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Simplified Independent Model for Predicting Global Solar Radiation

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Abstract

In this investigation, five existing independent empirical models were calibrated and evaluated to calculate daily and monthly mean global solar radiation on a horizontal surface in Adrar city located in the south of Algeria, using meteorological data measured from 2013 to 2018. The measured data were divided into two periods; the first period (2015-2018) was used to calculate the empirical coefficients of the models, while the second period (2013-2014) was used to validate the correlations. Additionally, the best model (Al-Salaymeh model) was compared with five dependent empirical extreme air temperature models. In general, the results show that dependent models exhibited privileged performance than independent models. However, Al-Salaymeh regression independent model can contend with regression dependent models. Because of they use only the day number as a key input with smaller relative errors. It is found that daily statistical tests mean absolute bias error, root mean square error and coefficient of determination were equal to 2.0117 MJ/m², 2.4612 MJ/m² and 0.8014 respectively. The best independent empirical model was also compared with the modified Algerian solar atlas model to show their effectiveness. As a conclusion, the simple independent models can satisfactorily describe the horizontal global solar radiation for Adrar.

Keywords: Adrar, day number, empirical model, global radiation, independent model

1. Introduction

Weather data information especially global solar radiation is crucial when simulating solar and building energy systems. According to Besharat, Dehghan, & Faghih (2013) many approaches artificial intelligence, statistical, satellite, empirical and theoretical models have been proposed in several studies to estimate global solar radiation around the word. It was shown from the literature that, because of their complicatedness some journal papers were developed for estimating solar radiation using Artificial intelligence, statistical and satellite models in Algeria. The Artificial Bayesian Neural Network (BNN) method has been employed by Yacef, Mellit, Belaid, & Sen (2014) and a statistical Support Vector Machine (SVM) method was used by Belaid and Mellit (2016) in Ghardaïa town. In other works, Artificial Neural Network (ANN), hybrid models (ANN + Markov transition matrices), (ANN + wavelet theory) and Adaptive Neuro-Fuzzy Inference System (ANFIS) were used by (Benghanem, Mellit, & Alamri, 2009; Mellit, Benghanem, Hadj Arab, & Guessoum, 2005; Mellit, Benghanem, & Kalogirou ,2006; Mellit, Kalogirou, Shaari,Salhi, & Hadj Arab, 2008) to obtain global solar radiation in isolated sites. Based on the exponential probability distribution, Angstrom equation and beta probability distribution Mefti, Bouroubi, & Adane (2003) have calculated the global solar radiation on an inclined surface over Algeria. In another work, Mefti, Adane, & Bouroubi (2008) used a satellite approach based on cloud cover classification.

Dependent empirical techniques are widely used in Algeria for solar radiation estimation. These models are based on the different meteorological parameters such as sunshine duration, air temperature and clearness index. Boukelia, Mecibah, Meriche (2014) and Bailek, Bouchouicha, Al-Mostafa,Mohamed, & Nouar (2018) tested many empirical models based sunshine duration for predicting monthly diffuse solar radiation in Algeria, the quadratic formula was selected as the best correlation. Based on sunshine duration, global solar radiation was estimated in many Algerian locations by (Chegaar and Chibani , 2001; Koussa, Malek, & Haddadi.,2009; Mecibah, Boukelia, Reda,& Gairaa,2014). The authors observed that sunshine models appear to be more suitable than air temperature models.

When the meteorological measurement stations are not available, the alternatives are theoretical and empirical independent models. The inputs of the theoretical models are the astronomical, atmospheric and geographical parameters. The first theoretical model was suggested by Capderou (1987), thereafter many researches (Gairaa, Benkaciali, & Guermoui, 2019; Marif, Chiba, Belhadj, Zerrouki, & Benhammou, 2018; Behar, Khellaf, & Mohammedi ,2015) were recorded about the assessment of theoretical models in Algeria. The previous models are limited by their complexity, independent models are relatively easy. Hassan, Khalil, Kaseb, & Kassem (2018) confirmed that these models have a good estimation of global solar radiation. The objectives of the present study are to: (1) development of five commonly applied independent empirical models for the first time in Adrar region and (2) assess the best model using three statistical indicators and compare it with other models.

2. Methodology

2.1 Dataset and Empirical Models

The data employed in this investigation have been recorded at the Research Unit in Renewable Energies in the Saharan Medium station located in Adrar (North 27°53’, East 0° 17’ and 264 m). The global solar radiation and ambient temperature measurements were recorded using a calibrated CMP21 pyranometer (Kipp & Zonen) and Campbell Scientific CS215 probe respectively (see Figure 1).

Figure 2 illustrates the correlation between daily global solar radiation and extraterrestrial horizontal radiation, declination angle and day number during the period 2015 to 2018 for Adrar location. It is obviously shown that there is sinusoidal or polynomial relation between global radiation and day number. Furthermore, global radiation semi-linear behavior has been observed throughout the year, as a function of extraterrestrial horizontal radiation and declination angle.

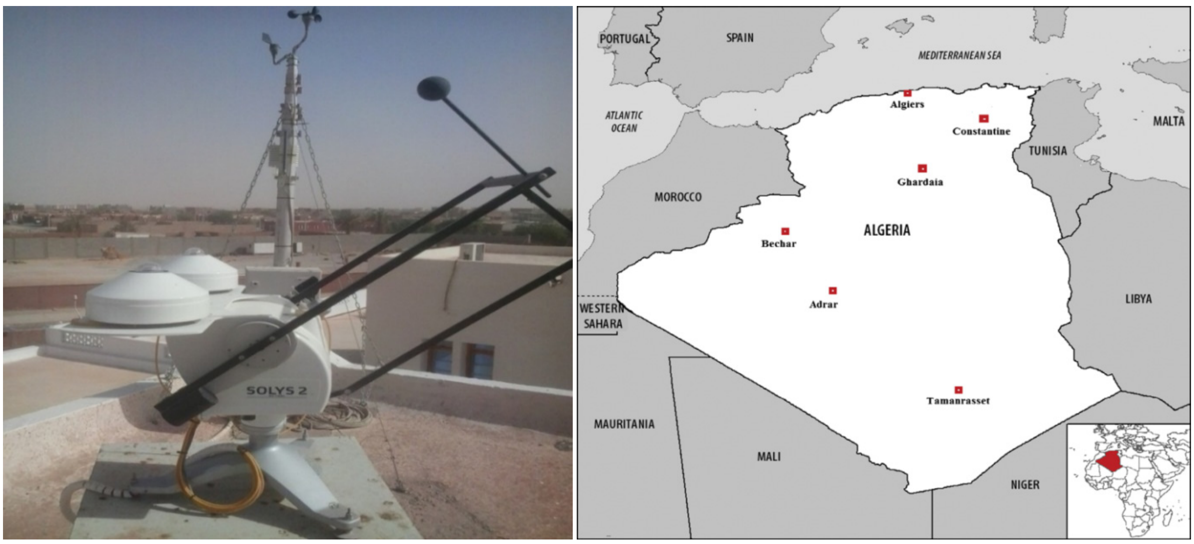

Figure 1. Geographical Location of Adrar (Right Part) and NEAL Station Instruments (Left Part)

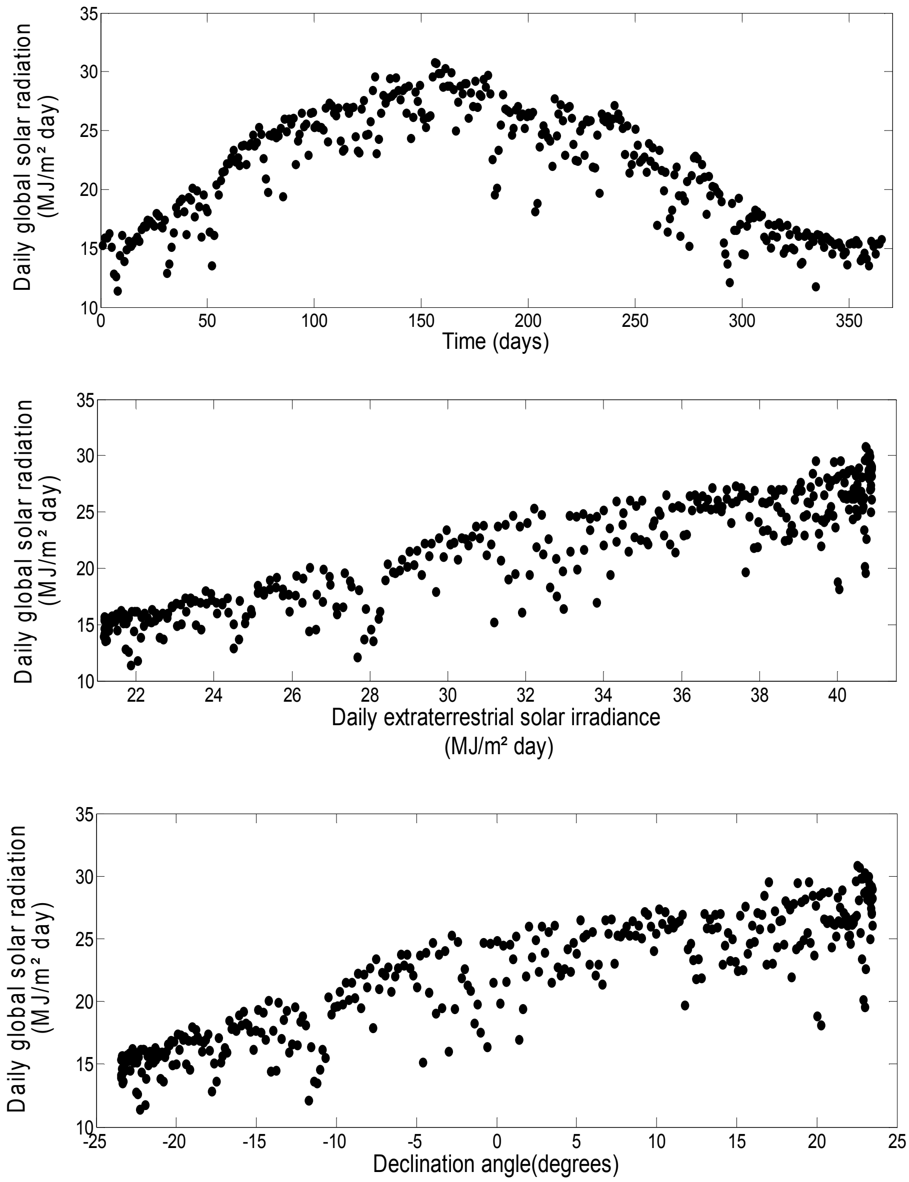

Figure 2. Correlation between Global Radiation and Day Number, Extraterrestrial Irradiation and Declination Angle

The extraterrestrial daily radiation H_0 can be determined by the following formula:

$$H_0 = \frac{24\times 3600\ I_0}{\pi}\left(cos\varphi\ \ sin\delta\ \ sin\omega_s + \frac{\pi\omega_s}{180} sin\varphi\ \ sin\delta\right) \quad (1)$$

Where I_0 is the sun constant (1367W/m²), φ is the site latitude (in degree) and ω_s is the sun set hour angle (in degree). The declination angle δ is depends on the day number N, the value of δ and ω_s are given by:

$$\delta = 23.45\ \ sin\left(\frac{360}{365}(N + 284)\right) \quad (2)$$

$$\omega_s = cos^{-1}(-tan\varphi\ \ tan\delta) \quad (3)$$

In this study, the performances of five independent models are evaluated. The best model is compared with five simple air temperature based models and modified Algerian solar atlas model proposed by Marif et al. (2018) (Table 1):

Table 1. Empirical models used in the paper

ID	Author	Equation
M1	Ertekin and Yaldiz (1999)	$H = a + b\delta$
M2	Togrul and Onut (1999)	$H = a + b\ \sin(\delta)$
M3	Togrul and Onut (1999)	$H = a + bH_0$
M4	Bulut and Buyukalaca (2007)	$H = a + (b - a)\ \left\|\sin(\frac{\pi}{365}(N+5))\right\|^{1.5}$
M5	Al-Salaymeh (2006)	$H = a + bN + cN^2 + dN^3 + eN^4$
T1	Richardson (2018)	$\frac{H}{H_0} = a(\Delta T)^b$
T2	Hargreaves and Riley. (1985)	$\frac{H}{H_0} = a + b\sqrt{\Delta T}$
T3	Chen, Kang, &Yang (2004)	$\frac{H}{H_0} = a\ \ + b\ \ ln(\Delta T)$
T4	Sarkar and Sifat (2016)	$\frac{H}{H_0} = a + b(\Delta T) + c\ \ (\Delta T)^2$
T5	Jahani, Dinpashoh, & Raisi Nafchi (2017)	$\frac{H}{H_0} = a\ \ + b\Delta T + c(\Delta T)^2 + d(\Delta T)^3$

2.2 Determination of Empirical Coefficients

The empirical coefficients of the models have been determined using the method proposed by Ozoegwu (2018). The coefficients column vector of any models (*X*) is the solution of linear system of equations. If there are *k* coefficients and *N* (365) measurements data points, the system can by written as flow:

$$AX = B \Rightarrow \begin{pmatrix} 1 & a_{11} & a_{12} \cdots & a_{1(k-1)} \\ 1 & a_{21} & a_{22} \cdots & a_{2(k-1)} \\ 1 & \vdots & \vdots \ \ldots. & \vdots \\ \vdots & & \ldots\ldots. \quad \ldots. & \vdots \\ 1 & a_{N1} \ldots a_{N2}.. & & a_{N(k-1)} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_k \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ \vdots \\ b_N \end{pmatrix} \tag{4}$$

A is k-by-N matrix, the multiplication of the both sides by the transposition matrix A^T can give a new system with k-by-k matrix identity (A^TA) and (A^TB) *k* vector dimension:

$$(A^T A)X = A^T B \tag{5}$$

The solution of the linear system is given by:

$$X = (A^T A)^{-1} A^T B \tag{6}$$

The series of obtained matrix and vectors elements for the ten selected models are reported in Table 2. In addition, experimental data of the second period (2015 to 2018) are used to calculate the newly empirical coefficients (see Table 3).

Table 2. Matrix and vectors elements

Model ID	k	Matrix and vectors elements for j=1,2,………..N
M1	2	$X = (a, b), B = H_j \quad and \quad a_{j1} = \delta_j$
M2	2	$X = (a, b), B = H_j \quad and \quad a_{j1} = \sin(\delta_j)$
M3	2	$X = (a, b), B = H_j \quad and \quad a_{j1} = H_{0j}$
M4	2	$X = (a, b - a), B = H_j \quad and \quad a_{j1} = \left\lvert \sin(\frac{\pi}{365}(j+5)) \right\rvert^{1.5}$
M5	5	$X = (a, b, c, d, e), B = H_j, \quad a_{j1} = j,$ $a_{j2} = j^2, a_{j3} = j^3 \quad and \quad a_{j3} = j^4$
T1	2	$X = (\ln(a), b), B = \ln(H_j/H_{0j})$ $and \quad a_{j1} = \ln(\Delta T_j)$
T2	2	$X = (a, b), B = (H_j/H_{0j}) \quad and \quad a_{j1} = \sqrt{\Delta T_j}$
T3	2	$X = (a, b), B = (H_j/H_{0j}) \quad and \quad a_{j1} = \ln(\Delta T_j)$
T4	3	$X = (a, b, c), B = (H_j/H_{0j}), a_{j1} = \Delta T_j$ $and \quad a_{j2} = (\Delta T_j)^2$
T5	4	$X = (a, b, c, d), B = (H_j/H_{0j}), a_{j1} = \Delta T_j,$ $a_{j2} = (\Delta T_j)^2 \quad and \quad , a_{j3} = (\Delta T_j)^3$

3. Result and Discussion

Using measured data covering the period 2013 to 2014, the developed models performance is assessed by calculating the daily and monthly average of tree statistical tests, mean absolute bias error (MABE), root mean square error (RMSE) and coefficient of determination (R^2). MABE and RMSE provide message about the long-term performance of the modeled regression equations and the short-term performance respectively. R^2 identify how well measured values are replicated by a model, higher values mean better performance.

$$MABE = \frac{1}{N}\sum_{i=1}^{N} \left|\left(H_i - \widehat{H}_i\right)\right| \tag{7}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(H - \widehat{H}_i\right)^2} \tag{8}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(H - \widehat{H}_i)^2}{\sum_{i=1}^{N}(\widehat{H}_i - \widehat{H}_m)^2} \tag{9}$$

Where $H_i$the ith estimated global radiation by the empirical models, $\widehat{H}_i$ is the ith measured value, $\widehat{H}_m$ is the mean measured value.

The series of obtained daily statistical tests for the empirical models are reported in Table 3. From wish it can be seen that independent models give a suitable fitting between the daily global radiation and day number. RMSE varies from 2.4612 to 2.6432 MJ/m², MABE varies from 2.0117 to 2.1112 MJ/m². The variation range of R^2 is between the minimum of 0.7572 (M4 model) and the maximum of 0.8014 in the case of Al-Salaymeh model (M5) wish is the best independent model. In addition, it is clear that air temperature models gives fairly close results. RMSE varies from 2.0443 to 2.4067 MJ/m², MABE varies from 1.5519 to 1.6472 MJ/m² and the best model (T3) had the highest rate of R^2 equal to 0.863.

Figure 3 show the comparison between experimental global solar radiation data and best estimated results for the two model categories independent (M5) and dependent (T3). It is clear that the model with extreme air temperature is an input has superior performance with highest fluctuation along the year compared to the independent model.

However, T5 model can be eliminated from the discussion because of their high values of MABE and RMSE and low R^2.

Table 3. Regression coefficients and statistical results for Adrar

Model ID	a	b	c	d	e	MABE (MJ/m^2day)	RMSE (MJ/m^2day)	R^2
M1	21.642	0.267	-	-	-	2.1112	2.6432	0.7709
M2	21.642	15.656	-	-	-	2.115	2.6435	0.7709
M3	1.1748	0.636	-	-	-	2.0497	2.5277	0.7905
M4	27.373	14.454	-	-	-	2.1517	2.7214	0.7572
M5	13.505	0.1210	$3.64x\ 10^{-4}$	$-4.9x10^{-6}$	$8.29x10^{-9}$	2.0117	2.4612	0.8014
T1	0.3124	0.2942		-	-	1.5639	2.0487	0.8624
T2	0.3040	0.1008	-	-	-	1.5519	2.0477	0.8625
T3	0.2063	0.1 801	-	-	-	1.5594	2.0443	0.863
T4	0.7730	-0.0296	0.0016		-	1.6472	2.4067	0.8101
T5	2.3559	-0.3955	0.0294	$6.93x10^{-4}$	-	1.8758	4.0310	0.4673

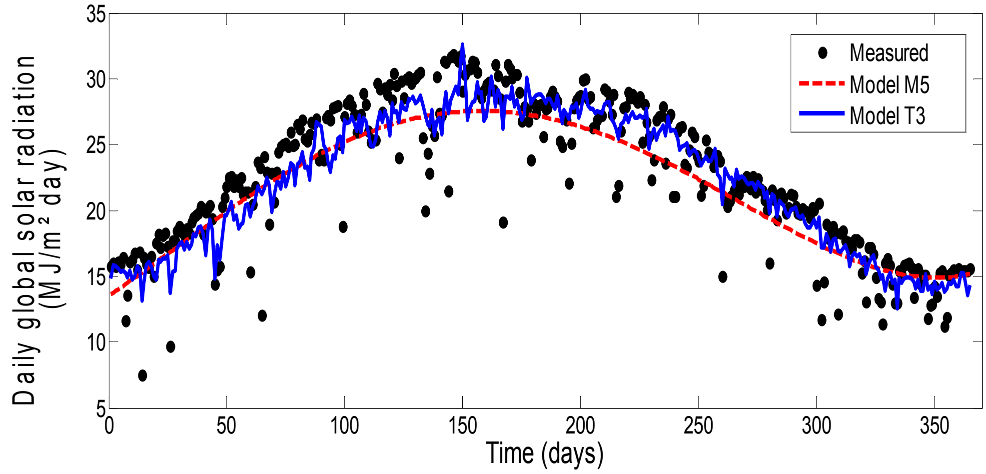

Figure 3. Daily global solar radiation comparison

Figure 4 present the monthly average global radiation values of the best independent model and modified Algerian solar atlas model. For Al-Salaymeh model (M5), it is found that monthly statistical tests MABE, RMSE and R^2 are equal to 1.0288 MJ/m^2, 1.2831 MJ/m^2 and 0.9336. Compared to modified solar Atlas model MABE, RMSE and R^2 are equal to 1.962 MJ/m^2 , 2.0817 MJ/m^2 and 0.8252. It is clear that the last model overestimate the monthly mean global radiation. The full agreement shows that M5 model is suitable for the estimation of the monthly mean global solar radiation under Adrar climates conditions. The maximum deviation observed during July can be explained considering the data quality in this month.

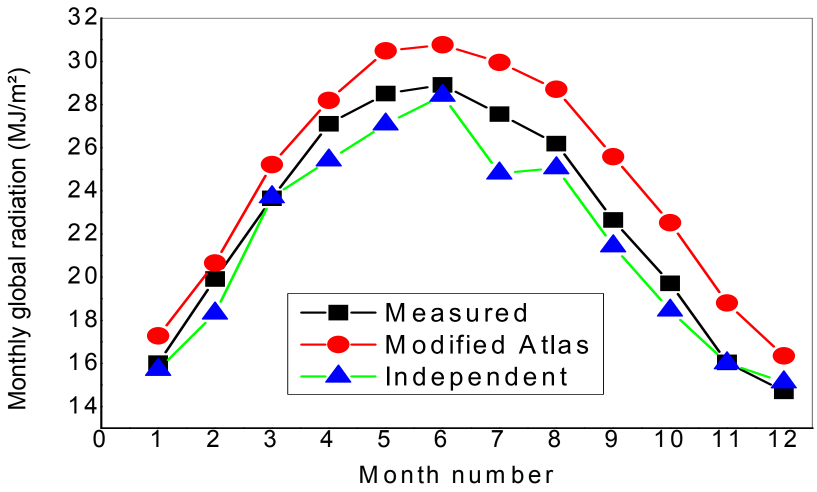

Figure 4. Monthly global solar radiation comparison

4. Conclusions

A relation between global radiation and day number, extraterrestrial horizontal radiation and declination angle can be obtained using independent empirical models. In this study five independent and air temperature based models are nominated from the literature, new empirical constants for these models have been obtained using simple method. After evaluating these models with tree statistical parameters, the results show that independent models are classed after dependent extreme air temperature models. Though, best independent empirical model is at the same accuracy level with the quadratic extreme temperature model and high accuracy level than the theoretical modified solar Atlas model. Consequently, this contribution can be helpful for students, engineers and researchers in order to estimate global solar radiation if solar radiation data are not available in Adrar, especially those who are experts in photovoltaic technologies and building thermal performance.

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