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DEVELOPMENT OF SUNSHINE BASED MODELS FOR ESTIMATING GLOBAL SOLAR RADIATION OVER KANO AND IKEJA, NIGERIA

***[1]Akpootu, D. O. and [2]Abdullahi, Z.**

[1]Department of Physics, Usmanu Danfodiyo University, Sokoto, Nigeria
[2]Department of Physics, Adamu Augie College of Education, Kebbi State, Nigeria

*Corresponding authors' email: davidson.odafe@udusok.edu.ng; profdon03@yahoo.com

ABSTRACT

In this present study, three (3) new sunshine based models were developed and evaluated using observed monthly average daily global solar radiation and sunshine hours meteorological variables spanning through thirty one years (1980-2010). The estimated global solar radiation values obtained from the empirical regression models for the developed models and nine (9) distinctive existing sunshine based models were compared through validation indicators of Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), t – test, Nash – Sutcliffe Equation (NSE), Index of Agreement (IA) and coefficient of determination (R^2) allowing the identification and recommendation of the most accurate model suitable for the estimation of global solar radiation in Kano and Ikeja located in the Sahelian and Coastal regions respectively. The results in this present study revealed that the developed exponent exponential and quadratic latitude 2 sunshine based models were found more appropriate for estimation of global solar radiation in Kano (Latitude 12.05 $°N$ and Longitude 8.20 $°E$) and Ikeja (Latitude 6.58 $°N$ and Longitude 3.33 $°E$) respectively. The evaluated existing linear (1st order) and quadratic (2nd order) sunshine based models for Kano were found more suitable for the estimation of global solar radiation as compared with those found through literature survey. The empirical regression equations and the values of the validation indicators obtained in this study for each model varies significantly in each of the regions under investigation indicating that the twelve (12) sunshine based models are site – specific. The correlation between the sunshine based models (developed and existing) with the observed values revealed that the most suitable models showed a good agreement with the observed global solar radiation data.

Keywords: Coastal region, global solar radiation, meteorological parameters, Sahelian region, sunshine based models, validation indicators

INTRODUCTION

The electromagnetic radiation emitted from the Sun radiant form to the earth's surface is referred to as solar radiation (Akpootu *et al*., 2019a). Solar radiation is seen to be a safe, efficient, effective and economic energy resource with the capacity and tendency of being the major source of energy in the near future (Dincer, 2000). The technology used for the measurement of global solar radiation data is expensive and has the tendency for instrumental hazards when in use (Alam *et al*., 2005). Thus, proposing new effective methods for the estimation of these data are necessary. Global solar radiation data in most regions are not readily available, thus, it becomes desirable for specialist dealing with the design of solar energy system to be acquainted with the different models or methods used in the estimation of global solar radiation in order to determine accurately the amount available at any region based on the available meteorological variables (Olomiyesan and Oyedum, 2016). One of these methods employed is the use of empirical models.

Genuine and reliable information relating to the availability of global solar radiation is germane to agro/hydro meteorologists, atmospheric Physicists and solar energy engineers for local and international marketing, designs and manufacturing of solar equipment. The commonly used correlations for predicting global solar radiation are basically based on the sunshine duration and air temperature. In most cases, the models that employed the sunshine duration are generally more accurate than those relating other meteorological observations (Baigorria *et al.*, 2004; Rivington *et al.*, 2005).

Several models have been proposed to estimate global solar radiation. Ogolo (2010) used linear and polynomial regression methods to develop some models based on sunshine hours and temperature dependent to predict global solar radiation for Kano, Jos, Lokoja and Portharcourt covering the four different climatic zones in Nigeria. According to him, the sum of the coefficients 'a' and 'b' tends to increases from the Sahelian to the coastal region. Also, the 3rd order Ångström type model exhibited co – linearly with the 2nd order for Jos, Lokoja and Portharcourt. It was reported that the 3rd order Ångström type does not have much impact on the accuracies of the models. Gana and Akpootu (2013a) compared four existing sunshine based models for estimation of global solar radiation in Kebbi. The result in their study revealed that model 2 (quadratic equation) which is the empirical regression equation based on Ogelman et al. (1984) performed better. In another study, Gana and Akpootu (2013b) 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 three (3) existing sunshine based models. Four validation indices including the coefficient of determination and correlation coefficient were used to validate the models; the results showed that various sunshine based models can be used to estimate global solar radiation in North – Eastern part of Nigeria. Akpootu and Momoh (2014) compared three (3) sunshine based models for prediction of global solar radiation in Makurdi. The models are linear Ångström type, Quadratic proposed by Akinoglu and Ecevit (1990); Cubic proposed by Samuel (1991). According to them, the developed empirical model based on modified Ångström-Prescott model could be accurately used with high degree of confidence for global solar radiation prediction in Makurdi, Nigeria. Akpootu and Sulu (2015) investigated the most suitable models for the estimation of global solar radiation in Zaria based on twelve existing sunshine based models; five different validation indices were used to validate the reliability of the recommended models. Akpootu and Iliyasu (2015a) developed one to six variable correlation models to investigate the effect of some meteorological variables on the estimation of global solar radiation in Kano, North Western, Nigeria. According to them, the developed models were found suitable based on the six validation indices employed. Akpootu and Iliyasu (2015b) developed twenty empirical models based on three variable correlation models for estimating global solar radiation in Kano. According to them, the three equations with three different meteorological variables were recommended for the estimation of global solar radiation in Kano, North – Western, Nigeria. Also, Akpootu et al. (2019b) carried out a study to present the most accurate sunshine dependent and temperature dependent models for estimation of global solar radiation in Makurdi and Ibadan located in the Guinea savannah region of Nigeria, this was done by comparing nine (9) distinctive existing sunshine dependent models. Similarly, two (2) developed temperature dependent models were compared to three (3) existing temperature dependent models. According to them, the results in their study indicated that the existing exponent sunshine regression model and the existing linear exponential sunshine regression model based on Bakirci were found more accurate for estimation of global solar radiation in Makurdi and Ibadan respectively. The results in their study also showed that the developed quadratic logarithmic and quadratic exponential temperature dependent models were found more accurate for estimation of global solar radiation in Makurdi and Ibadan respectively.

Majority of the studies on global solar radiation estimation carried out in Nigeria are based on using only the Ångström type sunshine based models for prediction of global solar radiation which was acclaimed to be suitable in all climatic conditions and region across the world. Also, by comparing the various existing sunshine based models found in the literature. In this regard, there is need to carry out thorough investigation to find out if this universally accepted model is actually suitable for estimation of global solar radiation in all regions in Nigeria. The search for the most accurate models for estimating global solar radiation necessitated the need to develop new models and compare these models with the nine (9) most popular existing sunshine based models available in the literature, hence, the motivation for this study. This study evaluated and compared nine (9) distinctive sunshine based models with three (3) developed (new) sunshine based models, aimed at investigating the most accurate sunshine based model for estimating global solar radiation in Kano and Ikeja located across the Sahelian and Coastal climatic zones respectively.

METHODOLOGY

Acquisition of Data

The World Meteorological Organization (1967) in Ojo and Adeyemi (2014) have suggested that optimal climate modeling can only be ensured if the data series spanned to thirty years and beyond. In this regard, the measured monthly average daily global solar radiation and sunshine hours data used in this study was for a period of thirty one years (1980-2010) and were obtained from the Nigerian Meteorological Agency (NIMET), Oshodi, Lagos, Nigeria. Twenty five (25) (1980- 2004) years data was used to develop the sunshine based empirical models while six (6) years (2005-2010) data was used to validate the models. The locations under investigation are Kano (Latitude 12.05 $°N$ and Longitude 8.20 $°E$) and Ikeja (Latitude 6.58 $°N$ and Longitude 3.33 $°E$) located across the Sahelian and Coastal climatic zones respectively.

Regression

The monthly average daily extraterrestrial radiation on a horizontal surface (H_o) was calculated for days given the average of each month using the equation (Iqbal, 1983):

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

The solar constant, $I_{sc} = 1367\ Wm^{-2}$, φ is the location's latitude, δ is the solar declination, ω_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} January to 31^{st} December. The solar declination (δ) and the mean sunrise hour angle (ω_s) was computed using the equations (Almorox *et al.*, 2011; Duffie and Beckman, 2013)

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

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

For a given month, the daily maximum possible sunshine duration (S_o) in hours is related to the ω_s through the equation (Iqbal, 1983):

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

The clearness index (K_T) is defined using the equation (Falayi *et al.*, 2011)

$$K_T = \frac{H}{H_o} \quad (5)$$

where H is the measured/observed global solar radiation in $MJm^{-2}day^{-1}$

Validation of Models

The estimated values of the global solar radiation obtained from the empirical models were compared with the measured/observed global solar radiation values for Kano and Ikeja 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) while the coefficient of determination (R^2) for each model was determined from the Minitab computer software. The MBE, RMSE and MPE were calculated using the equation (El-Sebaii and Trabea, 2005).

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

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

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

The t-test was calculated using the equation (Bevington, 1969).

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

The locations was statistically tested at the $(1-\alpha)$ confidence levels of significance of 95% and 99%. For the critical t-value, i.e., at α level of significance and degree of freedom, the calculated t-value must be less than the critical value $(t_{critical} = 2.20,\ df = 11, p < 0.05)$ for 95% and $(t_{critical} = 3.12, df = 11, p < 0.01)$ for 99%.

The Nash-Sutcliffe equation (NSE) is given by the expression (Jiandong *et al*., 2012)

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

The Index of Agreement (IA) is given as (Willmott, 1981)

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

From equations (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 radiation. Halouani et al. (1993), Almorox et al. (2005) and Chen et al. (2004) have recommended that a zero value for MBE is ideal and a low RMSE and MPE is desirable. Therefore, the smaller the value of the MBE, RMSE, MPE and t – test the better is the model's performance. Positive values of MPE and MBE provide the averages amount of overestimation in the calculated values, while the negative values give underestimation. Merges et al. (2006) has reported that the percentage error between -10% and $+10\%$ is the acceptable range. The smaller the value of t the better is the performance. The closer the value of NSE is to 1.0 (100 %), the better is the model (Chen *et al*., 2004). The higher the values of R^2 , NSE and IA the better is the model's performance (Akpootu *et al*., 2019b). The MBE and RMSE are in $MJm^{-2}day^{-1}$, while R^2, MPE, NSE and IA are in percentage (%), t – test has no unit.

Table 1: Proposed sunshine based models from 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 (1924) and Prescott (1940)
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. (1984)
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 (1991)
4	Linear Logarithmic	$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + c\ \ln\left(\frac{S}{S_0}\right)$	Newland (1988)
5	Logarithmic	$\frac{H}{H_0} = a + b\ \ln\left(\frac{S}{S_0}\right)$	Ampratwum and Dorvlo (1999)
6	Linear Exponential	$\frac{H}{H_o} = a + b\left(\frac{S}{S_o}\right) + c\ exp\left(\frac{S}{S_0}\right)$	Kadir Bakirci (2009)
7	Exponential	$\frac{H}{H_o} = a + b\ exp\left(\frac{S}{S_0}\right)$	Almorox and Hontoria (2004)
8	Linear	$\frac{H}{H_0} = a + b\left(\frac{S}{S_{nh}}\right)$	Louche et al. (1991)
9	Exponent	$\frac{H}{H_0} = a\left(\frac{S}{S_0}\right)^b$	Kadir Bakirci (2009)

S is the monthly average daily hours of bright sunshine. Model 8 is a modification of the Angström-Prescott model 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. (1991) 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: Sunshine based models proposed in this study

Model No.	Model Type	Regression equation
10	Exponent with exponential	$\frac{H}{H_o} = a\left[exp\left(\frac{S}{S_0}\right)\right]^b$
11	Quadratic, latitude related 1	$\frac{H}{H_o} = a + bcos\varphi\left(\frac{S}{S_0}\right) + ccos\varphi\left(\frac{S}{S_0}\right)^2$
12	Quadratic, latitude related 2	$\frac{H}{H_o} = a + \frac{b\left(\frac{S}{S_0}\right)}{cos\varphi} + \frac{c\left(\frac{S}{S_0}\right)^2}{cos\varphi}$

The proposed models which were developed through the regression analysis are modified form of the existing exponent and quadratic sunshine based models which took the form of an exponent exponential and the incorporation of the location's latitude. The modification of the existing models was to attest if the accuracies of the models are improved or not through statistical validation indicators when compared to the existing models.

RESULTS AND DISCUSSION

Sunshine Based Models for Kano

The results of the existing sunshine regression models for Kano from Table 1 are

$$\frac{H}{H_0} = 0.059 + 0.945\ \frac{S}{S_0} \quad (12a)$$

$$\frac{H}{H_0} = 0.03 + 1.03\frac{S}{S_0} - 0.07\left(\frac{S}{S_0}\right)^2 \quad (12b)$$

$$\frac{H}{H_0} = -16.9 + 81\ \frac{S}{S_0} - 125\left(\frac{S}{S_0}\right)^2 + 65\left(\frac{S}{S_0}\right)^3 \quad (12c)$$

$$\frac{H}{H_0} = 0.21 + 0.8\frac{S}{S_0} + 0.11\ln\left(\frac{S}{S_0}\right) \quad (12d)$$

$$\frac{H}{H_0} = 0.931 + 0.596\ln\left(\frac{S}{S_0}\right) \quad (12e)$$

$$\frac{H}{H_0} = 0.10 + 1.0\frac{S}{S_0} - 0.05\exp\left(\frac{S}{S_0}\right) \quad (12f)$$

$$\frac{H}{H_0} = -0.286 + 0.501\exp\left(\frac{S}{S_0}\right) \quad (12g)$$

$$\frac{H}{H_0} = 0.059 + 1.08\ \frac{S}{Snh} \quad (12h)$$

$$\frac{H}{H_0} = 1.00\left(\frac{S}{S_0}\right)^{0.934} \quad (12i)$$

The results of the proposed sunshine regression models for Kano from Table 2 are

$$\frac{H}{H_0} = 0.257\left[\exp\left(\frac{S}{S_0}\right)\right]^{1.479} \quad (12j)$$

$$\frac{H}{H_0} = 0.03 + 1.1\ cos\varphi\left(\frac{S}{S_0}\right) - 0.07\ cos\varphi\left(\frac{S}{S_0}\right)^2 \quad (12k)$$

$$\frac{H}{H_0} = 0.03 + 1.01\ \frac{\left(\frac{S}{S_0}\right)}{cos\varphi} - 0.06\ \frac{\left(\frac{S}{S_0}\right)^2}{cos\varphi} \quad (12l)$$

Table 3: Sunshine based models statistical error indicators for Kano

Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.12a	42.7	0.0215	1.4285	-0.3083	0.0499	96.0439	99.0008
Eqn.12b	42.7	-0.0953	1.4286	0.2014	0.2217	96.0435	98.9843
Eqn.12c	43	4.0309	4.3178	-17.7938	8.6381	63.8582	94.4252
Eqn.12d	42.7	0.3242	1.473	-1.6288	0.7483	95.7940	98.9811
Eqn.12e	42.7	0.0333	1.4303	-0.3579	0.0772	96.0342	99.0002
Eqn.12f	42.7	-0.6200	1.5422	2.4914	1.4563	95.3891	98.7243
Eqn.12g	42.7	0.0543	1.4299	-0.4524	0.1260	95.3891	99.0033
Eqn.12h	42.5	-7.0139	7.2037	30.6444	14.161	-0.6006	36.6915
Eqn.12i	42.5	-0.0158	1.4281	-0.1454	0.0367	96.0461	98.9962
Proposed models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.12j	42.4	-0.0129	1.4279	-0.1598	0.0299	96.0476	98.9968
Eqn.12k	42.7	0.9386	1.7301	-4.3106	2.1420	94.1971	98.7048
Eqn.12l	42.7	0.0862	1.4328	-0.5906	0.1999	96.0200	99.0038

Tables 3 summarized the different statistical validation tests evaluated in this study. The existing model, equation 12c (cubic) has the highest value of R^2 with 43.0 %. The developed model equation 12j (exponent exponential) has the lowest MBE, RMSE and t – test values with underestimation of 0.0129 $MJm^{-2}day^{-1}$ in its estimated value, 1.4279 $MJm^{-2}day^{-1}$ and 0.0299 respectively; the model also has the highest NSE value with 96.0476 %. The developed model equation 12l (quadratic latitude 2) has the highest value of IA with 99.0038 %. The existing model equation 12i (exponent) has the lowest MPE with underestimation of 0.1454 % in its estimated value. The results of the sunshine dependent models for Kano showed that all the MPE values are ($MPE \leq \pm 10\%$) apart from the existing models (equations 12c and 12h). Similarly, the calculated t – test values are significant at 95% and 99% apart from the existing models (equations 12c and 12h).

Table 4: Ranks obtained from the determined sunshine based models for Kano

Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Rank
Eqn.12a	2	3	3	4	3	3	3	21
Eqn.12b	2	7	4	3	7	4	7	34
Eqn.12c	1	11	11	11	11	10	8	63
Eqn.12d	2	8	8	8	8	7	10	51
Eqn.12e	2	4	6	5	4	5	4	30
Eqn.12f	2	9	9	9	9	8	9	55
Eqn.12g	2	5	5	6	5	8	2	33
Eqn.12h	3	12	12	12	12	11	12	74
Eqn.12i	3	2	2	1	2	2	6	18
Proposed models	R^2	MBE	RMSE	MPE	t	NSE	IA	Rank
Eqn.12j	4	1	1	2	1	1	5	15
Eqn.12k	2	10	10	10	10	9	10	61
Eqn.12l	2	6	7	7	6	6	1	35

Tables 4 summarized the ranks obtained from the sunshine based models for Kano. The rank obtained by each of the models varies between the value 15 and 74. The overall results for Kano; revealed that the developed exponent exponential sunshine regression model as given in equation 12j was found more accurate for estimating global solar radiation in Kano as compared to other models.

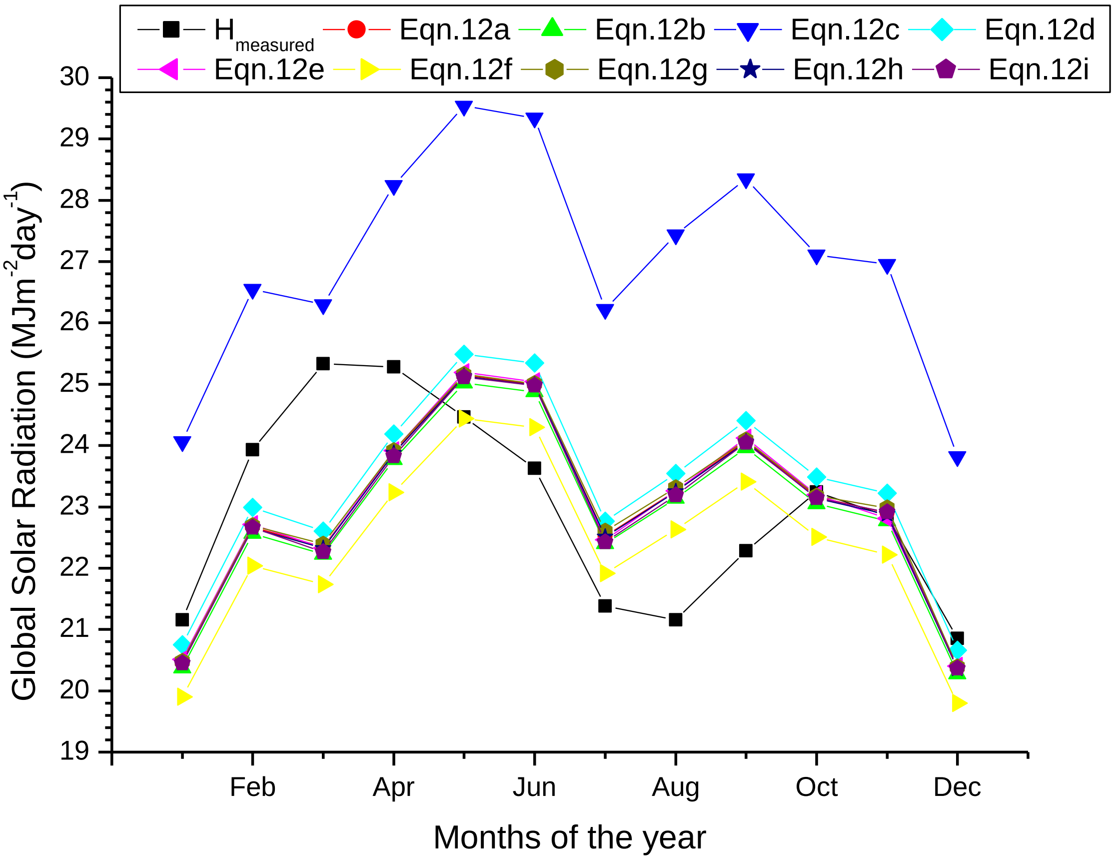

Figure 1a: Comparison between the measured and estimated existing sunshine based global solar radiation models for Kano. $H_{measured}$ – measured global solar radiation; Eqn.12a – linear (Angstrom); Eqn.12b – Quadratic; Eqn.12c – Cubic; Eqn.12d – Linear logarithmic; Eqn.12e – Logarithmic; Eqn.12f –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

Figure 1a shows the comparison between the measured and estimated existing global solar radiation for Kano based on the sunshine models. It is apparent from the figure that a considerable deviation occurred as there is a large overestimation depicted by the existing cubic model as compared with the observed global solar radiation data and other estimated models although the months of the studied period. All the evaluated models, except the existing cubic model underestimated the measured from January to April and in December; also, all the estimated models overestimated the measured global solar radiation in their estimated values in the months from June to September. The existing linear exponential model shows underestimation in its estimated values from January to May and from October to December.

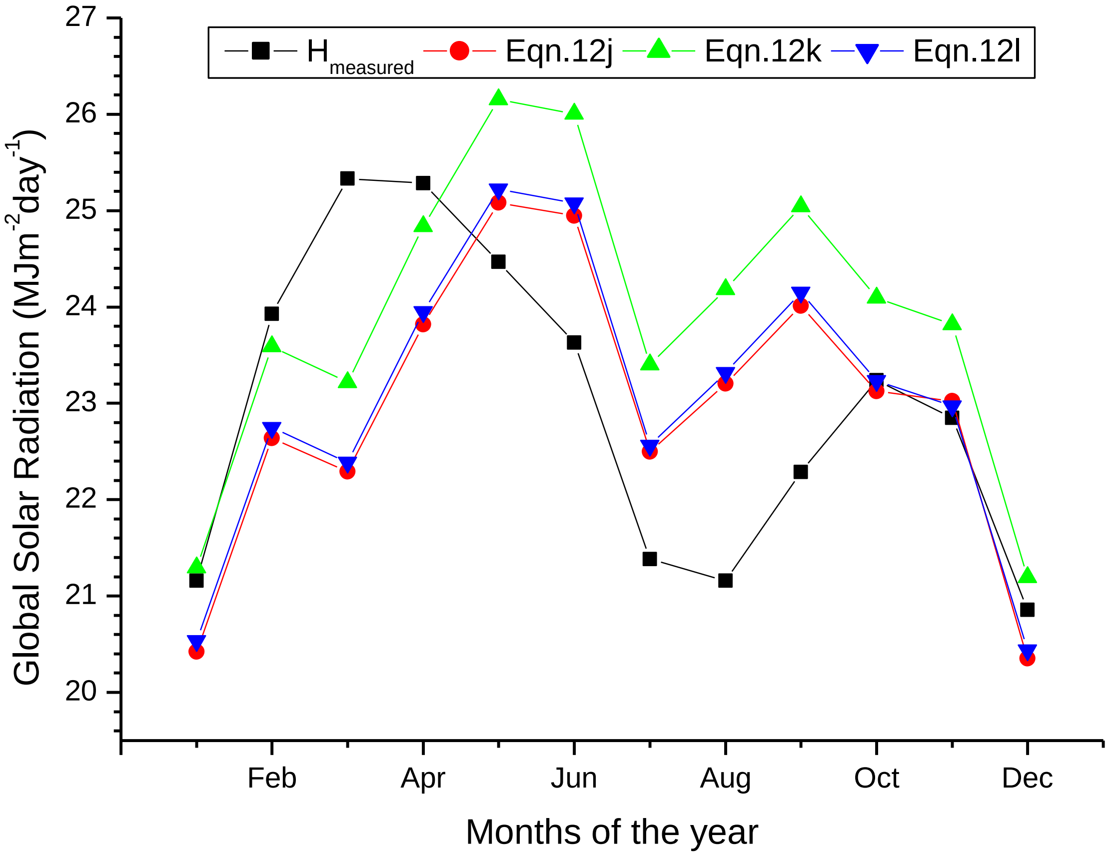

Figure 1b: Comparison between the measured and developed sunshine based global solar radiation models for Kano. $H_{measured}$ – measured global solar radiation; Eqn.13j – Exponent exponential; Eqn.13k – Quadratic latitude 1; Eqn.13l - Quadratic latitude 2

Figure 1b shows the comparison between the measured and estimated developed global solar radiation for Kano based on the sunshine models. The evaluated developed models underestimated the measured global solar radiation data in the months from February to April and overestimated the measured from May to September. The quadratic latitude 1 model overestimated the measured and other evaluated developed models in the months from May to December.

The 1st order and 2nd order Ångström type models results obtained for Kano in this study were compared to that carried out by Ogolo (2010). The model equation with its empirical constants is given in equation 12a and 12b while the empirical constants given by Ogolo (2010) are 0.441 and 0.292 for 1st order Ångström; 1.111, -1.828 and 1.66 for 2nd order Ångström type.

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

Statistical indicators	In this study	Ogolo (2010)
MBE	0.0215	-0.0200
RMSE	1.4285	2.4300
MPE	-0.3083	-0.4000
IA	99.0008	58.0000

Table 6: Comparison of evaluated 2nd order Ångström model for Kano

Statistical indicators	In this study	Ogolo (2010)
MBE	-0.0953	0.2400
RMSE	1.4286	2.2000

MPE	0.2014	0.7000
IA	98.9843	69.0000

The statistical validation indicators of MBE, RMSE, MPE and IA for the 1st order and 2nd order Ångström type sunshine based models in this study were compared to that of Ogolo (2010). A critical examination indicated that the results in this study performed better as shown in Tables 5 and 6.

Sunshine Based Models for Ikeja

The results of the existing sunshine regression models for Ikeja from Table 1 are

$$\frac{H}{H_0} = 0.166 + 0.602\ \frac{S}{S_0} \quad (13a)$$

$$\frac{H}{H_0} = -0.190 + 2.53\frac{S}{S_0} - 2.45\left(\frac{S}{S_0}\right)^2 \quad (13b)$$

$$\frac{H}{H_0} = -0.06 + 1.52\ \frac{S}{S_0} + 0.200\left(\frac{S}{S_0}\right)^2 - 2.200\left(\frac{S}{S_0}\right)^3 \quad (13c)$$

$$\frac{H}{H_0} = 1.55 - 1.22\ \frac{S}{S_0} + 0.695\ln\left(\frac{S}{S_0}\right) \quad (13d)$$

$$\frac{H}{H_0} = 0.628 + 0.233\ln\left(\frac{S}{S_0}\right) \quad (13e)$$

$$\frac{H}{H_0} = 3.14 + 5.48\ \frac{S}{S_0} - 3.29\exp\left(\frac{S}{S_0}\right) \quad (13f)$$

$$\frac{H}{H_0} = -0.194 + 0.401\exp\left(\frac{S}{S_0}\right) \quad (13g)$$

$$\frac{H}{H_0} = 0.166 + 0.689\ \frac{S}{Snh} \quad (13h)$$

$$\frac{H}{H_0} = 0.708\left(\frac{S}{S_0}\right)^{0.600} \quad (13i)$$

The results of the proposed sunshine regression models for Ikeja from Table 2 are

$$\frac{H}{H_0} = 0.216\left[\exp\left(\frac{S}{S_0}\right)\right]^{1.544} \quad (13j)$$

$$\frac{H}{H_0} = -0.190 + 2.54\ cos\varphi\left(\frac{S}{S_0}\right) - 2.46\ cos\varphi\left(\frac{S}{S_0}\right)^2 \quad (13k)$$

$$\frac{H}{H_0} = -0.190 + 2.51\ \frac{\left(\frac{S}{S_0}\right)}{cos\varphi} - 2.43\ \frac{\left(\frac{S}{S_0}\right)^2}{cos\varphi} \quad (13l)$$

Table 7: Sunshine based models statistical error indicators for Ikeja

Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.13a	79.6	-0.0139	0.9976	-0.4165	0.0463	83.2865	95.1070
Eqn.13b	85.3	0.0246	0.8640	-0.4662	0.0946	87.4639	96.5526
Eqn.13c	85.3	0.3835	0.9458	-2.8648	1.4711	84.9774	95.7616
Eqn.13d	85	-0.1179	0.8801	0.5003	0.4484	86.9897	96.4797
Eqn.13e	82.6	0.0106	0.9247	-0.4912	0.0380	85.6395	95.8926
Eqn.13f	85.3	-0.1947	0.8860	1.0181	0.7470	86.8176	96.4833
Eqn.13g	78.1	-0.0131	1.0327	-0.4680	0.0421	86.8176	94.692
Eqn.13h	79.6	-0.0092	0.9975	-0.4481	0.0307	83.2899	95.1046
Eqn.13i	84.7	-0.0451	0.9657	-0.1121	0.1549	84.3371	95.5804
Proposed models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.13j	81.1	-0.0776	1.0553	0.0214	0.2445	81.2951	94.6608
Eqn.13k	85.3	-0.0351	0.8645	-0.0611	0.1347	87.4493	96.5764
Eqn.13l	85.3	0.0000	0.8636	-0.2975	0.0002	87.4736	96.5683

Table 7 summarized the distinct statistical validation tests evaluated in this study. Based on R^2, the models, equation 13b (quadratic), 13c (cubic), 13k (quadratic latitude 1) and 13l (quadratic latitude 2) sunshine based model has the maximum value with of 85.3 %. The developed model equation 13l (quadratic latitude 2) has the lowest MBE, RMSE and t – test with 0.0000 $MJm^{-2}day^{-1}$ (ideal value), 0.8636 $MJm^{-2}day^{-1}$ and 0.0002 respectively; the model also has the highest NSE value of 87.4736 %. The developed model equation 13j (exponent exponential) has the lowest MPE value with overestimation of 0.0214 % in its estimated value. The developed model equation 13k (quadratic latitude 1) has the highest value of IA with 96.5764 %. The results of the accuracy test for Ikeja showed that the MPE values are all in the satisfactory range ($MPE \leq \pm 10\%$) and are all significant at 95% and 99% confidence levels.

Table 8: Ranks obtained from the evaluated sunshine based models for Ikeja

Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Rank
Eqn.13a	6	5	10	5	5	10	9	50
Eqn.13b	1	6	2	7	6	2	3	27
Eqn.13c	1	12	7	12	12	7	7	58
Eqn.13d	2	10	4	10	10	4	5	45
Eqn.13e	4	3	6	9	3	6	6	37
Eqn.13f	1	11	5	11	11	5	4	48
Eqn.13g	7	4	11	8	4	5	11	50

Eqn.13h	6	2	9	6	2	9	10	44
Eqn.13i	3	8	8	3	8	8	8	46
Proposed models	R^2	MBE	RMSE	MPE	t	NSE	IA	Rank
Eqn.13j	5	9	12	1	9	11	12	59
Eqn.13k	1	7	3	2	7	3	1	24
Eqn.13l	1	1	1	4	1	1	2	11

Table 8 summarized the ranks obtained from the sunshine based models for Ikeja. The rank obtained by each of the models varies between the value of 11 and 59. The overall results for Ikeja; revealed that the developed quadratic latitude 2 sunshine based regression model as given in equation 13l was found more accurate for the estimation of global solar radiation in Ikeja as compared to other models.

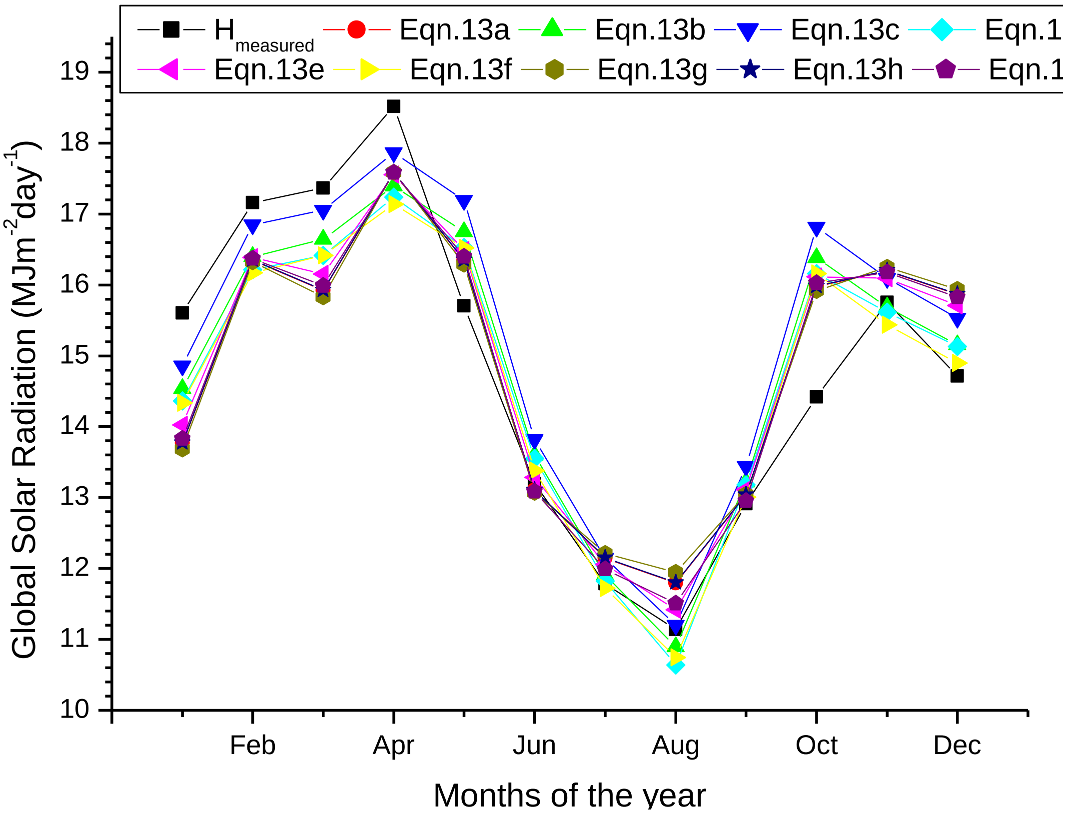

Figure 2a: Comparison between the measured and estimated existing sunshine based global solar radiation models for Ikeja. $H_{measured}$ – measured global solar radiation; Eqn.13a – linear (Angstrom); Eqn.13b – Quadratic; Eqn.13c – Cubic; Eqn.13d – Linear logarithmic; Eqn.13e – Logarithmic; Eqn.13f – Linear exponential; Eqn.13g – Exponential; Eqn.13h – Linear (Louche et al) ; Eqn.13i - Exponent

Figure 2a depicts the comparison between the measured and estimated existing global solar radiation for Ikeja based on the sunshine models. It is evident that the estimated models overestimated the measured global solar radiation in the months of May, October and December and underestimated the measured global solar radiation in the months of January, February, March and April. The figure revealed that there is an overestimation depicted by the existing cubic model as compared with the measured and other estimated models in the months of May, June, September and October.

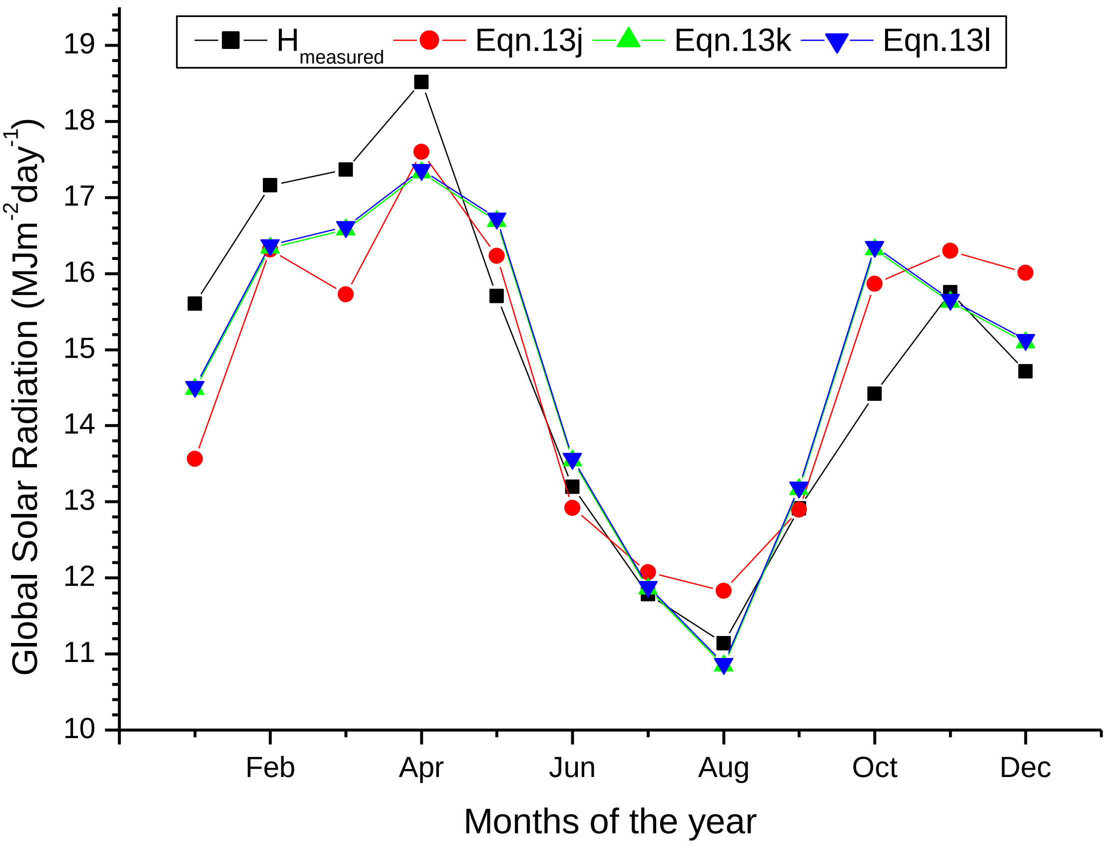

Figure 2b: Comparison between the measured and estimated developed sunshine based global solar radiation models for Ikeja. Hmea – measured global solar radiation; Eqn.13j – Exponent exponential; Eqn.13k – Quadratic latitude 1; Eqn.13l - Quadratic latitude 2

Figure 2b shows the comparison between the measured and estimated developed global solar radiation for Ikeja based on the sunshine models. It is obvious that the estimated overestimated the measured global solar radiation in the months of May, October and December and underestimated the measured global solar radiation in the months of January, February, March and April. The exponent exponential model overestimated the measured and other estimated models in July, August, November and December.

CONCLUSION

Accurate and reliable regression models developed from observed meteorological variables offers a very important alternative for the prediction of global solar radiation in any location in the absence of measured/observed data. In this study three (3) sunshine based regression models were developed and compared to nine (9) distinctive existing sunshine based models through the statistical validation test indicators of Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), t – test, Nash – Sutcliffe Equation (NSE), Index of Agreement (IA) and coefficient of determination (R^2). The models (developed and existing) were subjected to ranking to determine the suitability, reliability and accuracy of each model for the prediction of global solar radiation in Kano and Ikeja located at the Sahelian and Coastal regions respectively. The results in this study indicated that the developed exponent exponential sunshine regression based model (equation 12j) with R^2, MBE, RMSE, MPE, t – test, NSE and IA of 42.4 %, $-0.0129\ MJm^{-2}day^{-1}$, $1.4279\ MJm^{-2}day^{-1}$, $-0.1598\ \%$, 0.0299, $96.0476\ \%$ and $98.9968\ \%$ respectively was found more reliable for estimation of global solar radiation in Kano. Also, the developed quadratic latitude 2 sunshine based regression model (equation 13l) with R^2, MBE, RMSE, MPE, t – test, NSE and IA of $85.3\ \%$, $0.0000\ (ideal)\ MJm^{-2}day^{-1}$, $0.8636\ MJm^{-2}day^{-1}$, $-0.2957\ \%$, 0.0002, $87.4736\ \%$ and $96.5683\ \%$ respectively was found more reliable for estimation of global solar radiation in Ikeja. The evaluated existing linear (1st order) and quadratic (2nd order) sunshine based models for Kano were found more suitable for the estimation of global solar radiation as compared with those found in the literature. The variation of the empirical regression equations and the validation indicators values for each model in Kano and Ikeja signifies that models are generally site – specific and requires to be calibrated when used to predict global solar radiation values in any location other than the location it was originally developed for. The most suitable models (equations 12j and 13l) showed good agreement with the observed values when correlated with the other models. The development of new models which was found more suitable for global solar radiation prediction in these locations indicates that there is always the need to carry out thorough investigation in search for the best model that will reliably give the values of global solar radiation in any location that lacks measured/observed global solar radiation data.

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REFERENCES

Akinoglu, B. G and Ecevit, A. (1990). Construction of a quadratic model using modified Angstrom coefficients to estimate global solar radiation, *Solar Energy*., **45**, 85-92.

Akpootu, D. O and Iliyasu, M. I. (2015a). The Impact of some Meteorological Variables on the Estimation of Global Solar Radiation in Kano, North Western, Nigeria. *Journal of Natural Sciences Research*., Vol.5, No.22, 1 – 13.

Akpootu, D. O and Iliyasu, M. I. (2015b). A Comparative Study of some Meteorological Parameters for Predicting Global Solar Radiation in Kano, Nigeria Based on Three Variable Correlations. *Advances in Physics Theories and Applications*., Vol.49, 1 – 9.

Akpootu, D. O and Momoh, M. (2014). Empirical Model for Estimating Global Solar Radiation in Makurdi, Benue State, North Central Nigeria. A paper presented at the 36th Annual Nigerian Institute of Physics, National Conference, held at the Department of Physics, University of Uyo, Nigeria on May 26-29, 2014.

Akpootu, D. O and Sulu, H. T. (2015). A Comparative Study of Various Sunshine Based Models for Estimating Global Solar Radiation in Zaria, North-Western, Nigeria. *International Journal of Technology Enhancements and Emerging Engineering Research*., **3**(12), 1 – 5.

Akpootu, D. O., Tijjani, B. I and Gana, U. M. (2019a). Empirical models for predicting global solar radiation using meteorological parameters for Sokoto, Nigeria. *International Journal of Physical Research*., 7(2): 48 – 60. DOI: 10.14419/ijpr.v7i2.29160

Akpootu, D. O., Tijjani, B. I and Gana, U. M. (2019b). Sunshine and Temperature Dependent Models for Estimating Global Solar Radiation Across the Guinea Savannah Climatic Zone of Nigeria. *American Journal of Physics and Applications*., 7(5): 125-135. doi: 10.11648/j.ajpa.20190705.15

Alam, M., Saha, S., Chowdhury, M and Rahman, M. (2005). Simulation of Solar Radiation System, *Am. J. Appl. Sci*., 2 (4), 751-758.

Almorox, J and Hontoria, C. (2004). Global solar radiation estimation using sunshine duration in Spain, *Energy Conversion and Management*., 45, 1529 – 1535.

Almorox, J., Benito, M and Hontoria, C. (2005). Estimation of monthly Ångström-Prescott Equation coefficients from measured daily data in Toledo, Spain. *Renewable Energy*., **30**, 931-936.

Almorox, J., Hontoria, C and Benito, M. (2011). Models for obtaining daily global solar radiation with measured air temperature data in Madrid (Spain). *Applied Energy*., 88: 1703 – 1709.

Ampratwum, D. B and Dorvlo, A. S. S. (1999). Estimation of solar radiation from the number sunshine hours, *Applied Energy*., 63, 161 – 167.

Ångström, M. S. (1924). Solar and terrestrial radiation, *Meteorol. Soc*., **50**: 121-126.

Baigorria, G. A., Villegas, E. B., Trebejo, I., Carlos, J. F and Quiroz, R (2004). Atmospheric transmissivity: distribution and empirical estimation around the central Andes. *International Journalof Climatology*, vol. 24, no. 9, pp. 1121–1136.

Bakirci, K. (2009). Correlations for estimation of daily global solar radiation with hours of bright sunshine in Turkey, *Energy*., **34**, 485 – 501.

Bevington, P. R. (1969). Data reduction and error analysis for the physical sciences, first ed. McGraw Hill Book Co., New York.

Chen, R., Ersi, K., Yang, J., Lu, S and Zhao, W. (2004). Validation of five global radiation Models with measured daily data in China. *Energy Conversion and Management*., **45**, 1759-1769.

Dincer, I. (2000). Renewable energy and sustainable development: a crucial review. Renewable sustainable energy review., 4: 157 – 175.

Duffie, J. A and Beckman, W. A. (2013). Solar engineering of thermal processes. 4th edition, New York: Wiley.

El-Sebaii, A and Trabea, A. (2005). Estimation of Global Solar Radiation on Horizontal Surfaces Over Egypt, *Egypt. J. Solids*, **28**(1), 163-175.

Falayi, E. O., Rabiu, A. B and Teliat, R. O. (2011). Correlations to estimate monthly mean of daily diffuse solar radiation in some selected cities in Nigeria, *Pelagia Research Library*., **2**(4): 480-490.

Gana, N. N and Akpootu, D. O. (2013a). Estimation of global solar radiation using four sunshine based models in Kebbi, North-Western, Nigeria. *Pelagia Research Library*., **4**(5), 409-421.

Gana, N. N and Akpootu, D. O. (2013b). Angstrom Type Empirical Correlation for Estimating Global Solar Radiation in North- Eastern Nigeria. *The International Journal of Engineering And Science*., **2**(11), 58-78.

Halouani, N., Nguyen, C. T and Vo-Ngoc, D. (1993). Calculation of monthly average Solar radiation on horizontal surfaces using daily hours of bright sunshine. *Solar Energy*., **50**, 247-248.

Iqbal, M. (1983). An introduction to solar radiation, first ed. Academic Press, New York.

Jiandong, L., Jingmiao, L., Hans, W. L., Deliang, C., Qiang, Y., Dingrong, W and Shigenori, H. (2012). Observation and calculation of the solar radiation on the Tibetan Plateau. *Energy conversion and Management*., 57: 23 – 32.

Louche, A., Notton, G., Poggi, P and Simonnot, G. (1991). Correlations for direct and Global horizontal irradiation on a French Mediterranean site, *Solar Energy*., 46, 261 – 6.

Merges, H. O., Ertekin, C and Sonmete, M. H. (2006). Evaluation of global solar radiation Models for Konya, Turkey. *Energy Conversion and Management*., **47**, 3149-3173.

Newland, F. J. (1988). A study of solar radiation models for the coastal regions of South China, *Solar Energy*., 31, 227 – 235.

Ogelman, H., Ecevit, A and Tasdemiroglu, E. (1984). A new method for estimating solar radiation from bright sunshine data, *Solar Energy*., **33**, 619 – 625.

Ogolo, E. O. (2010). Evaluating the performance of some predictive models for estimating global solar radiation across varying climatic conditions in Nigeria. *Indian Journal of Radio & space Physics*., **39**, 121-131.

Ojo, O. S and Adeyemi, B. (2014). Estimation of Solar Radiation using Air Temperature and Geographical Coordinate over Nigeria, *The Pacific Journal of Science and Technology*., **15**(2), 78 – 88.

Olomiyesan, B. M and Oyedum, O. D. (2016). Comparative Study of Ground Measured, Satellite-Derived, and Estimated Global Solar Radiation Data in Ni-geria. Hindawi Publishing Corporation. Journal of Solar Energy Volume 2016: Article ID 8197389, 7 pages https://doi.org/10.1155/2016/8197389.

Prescott, J. A. (1940). Evaporation from water surface in relation to solar radiation, *Transactions of the Royal Society of Australia*, **46:** 114-118.

Rivington, M. Bellocchi, G., Matthews, K. B and Buchan, K. (2005). Evaluation of three model estimations of solar radiation at 24 UK stations," *Agricultural and Forest Meteorology*, vol. 132, no. 3-4, pp. 228–243.

Samuel, T. D. M. A. (1991). Estimation of global radiation for Sri Lanka, *Solar Energy*., **47**, 333-337.

Willmott, C. (1981). On the validation of models. *Phys. Geography*., **2**, 211-228.

WMO (1967). A Note on Climatological Normal. Technical Note. World Meteorological Organization, Geneva, Switzerland.