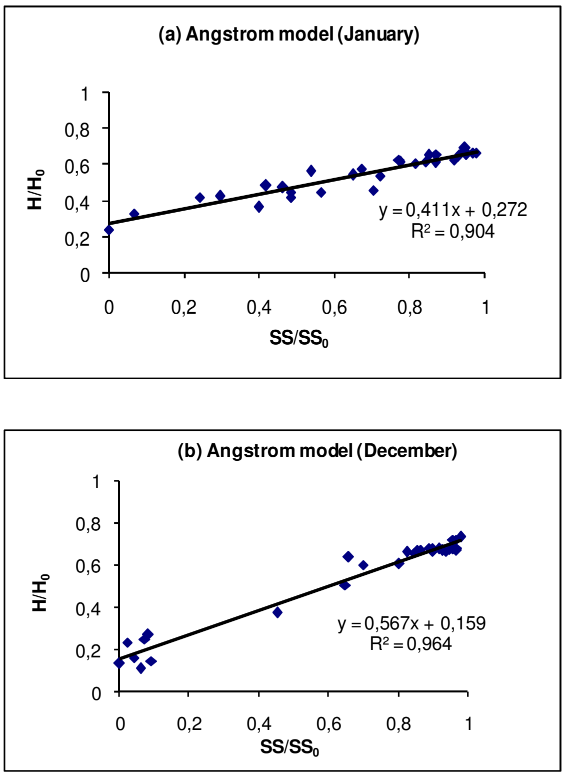


Fig. 2. H/H_0 versus corresponding SS/SS0 for January (a) and December (b) for Gabes city

The monthly global solar radiation was calculated for one complete year and the results were compared with average measured data for the period between 2002 and 2008 (Fig. 3).

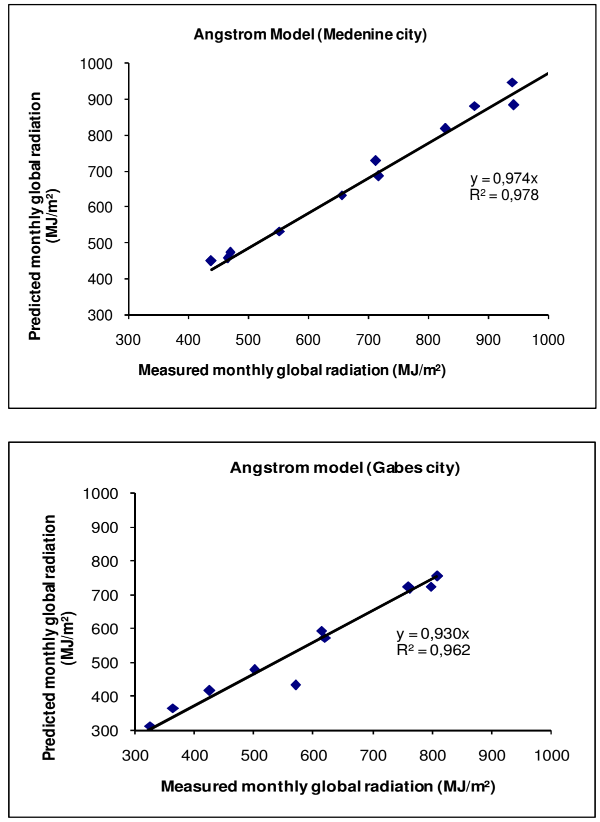
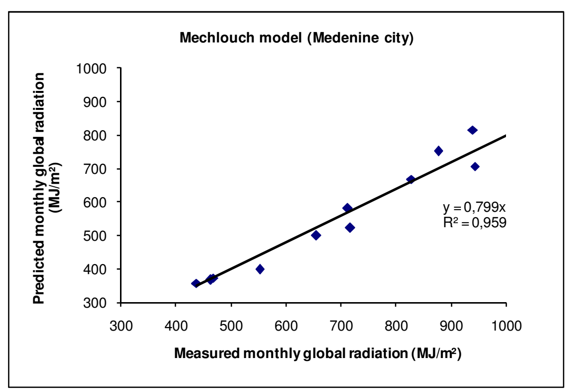


Fig. 3. Global monthly radiation, modeled versus measured

3.2. Estimation by model 2

The monthly global solar radiation is estimated by equations (5-11) and comparison with measurements is given in Fig. 4.



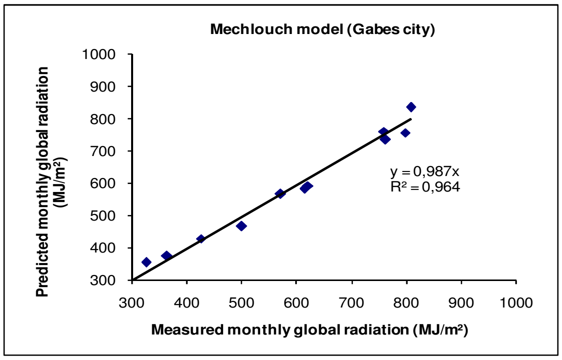
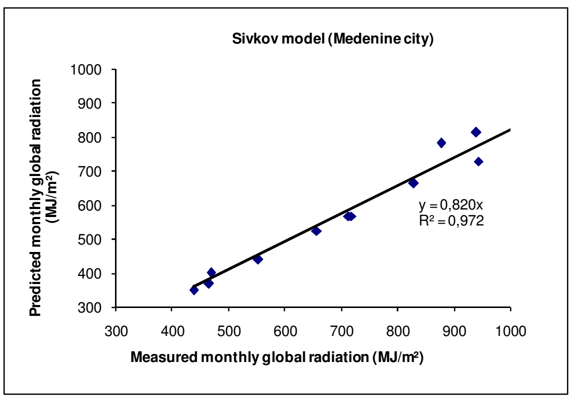


Fig. 4. Global monthly radiation, modeled versus measured.

3.3. Estimation by model 3

The monthly global radiation was calculated using the expression (12). The calculated values were compared with measured data in Fig. 5.



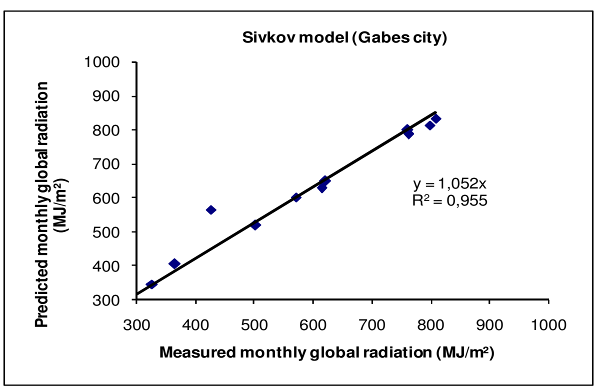


Fig. 5. Global monthly radiation, modeled versus measured.

Table 3 compares the predicted values of monthly global solar radiation for the two cities and the measured values using coefficients of determination. As shown, most of the points fall along the diagonal line (Fig. 3, 4, 5). The predicted values have good agreement with the measured values. The coefficient of determination (R^2 value) obtained for the data set is 0.90. In this respect, the closer to unity is the coefficient of determination, the better the prediction accuracy. R^2 approaching 1 means that the solution of the problem gives accurate answers.

Table 3. Coefficients of determination for three models

Cities	Medenine	Gabes
Models	**Coefficients of determination**	
Mechlouch	0.959	0.964
Angström-Prescott	0.978	0.962
Sivkov	0.972	0.955

It is important to underline that the same set of data was utilized for the performance tests of all the models. The performance of the models was checked with three statistical indices: the Mean Percentage Error (MPE), the Root Mean Square Error (RMSE) and Mean Bias Error (MBE).
The mean percentage error (MPE) is defined as:

$$MPE = \frac{1}{N_T}\frac{\sum(X_{mC} - X_{mD})}{X_{mD}} * 100 \quad (14)$$

Where X_{mC} is the calculated global solar radiation and X_{mD} is the measured data and NT is the total number of observations.
The RMSE informs us about the dispersion of the experimental data and it is defined as:

$$RMSE = \left(\frac{\sum(X_{mC} - X_{mD})^2}{N_T}\right)^{\frac{1}{2}} \quad (15)$$

The MBE informs us about the tendency above the underestimation of experimental data and it is expressed by the following equation:

$$MBE = \frac{\sum(X_{mC} - X_{mD})}{N_T} \quad (16)$$

Table 4. Prediction errors for monthly global solar radiation of three models for the two cities

Cities	Medenine			Gabes		
Models	MPE (%)	MBE (MJ/m^2)	RMSE (MJ/m^2)	MPE (%)	MBE (MJ/m^2)	RMSE (MJ/m^2)
Angstrom-Prescott	1.7	-1.4	2.8	5.9	-2.6	3.8
Mechlouch	6.2	-2.1	4.8	2.1	-1.9	3.2
Sivkov	4.3	-2.8	3.9	6.5	-3.4	5.2

We can see the statistical results of about 8760 measurements for the global solar radiation. Table 4 summarizes the prediction errors of the three tested models for calculating monthly global solar radiation of the two cities. All the models provide good predictions for monthly global solar radiation. Angström-Prescott model has the minimum MPE and RMSE for Medenine city (MPE = 1.7%, RMSE = 2.8 MJ/m^2), for Gabes city Mechlouch model has the minimum MPE and RMSE (MPE = 2.1%, RMSE = 3.2 MJ/m^2). So comparison results show that Angström-Prescott and Mechlouch model provide the best results among the three models respectively for Medenine city and for Gabes city.

Models produce low values of MPE, MBE and RMSE with estimating the mean monthly global solar radiation. The yearly global solar radiations have an accuracy of 1.8%, 6.3% and 4.4% respectively for Angström-Prescott, Mechlouch and Sivkov model for Medenine city, for Gabes city are 6%, 2.3% and 6.6% respectively for Angström-Prescott, Mechlouch and Sivkov model.

3.4. Seasonal variation of global solar irradiance

For Medenine city, the mean monthly global solar radiations measured and also estimated by the model of Angström-Prescott are plotted in Fig. 6. From this figure, we find that the maximal monthly mean of global radiation occurs in summer (1042 MJ/m² per month) and in spring (943 MJ/m² per month). In autumn and winter we find respectively 712 MJ/m² per month and 552 MJ/m² per month.

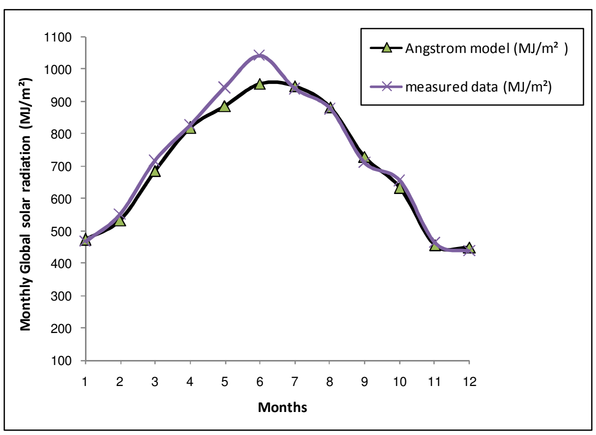


Fig. 6. Variation of means monthly solar radiation for Medenine city

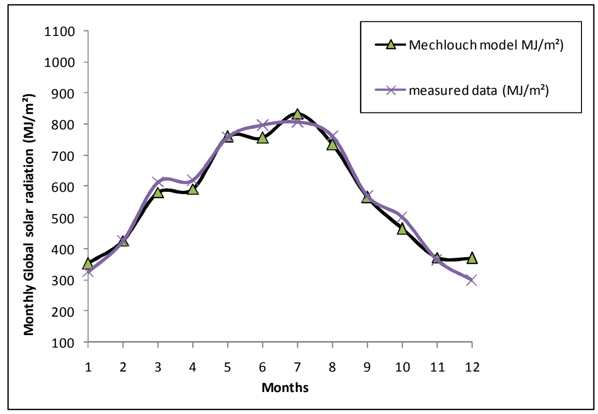


Fig. 7. Variation of means monthly solar radiation for Gabes city

For Gabes city, the mean monthly global solar radiations measured and also estimated by the model of Mechlouch are plotted in Fig.7. We find that the maximal of global solar radiation is high throughout the summer months reaching 808 MJ/m² per month, in spring months 760 MJ/m² per month. In autumn and winter we find respectively 570 MJ/m²/month and 425 MJ/m² per month.

4. CONCLUSION

This study provides methods for estimating global solar radiation for two cities in the south of Tunisia (Medenine city and Gabes city) based upon three empirical models (Angström-Prescott, Mechlouch and Sivkov model).

The performance of the models was checked with coefficient of determination R^2 and three statistical indices: the Mean Percentage Error (MPE), the Root Mean Square Error (RMSE) and Mean Bias Error (MBE).

The agreement between the measured and estimated global solar radiation values was found to be satisfactory for all the models in the two southern Tunisian cities, but Angström-Prescott model provides the best results among the three models for Medenine city and Mechlouch model provides the best results among the three models for Gabes city. The MPE, MBE and RMSE are respectively 1.7%, -1.4 MJ/m²

and 2.8 MJ/m² for Angström-Prescott model for Medenine city, for Gabes city are respectively 2.1%, -1.9 MJ/m² and 3.2 MJ/m² for Mechlouch model.
The yearly global solar radiations have an accuracy of 1.8%, 6.3% and 4.4% respectively for Angström-Prescott, Mechlouch and Sivkov model for Medenine city, for Gabes city are 6%, 2.3% and 6.6 % respectively for Angström-Prescott, Mechlouch and Sivkov model.

The results show that these models will be useful for the design of various systems using solar energy in the south of Tunisia especially in cases where radiation measurements are not readily available.

Acknowledgements

The corresponding author thanks the meteorological stations of Medenine city and Gabes city for their cooperation.

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NOMENCLATURE

A_t: Time function defined by Eq. (8)
A_q: Function depending on the Julian day, defined by Eq. (7)
A_N: Function depending on cloud cover, defined by Eqs. (5 and 6)
a, b : Linear regression coefficients defined in Eq. (1)
f : Eccentricity correction factor
G_H : Hourly global solar irradiation on a horizontal surface (W/m²)
G_d : Daily global solar irradiation on a horizontal surface (W/m²)
H : Monthly average of the daily global irradiance on a horizontal surface (W/m^2)
H_0 : Extraterrestrial solar irradiance(W/m^2)
h : Noon altitude of the sun
I_s : Solar constant (W/m^2)
MBE : Mean bias error
MPE : Mean percentage error
N : Average of cloud cover
N_T: The total number of observations
n_m : Monthly sunshine hours (h)
q : Quantum of the day (Julian date, q=1 for Junuary 1 and q=365 for 31 December)
RMSE : Root mean square error
R^2 : Coefficients of determination
SS: Monthly average daily sunshine-duration (h)
SS_0: Maximum possible monthly average daily sunshine-duration (h)
t : Hour of the day (h)
X_{mC} : The calculated data of global solar radiation
X_{mD} : The measured data of global solar radiation
φ : Latitude (degrees)
δ : Solar declination (degrees)
ω : Sunrise hour angle (degrees)