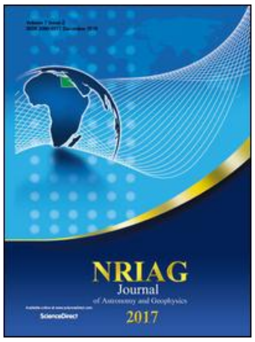

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Developing a new model for predicting global solar radiation on a horizontal surface located in Southwest Region of Algeria

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ABSTRACT
Global solar radiation data is essential in the design of solar energy conversion devices. The most widely used model in the estimation of the global solar radiation coming to the earth's surface is the Angtröm-Prescott model. In this model, relative sunshine duration plays an important role. In the current study, it was attempted to review different models and to determine the best performing model developed for the city of Bechar and two locations of Algerian Big South desert for solar energy projects and compare them with the different established models available in the literature up until now, based on measured sunshine hours data. The new models give high accuracies on the application, where (R^2) ranges between 0.70 and 0.99. In addition, MBE and RMSE values are very low in the studied stations. The results presented in this paper are quite useful for quick estimation of global solar radiation data required for performance evaluation of solar collector used for different applications of solar energy.

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Solar energy assessment; global solar radiation; sunshine hours; empirical models

1. Introduction

Algeria possesses an exceptional solar resource in the Mediterranean basin, which is estimated at 60 times of the need for European countries of electric power (Khraief et al. (2018)). The insolation time over the Algerian Sahara of the national territory exceeds 2000 hours annually and may reach a maximum of 3900 h (Bailek et al. 2017a). The daily obtained solar energy on a horizontal surface is 5 kWh/m^2 over the major part of the national territory or about 1700 kWh/m^2/year for the North and 2263 kWh/m^2/year for the South of the country (Stambouli (2011)). For these reasons, solar radiation is an ample source of energy in Algeria which could be harnessed to fill the gap of energy demand. A large investment of the country was implemented by the national Programme, to exploit renewable energies, which is expected to ensure the generation of electricity by 40% of energy needs by 2030 (Bailek et al. (2017a) and Stambouli et al. (2012)).

Solar radiation data at a given site are a fundamental input for reliable predicting performance behaviour and potential of solar applications. Unfortunately, this parameter is not measured or not reliably estimated in many parts of the world, especially in the developing countries because of the lack of measuring devices (Bailek et al. (2017b); Jamil and Akhtar (2017)). Solar radiation data for many locations of these countries are extrapolated. The traditional method of obtaining the information on the amount of global solar radiation in a particular region is to instal spectral pyranometers in as many locations as possible within a region, which requires daily maintenance, data recording and handling, consequently increasing the cost of global solar radiation data collection. Therefore, it is rather more convenient and economical to develop methods to estimate global solar radiation using different climatological parameters. These models were first reviewed and their potential discussed as early as the 1970 s. Since then, much more such models for estimating solar radiation have been proposed in the literature (Almorox et al. (2005); Bahel et al. (1987); Ertekin and Yaldiz (1999); Bouchouicha et al. (2018); Khan et al. (2016)).

From the available literature, different models have been developed to estimate global solar radiation. Angström-Prescott sunshine-based model is widely used and there are some other approaches available as well in the literature. Some of the studies have been

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discussed here. Duzen and Aydin (2012)estimated and validated monthly average global solar radiation on horizontal surface using previously developed sunshine-based models like linear, quadratic, cubic, logarithmic and exponential for the Lake Van region in Turkey. The performances of models were evaluated by comparing the calculated and measured clearness index. According to their study, best performance was achieved by the cubic regression model for Bitlis, Gevas, Hakkari, Mus stations and quadratic model for Malazgirt, Tatvan and Van stations for the prediction of global solar radiation. They reported the annual average solar energy potential ranged between 750 KWh/m^2 and 2485 KWh/m^2. The annual average solar energy for the Lake Van was reported as 1610 KWh/m^2.Ayodele and Ogunjuyigbe (2015) proposed the probability distribution of clearness index for the prediction of global solar radiation. The inverse transformation of the cumulative distribution function was used as a function of clearness index for the prediction. For the purpose of validation, 8 years of global solar radiation data of Ibadan in Nigeria were used. Their results indicated that the logistic distribution gives the best fit for clearness index for the location considered and were found effective in the estimation of global solar radiation. Muzathik et al. (2011) estimated global solar radiation on horizontal as well as inclined surfaces for Malaysia. They used 3 years measured hourly solar radiation data and estimated monthly average daily solar radiation using selected Ångström-Prescott type models. The models were then compared on the basis of statistical analysis. New exponential regression model was developed based on Bakirci exponential regression model to estimate monthly average daily global solar radiation at horizontal surface. They also reported a correlation based on the proposed model by Olmo et al. (1999) to convert the horizontal solar radiation into radiation on an inclined surface. Al-Mostafa et al. (2014) reported a review and a case study of sunshine-based models for the estimation of solar radiation. They reported the performance of 52 sunshine-based models for the estimation of monthly average global solar radiation in Jouf in Saudi Arabia. Kada Bouchouicha et al. (2018)developed regression-based models of solar radiation estimation for Adrar province in Algeria, and compared it with other models in the literature. More accurate estimation was done by Bouchouicha et al. (2019) to reduce ambiguities and improve quality in the estimation of the daily and monthly mean daily global solar irradiations over Algerian Big South based on measured ground data on air temperature and sunshine hours, as well as the day/month number. (Teke and Yıldırım (2014)estimated monthly average global solar radiation for the four main cities (Adana, Mersin, Antakya and Kahramanmaras) of the Eastern Mediterranean region using the available meteorological data based on several Angström-Prescott sunshine-based models. They estimated coefficients of three Angström-based sunshine models for each month using curve estimation techniques with MINITAB statistical program. They reported that Angström-Prescott models were the most suitable models in the winter for the Eastern Mediterranean Region. Teke and Yıldırım (2014) developed three empirical models to predict the daily global solar radiation for Eastern Anatolia Region of Turkey. They analysed the measured satellite data on a horizontal surface for the period of 1991–2005. The estimated daily global solar radiation from the developed model was compared with the values of daily global solar radiation of the NASA-SSE. In another study, Bakirci (2009)obtained seven different sunshine-based empirical correlations to estimate the global solar radiation on horizontal surfaces in different regions of Turkey. Statistical test methods were applied to observe the performance of the developed models. Camargo and Dorner (2016) determined and explored a source of global solar radiation data with the best spatiotemporal resolution for Lerma Valley (Salta, Argentina). The study demonstrated the sources of the global solar radiation for the Lerma Valley to assess the most suitable available data set. Global solar radiation was evaluated from the reanalysis data set provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the METEOSTAT second generation derived data set provided by Land Surface Analysis Satellite Applications Facility (LSASAF). ECMWF and LSASAF were compared with each other, with data generated using statistical methods and with data from a pyranometer. Their results expressed the data from LSASAF as a fit best to the ground measurements. Calif and Soubdhan (2016) developed the correlation based on coefficient of variation assuming time scale separation. Chelbi et al. (2015) studied and compared several Angström-Prescott sunshine duration based regression models and different interpolation techniques to estimate global solar radiation for Tunisia (North Africa). They also produce mappings of monthly and annual mean daily global solar radiation.

Despite a number of these studies done on the development of empirical correlation for estimation of global solar radiation in locations across the globe, no much empirical models have been found in the Southwest region of Algeria in the literature. Therefore, the main objective of this paper is to review different models fitted in literature for calculating the global solar radiation based on sunshine duration and to present and validate new empirical models of the Angstrom-Page type for the estimation of solar radiation incident on horizontal surface located at south-western Algeria. The evaluation of all models in two categories is based on comparing four statistical indicators.

2. Characteristics of location under study and its meteorological data

The Study area is located in the south west of Algeria, with arid climate and irregular precipitation, with an average of 71.48 mm/year. The meteorological collected data over 21 years, from 1988 through 2008 show that the lowest and highest temperatures are recorded in January and July, respectively, with values of 4°C and 40°C, and average annual temperature of 27.16°C. The annual rate of the evaporation (mean of 305.29 mm) and the evapotranspiration in this region exceeds the precipitation. Therefore, there are warm temperatures during the entire year (Kabour et al. (2011)).

In this study, three datasets of the solar radiation and sunshine hours' are collected, respectively, from the two meteorological measuring stations at Bechar and Tamanrasset sites of the Algerian National Meteorology Office (ONM) and the radiometric measuring station at the Renewable Energy Research Unit at Saharian Medium Adrar site (URER-MS) of the Centre for Renewable Energy Development (CDER). Table 1 shows specific information about the three sites used in this paper (Bouchouicha et al. (2015). The WMO N° represents the World Meteorological Organization station index number.

Table 1. Specific information of the measurement sites in South region of Algeria.

No.	Station	Latitude (°)	Longitude (°)	Elevation (m)	WMO No.
1	Bechar	31.38	−2.15	806	60,571
2	Adrar	27.88	−0.28	269	-
3	Tamanrasset	22.78	5.52	1378	60,680

The three datasets of long-term monthly averages for the period 1990 to 1994 for the Bechar site, 2012 to 2014 for the Tamanrasset station and 2010–2015 for Adrar which are representative stations of the Algerian Big South (see Figure 1), with subject to conditions of quality control and unrealistic data as described in (Bailek et al. (2018)).

3. Methods

The fundamental parameter of sunshine duration fraction, daily extra-terrestrial radiation on the horizontal surface is significant for the estimation of global solar radiation. The most widely model used in different locations of the world which presents a linear regression model used in correlating the global solar radiation data with relative sunshine duration was proposed by Angstrom–Prescott (Angstrom (1924)). Several modifications have been proposed to it since it was developed by many researchers who have established correlations based on this model and exploring other regression forms. The most commonly used model is given by:

$$G/G_o = a + bS_f \quad (1)$$

where$S_f$is the ratio of actual sunshine duration to maximum possible sunshine duration and, a and b are empirical coefficients. The values of the daily extra-terrestrial solar on the horizontal surface$(G_o)$is given as:

$$G_o = \left(\frac{24*3600*I_{sc}}{\pi}\right)(1 + 0.033cos(360n/365))(\cos\delta\ \cos\lambda\cos\sin\omega_s + (\pi/180)\omega_s\sin\delta\sin\varphi) \quad (2)$$

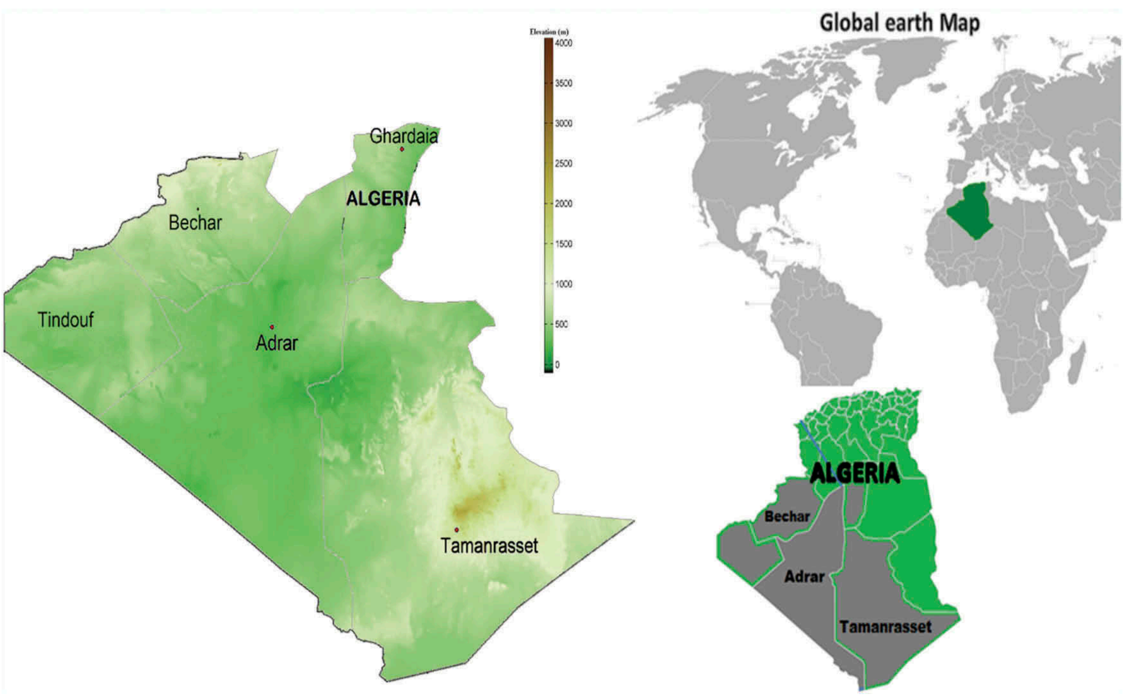

Figure 1. Location map of the station.

whereI_{sc} is the solar constant (= 1367 W/m^2),φ and $\delta$are the latitude and declination angles, respectively (both in degrees), $\omega_s$is the sunset hour angle (in degrees) given by (Anis et al. (2019)) and n the number of day of the year starting from the first of January.

Many widely used models to obtain the monthly mean global fraction (G/G_o) were linear models as a ratio function ofS_f. Later, other models (Non-linear models) were presented using polynomials of cubic and quadratic order as well as other functions such as the logarithmic, power and inverse forms. Based on the careful review of available literature on the empirical modelling of daily horizontal global radiation models, it is notorious that the majority of the models were derived using a linear form, followed by a polynomial, and the double exponential and logistic functions. For more details on the history of global solar radiation estimation from sunshine duration, the reader is referred to recent reviews of Despotovic et al. (2015) and Makade and Jamil (2018).

4. Method of statistical comparison

In the literature, there are numerous statistical methods available to compare solar radiation models (El-Metwally (2004), Elagib et al. (1999) and Khogali et al. (1983)). In the present study, R^2, MBE, RMSE and RRMSE tests have been used to evaluate the performance of models (Aoun et al. (2019); Duzen and Aydin (2012) and Maleki et al. (2014)). These statistical indicators are calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(H^{i,m} - \overline{H^m}\right)^2}{\sum_{i=1}^{n}\left(H^{i,c} - \overline{H^c}\right)^2} \tag{3}$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(H^{i,m} - H^{i,c}\right) \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(H^{i,m} - H^{i,c}\right)^2} \tag{5}$$

$$RRMSE = \frac{100}{H^{i,m}}\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(H^{i,m} - H^{i,c}\right)^2} \tag{6}$$

where n is the total number of the available data points.

5. Results and discussion

Figure 2 represents the variations, and frequency distribution of daily; monthly and annual global radiation and its clearness index that was drawn using the data collected at the station considered in this study. As shown in the figure, the annual mean daily global irradiation is 22.89MJ/m^2 with a standard deviation of 3.848 MJ/m^2.day. In addition, for the annual mean, the clearness index is 0.74 on this site.

5.1. Evaluation of models on validation data set

In the first step, a preliminary test was performed among many models chosen from the literature to estimate the global radiation component. These models are illustrated in Table 2.

Table 2 summarises the statistical analysis for selected models taken from the literature with respect to all statistical quantitative indicator values for the linear and the non-linear models. It deals with the most important statistical criteria for choosing the best model, which are the two-root mean squares

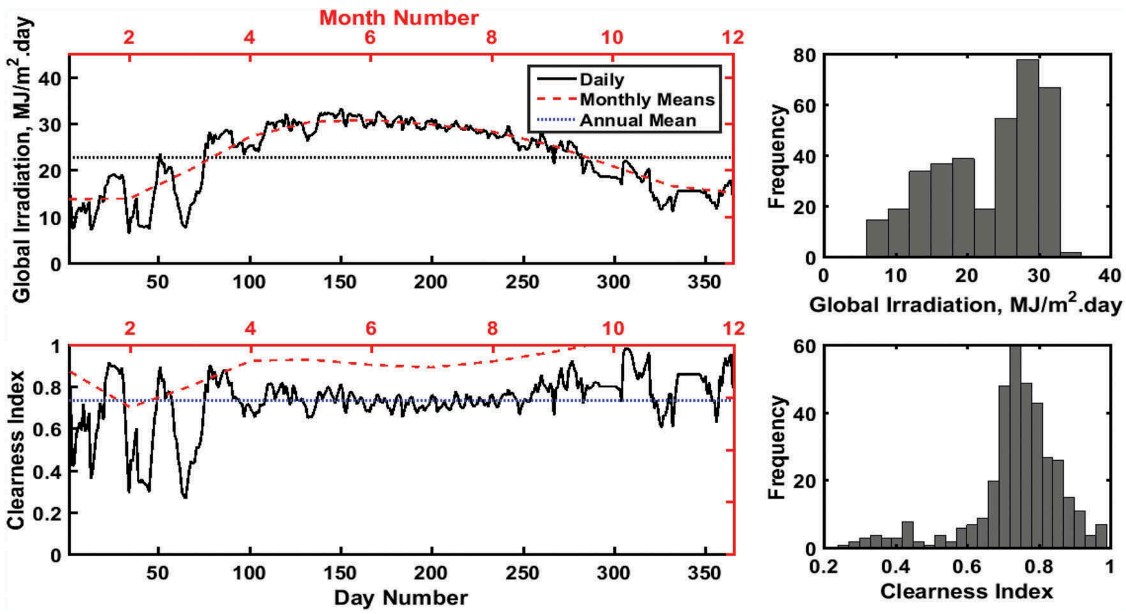

Figure 2. Variations and frequency distributions of the global solar irradiation and its clearness index for station.

Table 2. Results of statistical indicators for all models selected in this study.

Models	Type	MBE	RMSE	RRMSE%	R^2	Source
M1	Linear	3.775	4.578	20.034	0.846	(Khogali et al. 1983)
M2		3.838	4.702	20.579	0.830	(Rensheng et al. 2006)
M3		4.647	5.310	23.240	0.856	(Fagbenle 1993)
M4		4.563	5.224	22.862	0.861	(Veeran and Kumar 1993)
M5		4.148	4.913	21.502	0.841	(Page 1961)
M6		8.952	9.486	41.518	0.851	(Kuye and Jagtap 1992)
M7		3.622	4.446	19.458	0.847	(Jackson and Akuffo 1992)
M8		3.311	4.261	18.648	0.835	(Louche et al. 1991)
M9		3.59	4.377	19.157	0.858	(Raja and Twidell 1990a)
M10		3.613	4.462	19.529	0.842	(Luhanga and Andringa 1990)
M11	Polynomials	3.208	4.133	18.089	0.844	(Raja and Twidell 1990b)
M12		15.517	16.236	71.059	0.876	(Tasdemiroglu and Sever 1991)
M13		3.678	4.569	19.996	0.831	(Aksoy 1997)
M14		3.544	4.438	19.422	0.836	(Said et al. 1998)
M15		3.332	4.226	18.497	0.844	(Ulgen and Ozbalta, 2000)
M16	Logarithmic & Exponential	2.728	3.895	17.047	0.827	(Almorox and Hontoria 2004)
M17		4.021	4.793	20.977	0.844	(Bakirci 2009)
M18		3.304	4.154	18.18	0.855	(De Souza et al. 2016)
M19		5.083	5.724	25.053	0.850	(Ampratwum and Dorvlo 1999)
M20		6.551	7.113	31.132	0.867	(Ampratwum and Dorvlo 1999)

(RMSE and RRMSE), MBE, and R^2 that varies for different models. Regarding Table 2, the MBE values are between 15.517 MJ/m^2.day and 8.952MJ/m^2.day and the root mean squares (RMSE) range between 3.895 MJ/m^2.day and 16.236 MJ/m^2.day, but the lowest RMSE value is obtained from the exponential regression model. When the models obtained on the basis of R^2 are examined, it is seen that the R^2 values belonging to M4 and M12 in linear and non-linear type, respectively, are higher than the values of the remaining models. Due to the limited data set used for this station, the R^2 value may be misleading to some readers, i.e. the R^2 value may be small even if the model performs well. Therefore, it is better to inspect the models' performances using the RRMSE. Depending on the obtained results, we can conclude that the M8 model is superior to the other models in the linear type, and its RMSE and RRMSE values are 4.261MJ/m^2.day and 18.648%, respectively, while the M16 model has lower statistical error values than those of the remaining non-linear models. The degrees of accuracy of the correlation are approximately the same in two models. Also, the values of the root-mean-square error does not exceed 0.3, which indicates that they give the same results approximately with a slight advantage of a model M16. The deviations of the estimated values of the superior models obtained from the measured values are given in Figure 3.

5.2. Development and statistical evaluation of models

By applying the regression analysis technique, based on the obtained data on measured sunshine duration and monthly averaged global on horizontal surface components by averaging the predictions of the models, seven new global solar radiation models from two different categories were established. The results are summarised in Table 3. It is obvious that the values of RMSE of the developed models with the new RMSE vary from 2.369 MJ/m^2.day to 2.464 MJ/m^2.day, whereas the MBE values for general models lie between −0.058 and 0.028 (MJ/m^2.day). On the other hand, the relative root-mean-square error (RRMSE) varies from 10.402%to 10.808%. In addition, the R^2values are larger than 0.83, which means that the calculated data show a good agreement with the measured ones. As shown in Table 3, the error parameters (MBE, RMSE, RRMSE and R^2) are very close from one model to another.

As shown in Table 3, the error parameters are very close from one model to another. To overcome this, Global Performance Indicator (GPI) can be used as used in some recent papers (Jamil and Siddiqui 2017; Bailek et al. 2018) to arrange the models in this study. This indicator (GPI) is defined mathematically as:

$$GPI_i = \sum_j \alpha_j \left(\bar{\sigma}_i - \bar{\sigma}_{i,j}\right) \quad (7)$$

where $\alpha_J$equal −1 for the indicator R^2 only, whereas for other indicators (MBE, RMSE and RRMSE) is equal to 1, $\bar{\sigma}_j$is the median of scaled values of indicator and$\bar{\sigma}_{i,j}$is the scaled value of indicator $j$for i^{th} model. The higher the values of *GPI* indicator, the better the accuracy of model.

In order to choose the two best models representing this study, the model of the high GPI must be identified. Therefore, the model 5 is found to be the best non-linear model justifying these conditions. From the equation of model 5, it can be reported that the monthly average daily extra-terrestrial solar radiation correlates with sunshine duration through a combination of linear and exponential relation. Scatter plots of estimated and

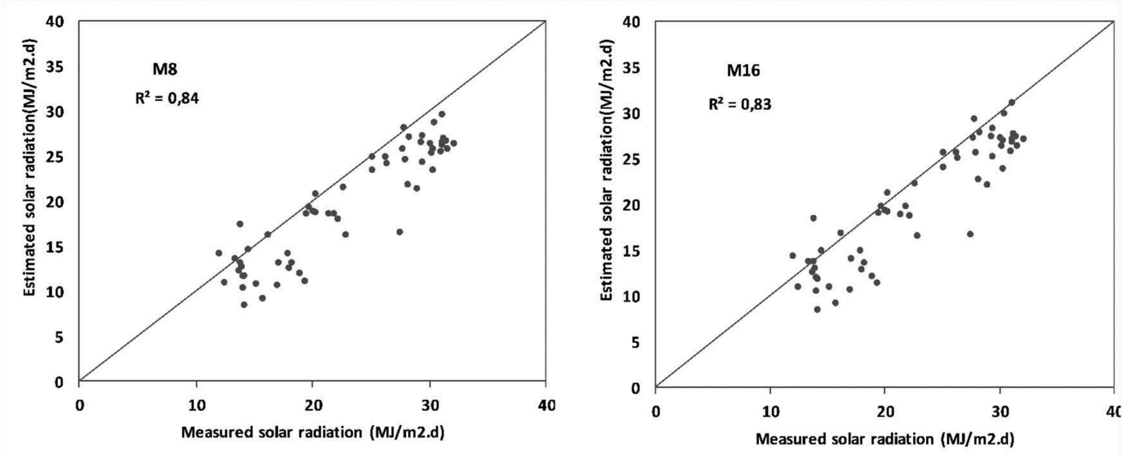

Figure 3. Scatter plots of estimated versus measured GSR of the best both linear and non-linear models.

Table 3. Statistical results of the locally calibrated global radiation models.

Models	Equations	MBE	RMSE	RRMSE%	R^2	GPI	Rank
1	$G/G_o = 0.663 + 0.080S_f$	−0.056	2.402	10.538	0.831	−0,293	5
Non-linear models							
2	$G/G_o = 0.977 - 0.861S_f + 0.680{S_f}^2$	−0.023	2.369	10.403	0.839	0,670	2
3	$G/G_o = 1.572 - 3.683S_f + 4.938{S_f}^2 - 2.07{S_f}^3$	0.028	2.464	10.808	0.838	−2,004	7
4	$G/G_o = 0.628 + 0.045exp(S_f)$	−0.058	2.402	10.538	0.833	−0,103	4
5	$G/G_o = 0.249 - 1.264S_f + 0.668\exp(S_f)$	−0.024	2.369	10.402	0.839	0,684	1
6	$G/G_o = 0.736 + 0.042\ln(S_f)$	−0.052	2.398	10.522	0.828	−0,508	6
7	$G/G_o = -0.58 + 1.398S_f - 0.878\ln(S_f)$	−0.016	2.380	10.446	0.840	0,450	3

measured global solar radiation show good agreement as depicted in Figure 4 for the two developed models.

5.3. Application on test cities

In this section, the advanced good models are verified for accuracy against selected Algerian Big South Desert sites (see Table 4). The results of various statistical indicators for the selected models are shown in Table 5. Some studies undertaken in other desert arid climates Algeria were also selected from literature to estimates global solar radiation on horizontal surfaces for the comparison with the proposed models in Table 3.

In the calculation conducted for the selected cities in the Algerian big southern desert, it was found that the two best models described in sections5.1 and 5.2 (no5 and M16) show the minimum root mean square error (RMSE) and they have maximum R^2, while the three nominated models described in Table 4 show the

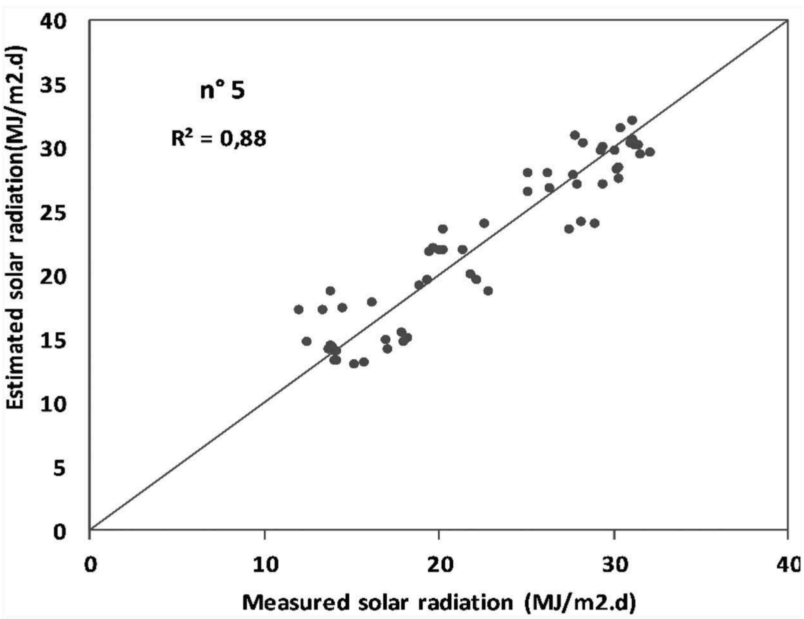

Figure 4. Scatter plots of estimated versus measured GSR of the best selected model.

Table 4. The functional form and the regression coefficients of the three nominated models.

No.	Station	Regression constants $G/G_o = a_1 + a_2S_f + a_2S_f^2 + a_4S_f^3$				Accuracy	Ref
		a_1	a_2	a_3	a_4		
N-1	General-Algeria	0.57211	0.00901	0.00028	−0.00002	$R^2 < 0.69$	(Mecibah et al. 2014)
N-2	Tamanrasset	−1.806	8.705	−10.03	−3.848	$R^2 = 0.718$	
N-3	Ghardaia	8.097	−28.62	36.47	−15.32	$R^2 = 0.726$	

Table 5. The statistical indicators for the test of the best and nominated models of Adrar and Tamanrasset located in the Algerian big southern desert.

Stations	Model #	MBE	RMSE	RRMSE%	R^2	GPI	Rank
	5	0.237	2.303	10.081	0.879	0.054	1
Study site	N-1	4.793	5.459	23.894	0.875	0.038	2
	N-2	<-20	>20	>30	0.791	−0.291	4
	N-3	0.14	4.204	18.397	0.625	−0.946	5
	M16	2.728	3.895	17.047	0.827	0.000	3
	5	−1.062	1.696	7.332	0.907	0.465	1
	N-1	3.749	4.002	17.303	0.868	0.271	2
Tamanrasset	N-2	<-20	>20	>30	0.781	−0.166	4
	N-3	−0.521	2.715	11.739	0.707	−0.535	5
	M16	−0.999	2.441	10.556	0.814	0.000	3
	5	−1.417	1.599	7.305	0.985	0.312	1
Adrar	N-1	3.217	3.386	15.469	0.971	0.000	3
	N-2	<-20	>20	>30	0.941	−0.688	5
	N-3	−0.525	0.916	4.185	0.98	0.206	2
	M16	−1.297	1.855	8.476	0.948	−0.509	4

maximum root mean square error (RMSE) and the minimum R^2 in all sites. Generally, the developed model (no5) had convergent results in all regions under study. From Table 5 and using the Global Performance Indicator (GPI), the following results can be obtained:

(1) The Model M16 swings equally between the three tested cities from the third to the fourth rank.
(2) N-1 swings between the second and the third rank of the three tested cities.
(3) The Model N-2 remains in the fourth rank in all of the tested cities.
(4) The Model no5 is superior to the other models in all of the tested sites, and can be used to determine the global solar radiation in any place of the Big Southern Desert.

6. Conclusion

New models for predicting the global solar radiation on a horizontal surface from bright sunshine hours in Becharregion of South-West Algeria are established according to the measured and calculated data recorded in locations under study. The statistical performances of these models in comparison with the performances of other candidate models from the literature show the superiority of the established models. The best model was selected according to the values of Global Performance Indicator (GPI). It is worth noting that for each site, the model no5 is superior to all other tested models. The correlation coefficients of this model illustrated very high values (approximately 0.9). On the other hand, the root mean squares showed a very low value (less than one). It was concluded that the models obtained in this study are believed to offer some insights for solar energy researchers about solar resource and can be used for the Algerian big southern desert for implementing futuristic solar energy projects.

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No potential conflict of interest was reported by the authors.

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