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Sunshine and Temperature Based Models for Estimating Global Solar Radiation in Maiduguri, Nigeria

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Abstract

Nine existing sunshine based models and three existing temperature based models were evaluated and compared to ascertain the most suitable models for estimating global solar radiation in Maiduguri; the most suitable sunshine based and most suitable temperature based models were also compared. The measured monthly average daily global solar radiation, sunshine hours, maximum and minimum temperature meteorological parameters during the period of thirty one years (1980 – 2010) was utilized and the evaluated models were tested statistically using validation indicators of coefficient of determination, Mean Bias Error, Root Mean Square Error, Mean Percentage Error, t – test, Nash – Sutcliffe Equation and Index of Agreement. The results indicated that the linear exponential sunshine based model and the logarithmic temperature based model were found more accurate for global solar radiation estimation in Maiduguri as compared to other evaluated models. Furthermore, the logarithmic temperature based model was found more accurate for estimating global solar radiation as compared to the linear exponential sunshine based model, and this was testified from the figure showing the comparison between the recommended sunshine based and temperature based models in which the recommended temperature based model depicts the best fitting with the measured global solar radiation data.

Keywords: global solar radiation, meteorological parameters, sunshine based models, temperature based models, validation indicators.

1. INTRODUCTION

The Sun is the source of energy that drives the cycle of life and death on earth. It is also the energy source that gives us warmth, evaporates water and melts snow. Thus, solar radiation is a key parameter for our understanding of the climate system, and the processes and interactions taking place within it [1]. Solar radiation data are essential for designing solar energy devices. However, the measurement of solar radiation is not easily available due to the cost and techniques involved [2]. The limited coverage of the measurement indicates that there is a need to establish theoretical methods for estimating solar radiation. Among the methods developed, those based on empirical correlations using commonly measured meteorological elements have attracted great attention owing to lower data requirement and computation cost [3]. The widely used correlations for estimating solar radiation are mainly based on sunshine duration and air temperature. In fact, the models estimating solar radiation from sunshine duration are generally more accurate than those involving other meteorological observations [4 – 6].

On a contrary, in the study carried out by Ogolo [7], he found that the temperature dependent models are more suitable for estimating global solar radiation in the sahelian and coastal region of Nigeria, except in the Midland and Guinea savannah where the sunshine dependent models are more suitable. [8] has also attest to the fact that the sunshine dependent models was found more suitable for estimating global solar radiation in the Guinea savannah climatic zone of Nigeria when compared to the temperature dependent models. However, sunshine duration is not as readily available as air temperature data at standard meteorological stations [9 – 10]. So, it is meaningful to elaborate models that estimate solar radiation based on air temperature as an alternative [11].

Several models have been proposed to estimate global solar radiation in Nigeria. Gana and Akpootu [12] compared four sunshine based models, the Ångström - Prescott [13], Ogelman et al. [14], El-Metwally [15] and Bakirci [16] to estimate global solar radiation in Kebbi. The result in their study revealed that model 2 (quadratic equation) which is an empirical regression equation based on Ogelman et al. [14] performed better. In another study, Gana and Akpootu [17] developed Ångström type empirical models for estimating global solar radiation for six locations situated across the North – Eastern part of Nigeria. The Ångström type models employed are based on Ångström - Prescott [13], Ogelman et al. [14] and Samuel [18]. Their results showed that various sunshine based models can be used to estimate global solar radiation in North – Eastern, Nigeria. Akpootu and Momoh [19] compared three sunshine based models for estimating global solar radiation in Makurdi. The models are linear proposed by Ångström [20] and Prescott [13]; Quadratic proposed by Akinoglu and Ecevit [21]; Cubic proposed by Samuel [18]. According to them, the developed empirical model based on modified Ångström-Prescott model could be accurately used with high degree of confidence to estimate the monthly average daily global solar radiation in Makurdi, Nigeria and regions of similar climatic conditions. Akpootu and Sulu [22] investigated the most suitable models for estimating global solar radiation in Zaria based on twelve existing sunshine based models; five different validation indices were used to ascertain the suitability of the recommended models.

Akpootu and Sanusi [23] developed new temperature based model for estimating global solar radiation in Portharcourt. The empirical model developed is a multivariate temperature based model that contains the differences in temperature and temperature ratio terms. More recently Akpootu et al. [8]; Akpootu et al. [24] and Akpootu et al. [25] developed new sunshine and temperature based models for global solar radiation estimation in some locations situated across the climatic zones in Nigeria. Other studies include that of Falayi et al. [26], Adedayo [27] to mention but a few.

The purpose of this study is to (i) evaluate and compare nine different existing sunshine dependent models to ascertain the most suitable model for estimating global solar radiation in Maiduguri (ii) compare three different existing temperature dependent models to ascertain the most suitable model for estimating global solar radiation in Maiduguri (iii) compare the most suitable sunshine and temperature dependent model with a view to find out which is more suitable for global solar radiation estimation in Maiduguri situated in the Sahelian climatic zone of Nigeria.

2. METHODOLOGY

2.1 Acquisition of data

The World Meteorological Organization [28] also in Ojo and Adeyemi [29] mentioned that optimal climate modeling can be achieved when data series extends beyond thirty years long. Based on this, the measured monthly average daily global solar radiation, sunshine hour, maximum and minimum temperatures meteorological data during the period of thirty one years (1980-2010) was used in this study. The meteorological data were obtained from the Nigerian Meteorological Agency (NIMET), Oshodi, Lagos, Nigeria. Twenty five (25) (1980- 2004) years data was used for developing the sunshine and temperature based models while six (6) years (2005-2010) data was used for validation of the models. This study adopted same method used by Akpootu and Abdullahi [30] and Akpootu et al. [31] where approximately 80.65% of the total years of the data were used for the development of models and 19.35% for validation of models. Olaniran [32] has reported that Nigeria is classified into four climatic zones; these are the Coastal zone, Guinea savannah zone, Midland zone and the Sahelian zone. The location under investigation is Maiduguri which is within the Sahelian climatic zone of Nigeria.

2.2 Regression analysis

The monthly average daily extraterrestrial radiation on a horizontal surface (H_o) was calculated using the equation [33]:

$$H_o = \left(\frac{24}{\pi}\right) I_{sc}\left[1 + 0.033cos\left(\frac{360n}{365}\right)\right]\left[cos\chi cos\psi sinh_s + \left(\frac{2\pi\omega_s}{360}\right) sin\chi sin\psi\right] \quad (1)$$

where I_{sc} is the solar constant (=1367 Wm^{-2}) as given in [34], φ is the latitude of the site, ψ is the solar declination and h_s is the mean sunrise hour angle for the given month and n is the number of days of the year starting from 1^{st} of January to 31^{st} of December. The solar declination, ψ and the mean sunrise hour angle, h_s was estimated using the equations

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

$$h_s = cos^{-1}(-tan\chi tan\psi) \quad (3)$$

For a given month, the maximum possible sunshine duration, monthly average day length (S_o) in hours can be computed equations [33] by

$$S_o = \frac{2}{15}h_s \quad (4)$$

The clearness index (C_i) was obtained using the equation [26]

$$C_i = \frac{H_m}{H_o} \quad (5)$$

where H_m is the measured global solar radiation.

2.3 Validation of the models

The estimated values of the models were statistically tested by calculating the Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), t-test, Nash-Sutcliffe equation (NSE) and the Index of Agreement (IA). Also, the coefficient of determination (R^2) was determined for each of the models through the regression analysis with Minitab 16.0 software. The expressions according to El-Sebaii and Trabea [35] are given as follows.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(H_{i,cal} - H_{i,mea}\right) \quad (6)$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(H_{i,cal} - H_{i,mea}\right)^2\right]^{\frac{1}{2}} \quad (7)$$

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{H_{i,mea}-H_{i,cal}}{H_{i,mea}}\right) \times 100 \quad (8)$$

The t-test according to Bevington [36] is given as.

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2-(MBE)^2}\right]^{\frac{1}{2}} \quad (9)$$

The detailed descriptions of the t – test validation is found in Akpootu et al. [8].

The Nash-Sutcliffe equation (NSE) is given by the expression

$$NSE = 1 - \frac{\sum_1^n\left(H_{i,mea}-H_{i,cal}\right)^2}{\sum_1^n\left(H_{i,mea}-\bar{H}_{i,meas}\right)^2} \quad (10)$$

The Index of Agreement (IA) is given as [37]

$$IA = 1 - \frac{\sum_{i=1}^{n}\left(H_{i,cal}-H_{i,mea}\right)^2}{\sum_{i=1}^{n}\left(\left|H_{i,cal}-\bar{H}_{i,mea}\right|+\left|H_{i,mea}-\bar{H}_{i,mea}\right|\right)^2} \quad (11)$$

The equations from (6) – (11), $H_{i,mea}$, $H_{i,cal}$ and n are respectively the i^{th} measured and i^{th} calculated values of daily global solar radiation and the total number of observations, also $\bar{H}_{i,mea}$ is the mean measured global solar radiation. [38 – 40] have suggested that a zero value for MBE is perfect. The smaller the value of the MBE, RMSE and MPE the better is the model's performance [41 – 42], similarly, is the t – test values. A negative and positive value of MPE and MBE signifies underestimation and overestimation respectively [43].

Merges et al. [44] proposed that the percentage error of ± 10 % is considered to be the best. A model is more efficient when is closer to 1 (100 %) [40]. Similarly, for better data modeling, the coefficient of determination. R^2, NSE and IA should approach 1 (100%) as closely as possible [42]. MBE and the RMSE are in $MJm^{-2}day^{-1}$, while R^2, MPE, NSE and IA are in percentage (%),t- test is non dimensional [25].

Table 1: Existing sunshine based regression models proposed in the literature

Model No.	Model Type	Regression equation	Source
1	Linear (Ångström)	$\frac{H}{H_o} = a + b\left(\frac{S}{S_o}\right)$	Ångström [20] and Prescott [13]
2	Quadratic	$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + c\left(\frac{S}{S_0}\right)^2$	Ogelman et al. [14]
3	Cubic	$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + c\left(\frac{S}{S_0}\right)^2 + d\left(\frac{S}{S_0}\right)^3$	Samuel [18]
4	Linear Logarithmic	$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + c\ \ln\left(\frac{S}{S_0}\right)$	Newland [45]
5	Logarithmic	$\frac{H}{H_0} = a + b\ \ln\left(\frac{S}{S_0}\right)$	Ampratwum and Dorvlo [46]
6	Linear Exponential	$\frac{H}{H_o} = a + b\left(\frac{S}{S_o}\right) + c\ exp\left(\frac{S}{S_o}\right)$	Kadir Bakirci [16]
7	Exponential	$\frac{H}{H_o} = a + b\ exp\left(\frac{S}{S_0}\right)$	Almorox and Hontoria [47]
8	Linear	$\frac{H}{H_0} = a + b\left(\frac{S}{S_{nh}}\right)$	Louche et al. [48]
9	Exponent	$\frac{H}{H_0} = a\left(\frac{S}{S_0}\right)^b$	Kadir Bakirci [16]

Model 8 was modified through the use of the ratio of $\left(\frac{S}{S_{nh}}\right)$ instead of $\left(\frac{S}{S_0}\right)$ by Louche et al. [48] and $\left(\frac{S}{S_{nh}}\right)$ is given by the relation: $\frac{1}{S_{nh}} = \frac{0.8706}{S_0} + 0.0003$

Table 2: Existing temperature based regression models proposed in literature

Model No.	Model Type	Regression equation	Source
1	Logarithmic	$\frac{H}{H_0} = a_2 + b_2 ln\Delta T$	Chen et al. [40]
2	Linear exponent	$\frac{H}{H_0} = a_3 + b_3 \Delta T^{0.5}$	Hargreaves and Samani [49]
3	Linear	$\frac{H}{H_0} = a_4 + b_4\left(\frac{\Delta T}{S_0}\right)$	Garcia [50]

In table 2, ΔT is the difference between the monthly average daily maximum and minimum temperatures, i.e., $T_{max} - T_{min}$. The constants a_2, a_3, a_4, b_2, b_3 *and* b_4 are empirical coefficients determined by regression techniques and are also known as the regression coefficients while the other terms are the correlated parameters. The three models are found to be the widely used temperature based models and are appropriate for different climatic conditions [25].

3. RESULTS AND DISCUSSION

3.1 Sunshine Based Models for Maiduguri

The global solar radiation can be estimated through the following evaluated existing sunshine based models.

$$\frac{H}{H_0} = 0.333 + 0.473\frac{S}{S_0} \qquad (12a)$$

$$\frac{H}{H_0} = -0.834 + 3.95\frac{S}{S_0} - 2.53\left(\frac{S}{S_0}\right)^2 \qquad (12b)$$

$$\frac{H}{H_0} = -0.11 + 0.7\frac{S}{S_0} + 2.4\left(\frac{S}{S_0}\right)^2 - 2.4\left(\frac{S}{S_0}\right)^3 \qquad (12c)$$

$$\frac{H}{H_0} = 3.45 - 2.82\frac{S}{S_0} + 2.22\ln\left(\frac{S}{S_0}\right) \qquad (12d)$$

$$\frac{H}{H_0} = 0.786 + 0.332\ln\left(\frac{S}{S_0}\right) \qquad (12e)$$

$$\frac{H}{H_0} = 1.95 + 5.59\frac{S}{S_0} - 2.57\exp\left(\frac{S}{S_0}\right) \qquad (12f)$$

$$\frac{H}{H_0} = 0.198 + 0.230\exp\left(\frac{S}{S_0}\right) \qquad (12g)$$

$$\frac{H}{H_0} = 0.332 + 0.542\frac{S}{Snh} \qquad (12h)$$

$$\frac{H}{H_0} = 0.804\left(\frac{S}{S_0}\right)^{0.532} \qquad (12i)$$

Table 3: Sunshine based models statistical error indices for Maiduguri

Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.12a	59.2	-0.0163	1.3809	-0.4035	0.0392	96.5194	99.0934
Eqn.12b	77.6	0.1154	1.0525	-0.7028	0.366	97.9782	99.494
Eqn.12c	77.7	1.4899	1.8245	-6.6933	4.6927	93.9243	98.7225
Eqn.12d	77.2	-0.0609	1.0578	0.0633	0.1912	97.9575	99.4767
Eqn.12e	64.1	-0.0212	1.2942	-0.3389	0.0543	96.943	99.2057
Eqn.12f	77.7	-0.0233	1.0455	-0.0999	0.0741	98.0049	99.4914
Eqn.12g	55.7	-0.0332	1.4414	-0.3564	0.0764	98.0049	99.0082
Eqn.12h	59.2	-0.0321	1.3813	-0.3343	0.0772	96.5178	99.0911
Eqn.12i	65.1	-0.0701	1.3381	-0.1436	0.1741	96.7321	99.144

In tables 3. Based on the R^2, the model, eqn.12c (cubic) and 12f (linear exponential) sunshine based model has the highest value with 77.77 %. The existing linear model eqn.12a (Ångström – Prescott) has the lowest MBE and t – test values with underestimation of 0.0163 $MJm^{-2}day^{-1}$ in its estimated value and 0.0392 respectively. The model eqn.12f (linear exponential) has the lowest RMSE value of 0.0455 $MJm^{-2}day^{-1}$. The model eqn.12d (linear logarithmic) has the lowest MPE value with overestimation of 0.0633 % in its estimated value. The model eqns.12f (linear exponential) and 12g (exponential) has the highest NSE value with 98.0049 %. The model eqn. 12b (quadratic) has the highest IA of 99.4940 %.

Table 4. Ranking of the determined sunshine based models for Maiduguri

Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total Rank
Eqn.12a	6	1	6	7	1	6	6	33
Eqn.12b	2	8	2	8	8	2	1	31
Eqn.12c	1	9	9	9	9	8	9	54
Eqn.12d	3	6	3	1	7	3	3	26
Eqn.12e	5	2	4	5	2	4	4	26
Eqn.12f	1	3	1	2	3	1	2	13
Eqn.12g	8	5	8	6	4	1	8	40
Eqn.12h	6	4	7	4	5	7	7	40
Eqn.12i	4	7	5	3	6	5	5	35

In tables 4. The ranks acquired by the models were in the range of 13 to 54. The results revealed that the existing linear exponential sunshine based model given in eqn. 12f as proposed by Bakirci [16] was found more accurate for estimating global solar radiation in Maiduguri as it has the lowest ranking value.

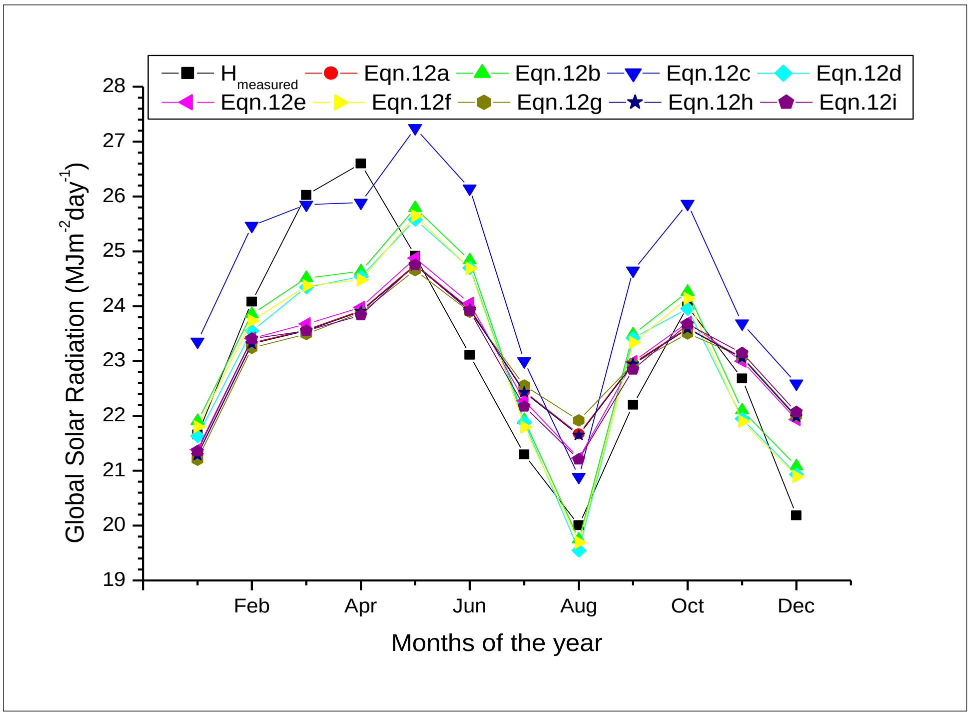

Figure 1: Comparison between the measured and estimated existing sunshine based global solar radiation models for Maiduguri. $H_{measured}$ – measured global solar radiation; Eqn.12a – linear (Angstrom); Eqn.12b – Quadratic; Eqn.12c – Cubic; Eqn.12d – Linear logarithmic; Eqn.12e – Logarithmic; Eqn.12f – Linear exponential; Eqn.12g – Exponential; Eqn.12h – Linear (Louche et al) ; Eqn.12i - Exponent

Figure 1 shows the comparison between the measured and estimated existing global solar radiation for Maiduguri based on the sunshine dependent models. It is obvious that the estimated existing models overestimated the measured global solar radiation in the months of June, July and September and December and underestimated the measured global solar radiation in the months of March and April. The figure revealed that the existing cubic model overestimated the measured and other estimated models in the months of January, February, May, June, July and September to December.

The 1st order Ångström type models results obtained for Maiduguri in this study were compared to that carried out by Adedayo [27]. The model equation with its empirical constants is given in equation 12a while the empirical constants given by Adedayo [27] are -0.122 and 4.709.

Table 5: Comparison of evaluated 1st order Ångström model for Maiduguri

Statistical indicators	In this study	Adedayo [27]
MBE ($MJm^{-2}day^{-1}$)	-0.0163	-5.9794
RMSE ($MJm^{-2}day^{-1}$)	1.3809	0.0294
MPE (%)	-0.4035	-
t-test	0.0392	-
R^2 (%)	59.2000	41.6000

This is evident that the model in this study performs better as shown in Table 5.

3.2 Temperature based models for maiduguri

The global solar radiation can be estimated through the following evaluated existing temperature based models.

$$\frac{H}{H_0} = 0.0574 + 0.224 \ln \Delta T \quad (13a)$$

$$\frac{H}{H_0} = 0.198 + 0.119 \, \mathrm{Sqrt} \, \Delta T \quad (13b)$$

$$\frac{H}{H_0} = 0.454 + 0.161 \frac{\Delta T}{S_0} \quad (13c)$$

Table 6: Temperature based models statistical error indices for Maiduguri

Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.13a	89.7	-0.0003	0.6470	-0.204	0.0018	99.2359	99.8056
Eqn.13b	87.6	-0.0586	0.7232	0.0218	0.2696	99.0455	99.7547
Eqn.13c	80.5	-0.0066	0.9236	-0.3005	0.0236	98.4432	99.5996

In tables 6. Based on the R^2, the model, eqn.13a (logarithmic) has the highest value with 89.7 %. The model, eqn.13a (logarithmic) also has the lowest MBE, RMSE and t – test values with underestimation of 0.0003 $MJm^{-2}day^{-1}$ in its estimated value, 0.6470 $MJm^{-2}day^{-1}$ and 0.0018 respectively. The model equation 13b (linear exponent) has the lowest MPE with overestimation of 0.0218 % in its predicted value. The model, eqn.13a (logarithmic) has the highest NSE and IA values with 99.2359 % and 99.8056 % respectively.

Table 7: Ranking of the determined temperature based models for Maiduguri

Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total Rank
Eqn.13a	1	1	1	2	1	1	1	8
Eqn.13b	2	3	2	1	3	2	2	15
Eqn.13c	3	2	3	3	2	3	3	19

In tables 7. The ranks acquired by the models were in the range of 8 to 19. The results revealed that the modified Chen et al. [40] temperature based model given in eqn.13a was found more accurate for estimating global solar radiation in Maiduguri as it has the lowest ranking value.

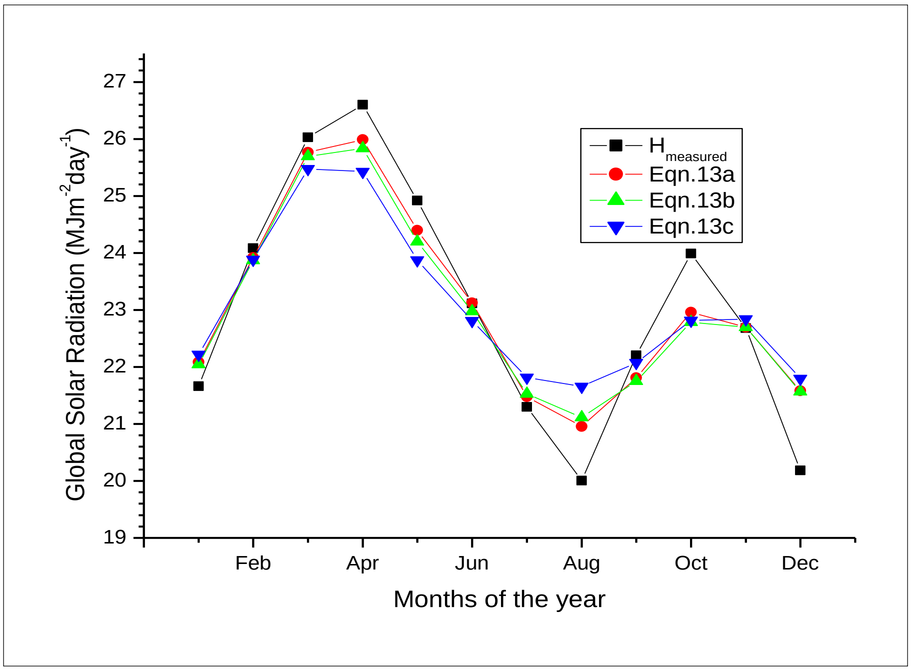

Figure 2: Comparison between the measured and estimated existing temperature based global solar radiation models for Maiduguri. $H_{measured}$ – measured global solar radiation; Eqn.13a – Logarithmic; Eqn.13b – Linear exponent; Eqn.13c – Linear

Figure 2 shows the comparison between the measured and estimated existing global solar radiation for Maiduguri based on temperature models. The evaluated existing models underestimated the measured global solar radiation in the months from February to May, September and October and overestimated the measured in January, July, August and December. The linear model proposed by Garcia [50] overestimated the measured and other models in January, July, August and December. The figure showed that the model (equation 13a) followed close pattern of variation with the measured data.

3.3 Comparison between the recommended sunshine and temperature based models for Maiduguri

Table 8: Comparison between the recommended Sunshine Based model (SBM) and Temperature Based Model (TBM) for Maiduguri

Models	Equation	R^2	MBE	RMSE	MPE	t	NSE	IA
SBM	Eqn.12f	77.7	-0.0233	1.0455	-0.0999	0.0741	98.0049	99.4914
TBM	Eqn.13a	89.7	-0.0003	0.647	-0.204	0.0018	99.2359	99.8056

Table 9: Ranking between the recommended Sunshine Based model (SBM) and Temperature Based Model (TBM) for Maiduguri

Models	Equation	R^2	MBE	RMSE	MPE	t	NSE	IA	Total	Best
SBM	Eqn.12f	2	2	2	1	2	2	2	13	
TBM	Eqn.13a	1	1	1	2	1	1	1	8	TBM

Tables (8 and 9) shows the comparison and ranking of the recommended sunshine based model (SBM) and temperature based model (TBM). The result shows that the temperature based model is more suitable for estimating global solar radiation in Maiduguri situated in the Sahelian region. This is in line with the result reported by Ogolo [7] where he reported that the temperature dependent models are more suitable for estimating global solar radiation in the Sahelian region.

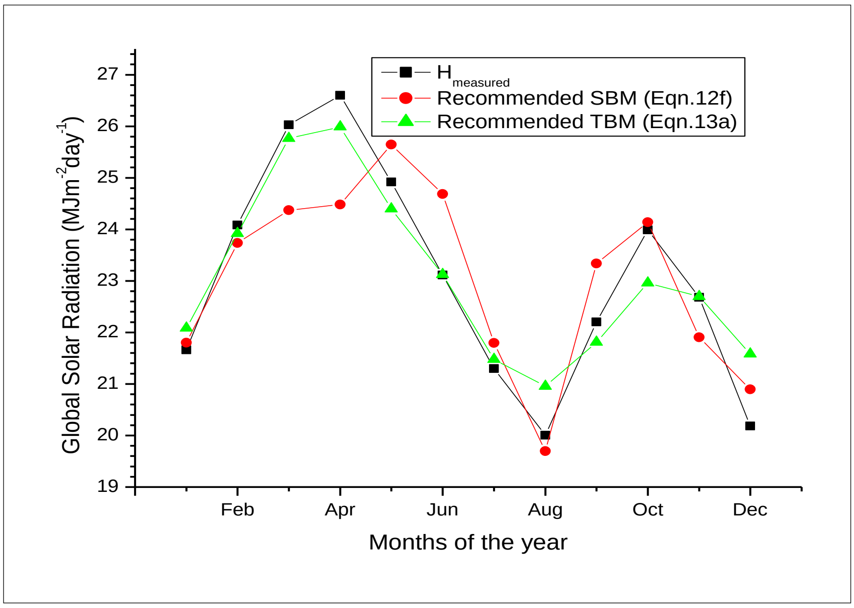

Figure 3: Comparison between the recommended sunshine based model and temperature based model for Maiduguri. $H_{measured}$ – measured global solar radiation; Eqn.12f – Linear exponential; Eqn.13a – Logarithmic

Figure 3 shows the comparison between the recommended sunshine based model and temperature based model for Maiduguri. The figure shows that all the recommended models underestimated the measured in the months from February to April and overestimated the measured in the months of July and December. There is a significant departure of the recommended sunshine model with the measured and recommended temperature based model in the months of March, April and June. Also, there is a significant departure of the recommended temperature model with the measured and recommended sunshine based model in the month of August. The figure revealed that the recommended temperature based model shows more close agreement with the measured values as compared to the recommended sunshine based model.

4. CONCLUSION

Prediction of global solar radiation from measured meteorological variables in any location around the world offers an important alternative in the absence of measured/observed global solar radiation. This study evaluated and compared nine different sunshine based models and three different temperature based models. The most suitable sunshine based model was compared with the most suitable temperature based model. The evaluated 1st order Ångström type sunshine based model was compared with that found in the literature. Seven validation indices were adopted to statistically test the evaluated models and were ranked with a view to recommend the most accurate model (s) for estimating global solar radiation in Maiduguri.

The results in this study revealed that the linear exponential developed empirical regression sunshine dependent model based on Bakirci was found more suitable for predicting global solar radiation in Maiduguri, also, the logarithmic developed empirical regression temperature dependent model based on Chen et al was found more suitable. Furthermore, the logarithmic empirical regression temperature dependent model based on Chen et al was found more accurate for global solar radiation prediction when compared to the linear exponential empirical regression sunshine dependent model based on Bakirci indicating that the temperature dependent models may be more accurate for predicting global solar radiation in the Sahelian region of Nigeria. The evaluated 1st order Ångström type sunshine based model in this study was found more suitable for estimating global solar radiation in the location when compared to that found in the literature. The evaluated models depicts good fittings with the measured global solar radiation data, however, the temperature dependent models depicts the best fittings.

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