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New Temperature Dependent Models for Estimating Global Solar Radiation across the Coastal Climatic Zone of Nigeria

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Abstract

In this study, five different temperature dependent models were proposed and compared with three existing temperature dependent models (Chen, Hargreaves and Samani (HS) and Garcia) using measured monthly average daily global solar radiation, maximum and minimum temperature meteorological parameters during the period of thirty one (1980 – 2010) years. The comparison assessment using seven different statistical validation indices of coefficient of determination (R^2), Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), t – test, Nash – Sutcliffe Equation (NSE) and Index of Agreement (IA) was employed to determine the most accurate model for estimating global solar radiation in the five tropical locations situated in the coastal climatic zone of Nigeria. It was found that in each of the locations under investigation the proposed temperature dependent models were reported more suitable for global solar radiation estimation. In Akure, Ogoja, Ikeja, Benin and Owerri; the proposed quadratic logarithmic, linear exponential, multiple linear, quadratic (exponential 2) and quadratic (exponential 1) temperature dependent models respectively were found more accurate and can be applied to locations with comparable weather condition, if properly calibrated against the local data. The HS and Garcia temperature dependent models evaluated in this study for Ikeja was compared with those available in literature and was found more accurate. The figures comparing the measured and estimated temperature dependent models indicates that the most accurate models in each location exhibit the best fitting with the measured global solar radiation data.

Keywords: Global Solar Radiation, Coastal Climatic Zone, Proposed Temperature Dependent Models, Statistical Validation Indices, Meteorological Parameters.

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1. INTRODUCTION

Solar energy is a renewable energy source with potential to mitigate some of the negative environmental problems. Therefore, with decreasing costs and rapidly improving technology, it plays a significant role in the energy system [1 – 2]. Global solar radiation on a horizontal surface is most commonly used in the prediction, study and design of solar energy systems [3]. Knowledge about solar radiation for a given location is very important for decision and assessment of solar energy conversion, which is gaining significant attention in Nigeria in particular and the world at large. On the basis of readily available meteorological data, it is very important to have methods for estimating solar radiation [1, 4].
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 [5]. 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 [6].

Several models have been proposed to estimate global solar radiation. Panday and Katiyar [7] analyzed the global solar radiation and temperature data of five India cities, viz. Jodhpur, Ahmedabad, Calcutta, Bombay and Pune using data obtained from India Meteorological Department (IMD) Pune, a Government of India organization during the periods between 2001 and 2005. According to them, it was concluded, that third order correlations provides much accuracy over first and second order for the estimation of monthly average daily global solar radiation as a function of ambient air temperature incident on a horizontal

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surface. Sanusi and Abisoye [8] presents and evaluates the behavior of three empirical models (Hargreaves – Samani model, Hargreaves model with linear regression and Hargreaves model with power regression) based on the difference between maximum and minimum temperature at Ibadan. The data used in their study were obtained from the International Institute of Tropical Agriculture (IITA), station of Ibadan, located within the rainforest climatic zone of Western Nigeria. The data obtained covered a period of 6 years (2001 – 2006). The best performing model was found to be Hargreaves model with linear regression and followed by Hargreaves model with power regression and original Hargreaves model. Therefore, they concluded that the Hargreaves model with linear regression was recommended for predicting global solar radiation at Ibadan and stations with similar geographical information.

Huashan et al. [9] proposed new model based on Hargreaves and Samani (HS) method for the estimation of global solar radiation at 65 meteorological stations in China. The new model was compared with the HS model and its two modification (Samani model and Chen model), using statistical error tests of MPE, MBE, RMSE and NSE. According to them, it was reported that the new model is more accurate and robust than the HS, Samani and Chen models in all climatic regions, especially in the humid region and therefore recommended for solar radiation estimation in regions where air temperature data are available in China. Olomiyesan et al. [10] compares the performances of four global solar radiation models for estimating global solar radiation in three selected locations (Gusau, Yelwa and Katsina) in North Western, Nigeria. The four models comprises of three existing models; Garcia, Hargreaves and Samani and the Angstrom Prescott models and the Authors model. The monthly metereological data of sunshine hours, global solar radiation, maximum and minimum temperatures used in their study were obtained from the Nigerian Meteorological Agency (NIMET), Oshodi-Lagos, Nigeria during the period of twenty two years (1984 – 2005). The Authors model which is a combination of the Angstrom Prescott and Garcia models was found to perform best with least RMSE values in the three locations and highest R^2 in two of the locations. According to them, the newly (Authors) developed model is suitable for estimating global solar radiation in North Western, Nigeria and other locations with similar meterological and climatic conditions. Girma [11] compare several existing sunshine and temperature based models using data on sunshine hours, minimum and maximum temperatures obtained from the Ethiopian Institute of Agricultural Research: Tepi National Spices Research Centre to estimate the global solar radiation for Tepi located in South West of Ethiopia. The monthly averages sunshine hour for 4 years (2013 – 2016) and monthly averages maximum and minimum temperatures for 5 years (2012 – 2016). The monthly averages daily global solar radiation from the Archives of National Aeronautics and Space Administration (NASA) for 22 years (July, 1983 – June, 2005) was utilized in his study. According to him, from the sunshine based models, the Samuel (polynomial) and the Newland (logarithm) models are appropriate for Tepi while the Chen et al model from the temperature based models is more appropriate for Tepi.

The purpose of this study is to develop new temperature dependent models capable of estimating global solar radiation in each of the five studied areas (Akure, Ogoja, Ikeja, Benin and Owerri) situated in the Coastal climatic zone of Nigeria using meteorological parameters of monthly average daily global solar radiation, maximum and minimum temperature during the period of thirty one (1980 – 2010) years.

2. METHODOLOGY

2.1 Acquisition of data

It was mentioned according to the World Meteorological Organization [12] and Ojo and Adeyemi [13] that to ensure the optimal climate modeling, data series should be a minimum of thirty years long. Based on this, the measured monthly average daily global solar radiation, maximum and minimum temperature 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 empirical models while six (6) years (2005 – 2010) data was used for validation of the models. According to Olaniran [14] Nigeria is classified into four climatic zones; these are the Coastal zone, Guinea savannah zone, Midland zone and the Sahelian zone. The locations within the Coastal climatic zone considered in this study are shown in Fig. 1.

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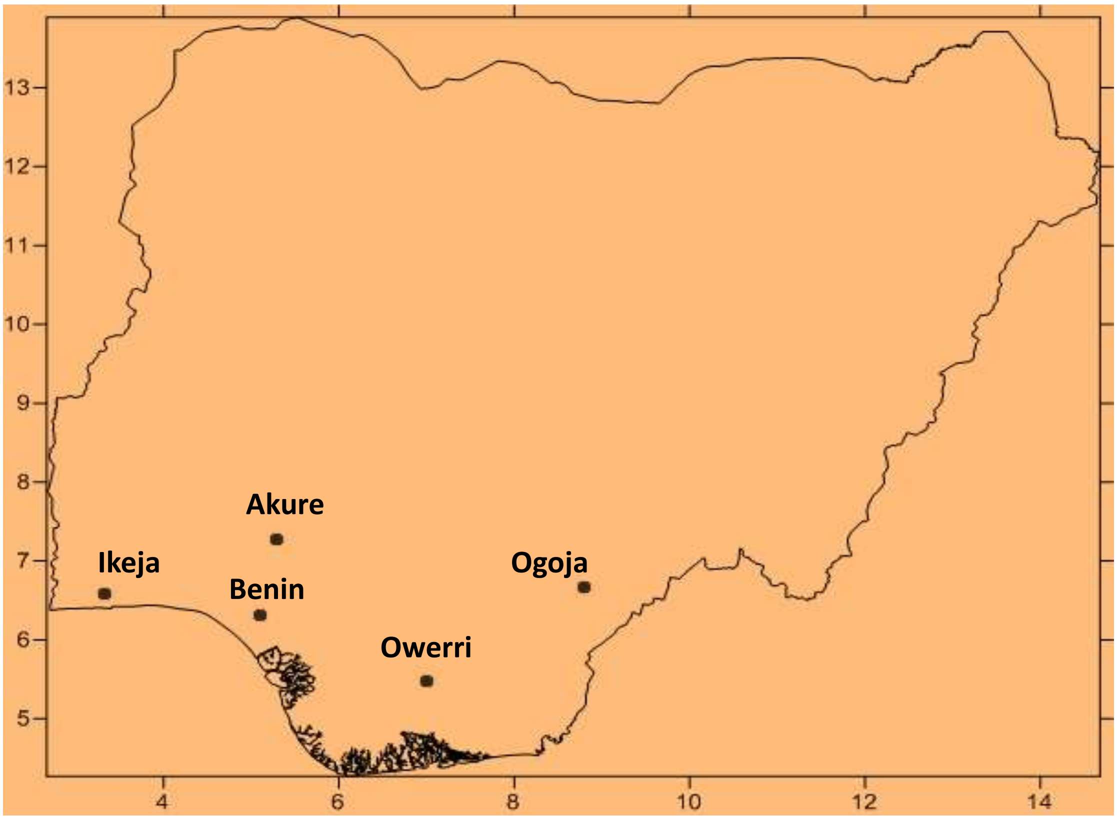

Fig. 1: Map of Nigeria showing the studied locations in the Coastal climatic zone

2.2 Regression analysis

The monthly average daily extraterrestrial radiation on a horizontal surface (H_o) in MJ/m^2/day can be calculated for days giving average of each month from the following equation [15 – 16]:

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

where I_{sc} is the solar constant (=1367 Wm^{-2}), φ is the latitude of the site, δ is the solar declination and 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} of January to 31^{st} of December.

The solar declination, δ and the mean sunrise hour angle, ω_s can be calculated using the following equation [15 – 16]:

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

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

For a given month, the maximum possible sunshine duration (monthly average day length (S_o)) in hours can be computed [15 – 16] by

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

The clearness index (K_T) is defined as the ratio of the observed/measured horizontal terrestrial solar radiation H, to the calculated/predicted/estimated horizontal extraterrestrial solar radiation H_o [17].

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

where$H$ is the monthly average daily global solar radiation on a horizontal surface (MJ/m^2/day).In this study, H_o and S_o were computed for each month using equations (1) and (4) respectively.

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Table 1: Temperature dependent regression models proposed in literature that was used in this study.

Model No.	Model Type	Regression equation	Source
1	Logarithmic	$\frac{H}{H_0} = a_2 + b_2 ln\Delta T$	Chen et al. [18]
2	Linear exponent	$\frac{H}{H_0} = a_3 + b_3 \Delta T^{0.5}$	Hargreaves and Samani [19]
3	Linear	$\frac{H}{H_0} = a_4 + b_4\left(\frac{\Delta T}{S_0}\right)$	Garcia [20]

Table 2: Temperature dependent regression models proposed in this study.

Model No.	Model Type	Regression equation
1	Linear exponential	$\frac{H}{H_o} = a + b(\Delta T)^{0.5} + cexp[(\Delta T)^{0.5}]$
2	Quadratic Logarithmic	$\frac{H}{H_o} = a + (\Delta T) + c(\Delta T)^2 + dln(\Delta T)$
3	Quadratic (exponential 1)	$\frac{H}{H_o} = a + b(\Delta T) + c(\Delta T)^2 + dexp(\Delta T)$
4	Quadratic (exponential 2)	$\frac{H}{H_o} = a + b\left(\frac{\Delta T}{S_0}\right) + c\left(\frac{\Delta T}{S_0}\right)^2 + dexp\left(\frac{\Delta T}{S_0}\right)$
5	Multiple linear	$\frac{H}{H_o} = a + b\,\Delta T + c\,\, T_{mean} + d\, T_r$

where H, H_0 and S_0 are as previously defined. $\Delta T$is the difference between the monthly average daily maximum and minimum temperature i.e., $T_{max} - T_{min}$

The constants $a_{2,}, a_3,\ a_4, b_2, b_3\ and\ b_4$ in Table 1 are empirical coefficients determined by regression analysis and the other terms are the model correlated parameters. The models are basically the three widely used temperature dependent models and has been found suitable in all climatic conditions. The five proposed temperature dependent models by the authors in this study are given in Table 2.

The models in Table 2 are proposed for this study in form of mathematical equations that relate the clearness index as the dependent variable and temperature as the independent variables. The proposed temperature dependent models are based on the modification of the existing models. The essence of modification is to find out if it improves the accuracy of the existing models.

The accuracy or validation of the estimated values was statistically tested by computing the MBE, RMSE, MPE, t-test, NSE and the IA, similarly, R^2 was determined for each of the models.The expressions for the MBE, RMSE and MPE as stated according to El-Sebaii and Trabea [21] are given as follows.

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

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

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

The t-test defined by student [22] in one of the tests for mean values, the random variable t with n-1 degrees of freedom may be written as follows.

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

The study site 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

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

The Index of Agreement (IA) is given as

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

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.

Chen et al. [18] have recommended that a zero value for MBE is ideal and a low RMSE and MPE are desirable. The smaller the value of the MBE, MPE and RMSE the better is the model's performance, a positive MPE and MBE values provide the averages amount of overestimation in the calculated values, while the negative values gives underestimation. The percentage error between -10% and $+10\%$ is considered acceptable [23]. The smaller the value of t the better is the performance. High value of R^2, NSE and IA are desirable. The MBE and the RMSE are in $MJm^{-2}day^{-1}$, while R^2, MPE, NSE and IA are in percentage (%), the t – test is non dimensional.

3. RESULTS AND DISCUSSION

3.1 Temperature Dependent Models across the Coastal Climatic Zone of Nigeria

3.1.1 Temperature Dependent Models for Akure

The empirical existing temperature dependent models for Akure obtained through regression analysis based on Table 1 are

$$\frac{H}{H_0} = -0.128 + 0.281 \ln \Delta T \qquad (12a)$$

$$\frac{H}{H_0} = -0.046 + 0.177 \operatorname{Sqrt} \Delta T \qquad (12b)$$

$$\frac{H}{H_0} = 0.256 + 0.303 \frac{\Delta T}{S_0} \qquad (12c)$$

The proposed developed empirical temperature dependent models for Akure obtained through regression analysis based on Table 2 are

$$\frac{H}{H_0} = -1.36 + 0.805 \operatorname{Sqrt} \Delta T - 0.0269 \exp Sqrt\,(\Delta T) \qquad (12d)$$

$$\frac{H}{H_0} = -0.77 + 0.152\,\Delta T - 0.0075\,(\Delta T)^2 + 0.24 \ln \Delta T \qquad (12e)$$

$$\frac{H}{H_0} = -0.644 + 0.214\,\Delta T - 0.00945\,(\Delta T)^2 + 0.00000003 \exp \Delta T \qquad (12f)$$

$$\frac{H}{H_0} = -0.94 + 2.01\frac{\Delta T}{S_0} - 1.56\left(\frac{\Delta T}{S_0}\right)^2 + 0.39 \exp\left(\frac{\Delta T}{S_0}\right) \qquad (12g)$$

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$$\frac{H}{H_0} = 2.79 + 0.140\,\Delta T - 0.0290\,T_{mean} - 1.98\,T_r \qquad (12h)$$

Table 3a: Statistical validation indicators of the temperature dependent models for Akure

Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.12a (Chen)	74.2	0.0336	1.2974	-0.7779	0.0858	81.3813	94.6173
Eqn.12b (HS)	70.6	-0.0194	1.3908	-0.5745	0.0462	78.6047	93.5613
Eqn.12c (Garcia)	66.8	-0.0083	1.4887	-0.7617	0.0184	75.4857	92.3709
Proposed Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.12d	91.2	-0.0905	0.7744	0.459	0.3903	93.3663	98.2932
Eqn.12e	91.2	**-0.0029**	0.7703	**-0.0479**	**0.0126**	93.4367	98.3383
Eqn.12f	91.3	-0.046	0.7684	0.2145	0.1989	93.4692	98.3387
Eqn.12g	**92.2**	-0.145	**0.7416**	0.7749	0.6613	**93.9163**	**98.4184**
Eqn.12h	75.2	0.1387	1.3053	-1.2537	0.3545	81.1526	94.9718

Table 3b: Ranking the temperature dependent models for Akure based on statistical validation indicators

Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total
Eqn.12a (Chen)	5	4	5	7	4	5	6	36
Eqn.12b (HS)	6	3	7	4	3	7	7	37
Eqn.12c (Garcia)	7	2	8	5	2	8	8	40
Proposed Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total
Eqn.12d	3	6	4	3	7	4	4	31
Eqn.12e	3	1	3	1	1	3	3	**15**
Eqn.12f	2	5	2	2	5	2	2	20
Eqn.12g	1	8	1	6	8	1	1	26
Eqn.12h	4	7	6	8	6	6	5	42

Table 3a and 3b summarizes the different statistical validation indicators utilized in this study and the ranking of the temperature dependent models for Akure. Based on the R^2, NSE and IA the result indicated that the proposed model developed in this study, equation 12g (Quadratic exponential 2) temperature dependent model has the highest values with 92.2 %, 93.9163 % and 98.4489 % respectively; the model also have the lowest RMSE value of 0.7416 $MJm^{-2}day^{-1}$. The proposed model, equation 12e (Quadratic logarithmic) temperature dependent model have the lowest MBE, MPE and t – test values with 0.0029 $MJm^{-2}day^{-1}$, 0.0479 % and 0.0126 respectively. The results revealed that despite the observed overestimation and underestimation exhibited by some of the existing and proposed models they all fall within the acceptable range ($MPE \leq \pm 10\%$) and the $t_{cal} < t_{critical}$ values for all the models under consideration; therefore the t –test shows that all models are significant at 95% and 99% confidence levels.

The total ranks acquired by the different models (Table 3b) were in the range 15 to 42, based on the overall results for Akure; the proposed empirical quadratic logarithmic temperature dependent model given in equation 12e was found more accurate for estimating global solar radiation in this location as compared to other evaluated temperature dependent models.

3.1.2 Temperature Dependent Models for Ogoja

The empirical existing temperature dependent models for Ogoja obtained through regression analysis based on Table 1 are

$$\frac{H}{H_0} = -0.0343 + 0.2091 \ln \Delta T \qquad (13a)$$

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$$\frac{H}{H_0} = 0.0411 + 0.128 \text{ Sqrt } \Delta T \qquad (13b)$$

$$\frac{H}{H_0} = 0.268 + 0.210 \frac{\Delta T}{S_0} \qquad (13c)$$

The proposed developed empirical temperature dependent models for Ogoja obtained through regression analysis based on Table 2 are

$$\frac{H}{H_0} = -1.02 + 0.610 \text{ Sqrt } \Delta T - 0.0185 \exp Sqrt\,(\Delta T) \qquad (13d)$$

$$\frac{H}{H_0} = -1.64 - 0.142\,\Delta T + 0.00081\,(\Delta T)^2 + 1.50 \ln \Delta T \qquad (13e)$$

$$\frac{H}{H_0} = -0.462 + 0.160\,\Delta T - 0.00668\,(\Delta T)^2 + 0.00000001 \exp \Delta T \qquad (13f)$$

$$\frac{H}{H_0} = -1.91 + 1.23 \frac{\Delta T}{S_0} - 2.37 \left(\frac{\Delta T}{S_0}\right)^2 + 1.31 \exp\left(\frac{\Delta T}{S_0}\right) \qquad (13g)$$

$$\frac{H}{H_0} = 1.45 + 0.073\,\Delta T - 0.0110\,T_{mean} - 0.99\,T_r \qquad (13h)$$

Table 4a: Statistical validation indicators of the temperature dependent models for Ogoja

Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.13a (Chen)	78.8	-0.0329	0.8388	-0.1934	0.1302	76.1832	92.0347
Eqn.13b (HS)	75.5	0.0137	0.9041	-0.5375	0.0504	72.3264	90.4054
Eqn.13c (Garcia)	70.1	**-0.0087**	1.0065	-0.4878	**0.0288**	65.7037	87.0912
Proposed Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.13d	95.8	-0.0302	0.3825	**0.1418**	0.2627	95.046	98.7365
Eqn.13e	**96.0**	0.0336	**0.3672**	-0.2393	0.3045	**95.4361**	**98.8522**
Eqn.13f	95.8	-0.1204	0.4004	0.6981	1.0462	94.5739	98.5971
Eqn.13g	94.8	0.3508	0.5565	-2.2247	2.694	89.5176	97.4784
Eqn.13h	80.6	0.0717	0.8111	-0.7329	0.2942	77.7265	93.5637

Table 4b: Ranking the temperature dependent models for Ogoja based on statistical validation indicators

Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total
Eqn.13a (Chen)	5	4	6	2	3	6	6	32
Eqn.13b (HS)	6	2	7	5	2	7	7	36
Eqn.13c (Garcia)	7	1	8	4	1	8	8	37
Proposed Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total
Eqn.13d	2	3	2	1	4	2	2	**16**
Eqn.13e	1	5	1	3	6	1	1	18
Eqn.13f	2	7	3	6	7	3	3	31
Eqn.13g	3	8	4	8	8	4	4	39
Eqn.13h	4	6	5	7	5	5	5	37

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Table 4a and 4b summarizes the different statistical validation indicators used in this study and the ranking of the temperature dependent models for Ogoja. Based on the R^2, NSE and IA the result indicated that the proposed model developed in this study, equation 13e (Quadratic logarithmic) temperature dependent model has the highest values with 96.0 %, 95.4361 % and 98.8522 % respectively; the model also have the lowest RMSE value of 0.3672 $MJm^{-2}day^{-1}$. The Garcia model has the lowest MBE and t – test values with 0.0087 $MJm^{-2}day^{-1}$ and 0.0288 respectively. The proposed model, equation 13d (Linear exponential) temperature dependent model have the lowest MPE with overestimation of 0.1418 % in its estimated value. The results revealed that despite the observed overestimation and underestimation exhibited by some of the existing and proposed models, they all fall within the acceptable range ($MPE \leq \pm 10\%$) and the $t_{cal} < t_{critical}$ values for all the models under study; indicating that the t −test are significant at 95% and 99% confidence levels.

The total ranks acquired by the different models (Table 4b) were in the range 16 to 39, based on the overall results for Ogoja; the proposed empirical linear exponential temperature dependent model given in equation 13d was found more accurate for estimating global solar radiation in this location as compared to other evaluated temperature dependent models.

3.1.3 Temperature Dependent Models for Ikeja

The empirical existing temperature dependent models for Ikeja obtained through regression analysis based on Table 1 are

$$\frac{H}{H_0} = -0.299 + 0.347 \ln \Delta T \qquad (14a)$$

$$\frac{H}{H_0} = -0.279 + 0.247 \,\mathrm{Sqrt}\, \Delta T \qquad (14b)$$

$$\frac{H}{H_0} = 0.113 + 0.455 \frac{\Delta T}{S_0} \qquad (14c)$$

The proposed developed empirical temperature dependent models for Ikeja obtained through regression analysis based on Table 2 are

$$\frac{H}{H_0} = -1.58 + 0.977 \;\mathrm{Sqrt}\, \Delta T - 0.0441 \;\exp Sqrt\,(\Delta T) \qquad (14d)$$

$$\frac{H}{H_0} = 2.02 + 1.55\, \Delta T - 0.0543\, (\Delta T)^2 - 5.07 \ln \Delta T \qquad (14e)$$

$$\frac{H}{H_0} = -0.273 + 0.117\, \Delta T - 0.0033\, (\Delta T)^2 - 0.00000502 \exp \Delta T \qquad (14f)$$

$$\frac{H}{H_0} = 8.0 + 7.9 \frac{\Delta T}{S_0} + 6.2 \left(\frac{\Delta T}{S_0}\right)^2 - 8.0 \exp\left(\frac{\Delta T}{S_0}\right) \qquad (14g)$$

$$\frac{H}{H_0} = -9.98 - 0.340\, \Delta T + 0.144\, T_{mean} + 6.85\, T_r \qquad (14h)$$

Table 5a: Statistical validation indicators of the temperature dependent models for Ikeja

Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.14a (Chen)	82.1	**-0.005**	0.9655	-0.5407	**0.0173**	84.344	95.2557
Eqn.14b (HS)	80.6	-0.0287	1.0049	-0.4297	0.0946	83.0393	94.8054
Eqn.14c (Garcia)	74.3	-0.0204	1.1618	-0.6651	0.0583	77.3302	92.6145
Proposed Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.14d	87.3	-0.0614	0.8196	**0.0752**	0.2492	88.7179	96.8486
Eqn.14e	88	-1.322	1.556	8.6291	5.3434	59.3381	91.4426
Eqn.14f	87.9	-0.0256	0.7952	-0.1749	0.1066	89.3789	97.0166
Eqn.14g	84.4	0.0337	0.9543	-0.408	0.1171	84.7038	95.9621
Eqn.14h	**96.2**	0.0092	**0.4488**	-0.131	0.0679	**96.6176**	**99.1369**

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Table 5b: Ranking the temperature dependent models for Ikeja based on statistical validation indicators

Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total
Eqn.14a (Chen)	6	1	5	6	1	5	5	29
Eqn.14b (HS)	7	5	6	5	4	6	6	39
Eqn.14c (Garcia)	8	3	7	7	2	7	7	41
Proposed Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total
Eqn.14d	4	7	3	1	7	3	3	28
Eqn.14e	2	8	8	8	8	8	8	50
Eqn.14f	3	4	2	3	5	2	2	21
Eqn.14g	5	6	4	4	6	4	4	33
Eqn.14h	1	2	1	2	3	1	1	**11**

Table 5a and 5b summarizes the different statistical validation indicators utilized in this study and the ranking of the temperature dependent models for Ikeja. Based on the R^2, NSE and IA the result indicated that the proposed model developed in this study, equation 14h (Multiple linear) temperature dependent model has the highest values with 96.2 %, 96.6176 % and 99.1369 % respectively; the model also have the lowest RMSE value of 0.4488 $MJm^{-2}day^{-1}$. The Chen model has the lowest MBE and t – test values with 0.0050 $MJm^{-2}day^{-1}$and 0.0173 respectively. The proposed model, equation 14d (Linear exponential) temperature dependent model have the lowest MPE with overestimation of 0.0752 % in its estimated value. The results revealed that despite the observed overestimation and underestimation exhibited by some of the existing and proposed models they all fall within the acceptable range ($MPE \leq \pm 10\%$) and the $t_{cal} < t_{critical}$ values for all the models under consideration; therefore the t −test shows that all models are significant at 95% and 99% confidence levels except for the proposed model, equation 14e (Quadratic logarithmic) that is not significant at both confidence levels.

The total ranks acquired by the different models (Table 5b) were in the range 11 to 50, based on the overall results for Ikeja; the proposed empirical multiple linear temperature dependent model given in equation 14h was found more accurate for estimating global solar radiation in this location as compared to other evaluated temperature dependent models.

The Hargreaves and Samani and the Garcia models results obtained for Ikeja in this study were compared to that carried out by Kolebaje et al. [24]. The model equations with its empirical constants are given in equations 14b and 14c while the empirical constants given by Kolebaje et al. [24] are -0.318 and 0.271 for HS model and 0.094 and 0.523 for Garcia model. In this study, the MBE, RMSE, MPE and t – test are found to be -0.0287 $MJm^{-2}day^{-1}$,1.0049 $MJm^{-2}day^{-1}$, -0.4297 % and 0.0946 respectively for HS model and MBE, RMSE, MPE, and t – test were found to be -0.0204 $MJm^{-2}day^{-1}$, 1.1618 $MJm^{-2}day^{-1}$,-0.6651 %and 0.0583 for Garcia model while the MBE, RMSE, MPE, and t – test given by Kolebaje et al. [24] are given as 0.3468 $MJm^{-2}day^{-1}$, 0.8870 $MJm^{-2}day^{-1}$, 3.0847 % and 1.4087 respectively for HS model and the MBE, RMSE, MPE and t – test are given as 0.4014 $MJm^{-2}day^{-1}$, 0.9622 $MJm^{-2}day^{-1}$,3.5957%and 1.5223 respectively for Garcia model. Thus, this is evident that the evaluated HS and Garcia models in this study perform better than those by Kolebaje et al. [24]. However, the proposed model, equation 14h (multiple linear) is reported as the best and therefore most suitable for estimating global solar radiation in this location as compared to other evaluated temperature dependent models.

3.1.4 Temperature Dependent Models for Benin

The empirical existing temperature dependent models for Benin obtained through regression analysis based on Table 1 are

$$\frac{H}{H_0} = -0.219 + 0.316 \ln \Delta T \qquad (15a)$$

$$\frac{H}{H_0} = -0.190 + 0.221\, \mathrm{Sqrt}\, \Delta T \qquad (15b)$$

$$\frac{H}{H_0} = 0.148 + 0.426\, \frac{\Delta T}{S_0} \qquad (15c)$$

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The proposed developed empirical temperature dependent models for Benin obtained through regression analysis based on Table 2 are

$$\frac{H}{H_0} = -1.26 + 0.810\ \text{Sqrt}\,\Delta T - 0.0336\exp Sqrt\,(\Delta T) \qquad (15d)$$

$$\frac{H}{H_0} = 0.76 + 0.770\ \Delta T - 0.0273\ (\Delta T)^2 - 2.27\ln\Delta T \qquad (15e)$$

$$\frac{H}{H_0} = -0.368 + 0.157\ \Delta T - 0.00668\ (\Delta T)^2 - 0.00000107\exp\Delta T \qquad (15f)$$

$$\frac{H}{H_0} = -6.46 + 6.23\frac{\Delta T}{S_0} + 5.06\left(\frac{\Delta T}{S_0}\right)^2 - 6.37\exp\left(\frac{\Delta T}{S_0}\right) \qquad (15g)$$

$$\frac{H}{H_0} = -15.6 - 0.550\ \Delta T + 0.217\ T_{mean} + 10.8\ T_r \qquad (15h)$$

Table 6a: Statistical validation indicators of the temperature dependent models for Benin

Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.15a (Chen)	87.1	**0.0061**	0.828	-0.3489	**0.0245**	86.0115	96.1224
Eqn.15b (HS)	84.9	0.0075	0.9014	-0.4248	0.0275	83.4222	95.3088
Eqn.15c (Garcia)	82	-0.0083	0.9933	-0.4395	0.0276	79.8707	93.9994
Proposed Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.15d	94.4	0.1734	0.5791	-1.1698	1.0409	93.157	98.2556
Eqn.15e	94.8	-0.0911	0.5426	0.516	0.5647	93.9935	98.4675
Eqn.15f	94.6	0.1206	0.5583	-0.7927	0.7335	93.6404	98.4108
Eqn.15g	**96.5**	-0.037	**0.4444**	**0.2037**	0.277	**95.9709**	**98.9839**
Eqn.15h	92.6	-0.5453	0.8308	3.4850	2.8851	85.9192	96.6334

Table 6b: Ranking the temperature dependent models for Benin based on statistical validation indicators

Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total
Eqn.15a (Chen)	6	1	5	2	1	5	6	26
Eqn.15b (HS)	7	2	7	3	2	7	7	35
Eqn.15c (Garcia)	8	3	8	4	3	8	8	42
Proposed Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total
Eqn.15d	4	7	4	7	7	4	4	37
Eqn.15e	2	5	2	5	5	2	2	23
Eqn.15f	3	6	3	6	6	3	3	30
Eqn.15g	1	4	1	1	4	1	1	**13**
Eqn.15h	5	8	6	8	8	6	5	46

Table 6a and 6b summarizes the different statistical validation indicators utilized in this study and the ranking of the temperature dependent models for Benin. Based on the R^2, NSE and IA the result indicated that the proposed model developed in this study, equation 15g (Quadratic exponential 2) temperature dependent model has the highest values with 96.5 %, 95.9709 % and 98.9839 % respectively; the model also have the lowest RMSE and MPE values of 0.4444 $MJm^{-2}day^{-1}$ and 0.2037 % respectively. The Chen model has the lowest MBE and t – test values of0.0061 $MJm^{-2}day^{-1}$ and 0.0245 respectively. The results revealed that

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despite the observed overestimation and underestimation exhibited by some of the existing and proposed models they all fall within the acceptable range ($MPE \leq \pm 10\%$) and the $t_{cal} < t_{critical}$ values for all the models under consideration are significant at 95% and 99% confidence levels, except for the proposed model, equation 15h (multiple linear) that is not significant at 95% confidence level.

The total ranks acquired by the different models (Table 6b) were in the range 13 to 46, based on the overall results for Benin; the proposed empirical quadratic exponential 2 temperature dependent model given in equation 15g was found more accurate for estimating global solar radiation in this location as compared to other evaluated temperature dependent models.

3.1.5 Temperature Dependent Models for Owerri

The empirical existing temperature dependent models for Owerri obtained through regression analysis based on Table 1 are

$$\frac{H}{H_0} = -0.196 + 0.311 \ln \Delta T \qquad (16a)$$

$$\frac{H}{H_0} = -0.149 + 0.211 \, \text{Sqrt} \, \Delta T \qquad (16b)$$

$$\frac{H}{H_0} = 0.185 + 0.395 \, \frac{\Delta T}{S_0} \qquad (16c)$$

The proposed developed empirical temperature dependent models for Owerri obtained through regression analysis based on Table 2 are

$$\frac{H}{H_0} = -1.27 + 0.800 \, \text{Sqrt} \, \Delta T - 0.0309 \exp Sqrt\,(\Delta T) \qquad (16d)$$

$$\frac{H}{H_0} = -3.41 - 0.89 \, \Delta T + 0.0223 \, (\Delta T)^2 + 4.61 \ln \Delta T \qquad (16e)$$

$$\frac{H}{H_0} = -0.998 + 0.327 \, \Delta T - 0.0180 \, (\Delta T)^2 + 0.00000193 \exp \Delta T \qquad (16f)$$

$$\frac{H}{H_0} = -9.9 - 2.71 \, \frac{\Delta T}{S_0} - 10.1 \left(\frac{\Delta T}{S_0}\right)^2 + 8.6 \exp\left(\frac{\Delta T}{S_0}\right) \qquad (16g)$$

$$\frac{H}{H_0} = -11.9 - 0.411 \, \Delta T + 0.157 \, T_{mean} + 8.41 \, T_r \qquad (16h)$$

Table 7a: Statistical validation indicators of the temperature dependent models for Owerri

Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.16a (Chen)	87	-0.0196	0.7816	-0.1178	0.0833	87.0019	96.4661
Eqn.16b (HS)	85	-0.0495	0.8419	**0.0144**	0.1953	84.918	95.7915
Eqn.16c (Garcia)	82.6	**-0.001**	0.909	-0.3478	**0.0035**	82.4188	94.99
Proposed Models	R^2	MBE	RMSE	MPE	t	NSE	IA
Eqn.16d	93.4	0.1461	0.5896	-0.9228	0.8483	92.6019	98.1992
Eqn.16e	94	0.4952	0.7434	-2.9244	2.9618	88.2391	97.4554
Eqn.16f	94.1	0.0466	**0.5304**	-0.2984	0.2928	**94.0147**	**98.5253**
Eqn.16g	**94.4**	3.1884	3.2653	-18.9461	15.0089	-126.877	75.9188
Eqn.16h	86.1	-2.0503	2.1962	12.1129	8.6391	-2.6373	70.3528

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Table 7b: Ranking the temperature dependent models for Owerri based on statistical validation indicators

Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total
Eqn.16a (Chen)	5	2	4	2	2	4	4	23
Eqn.16b (HS)	7	4	5	1	3	5	5	30
Eqn.16c (Garcia)	8	1	6	4	1	6	6	32
Proposed Models	R^2	MBE	RMSE	MPE	t	NSE	IA	Total
Eqn.16d	4	5	2	5	5	2	2	25
Eqn.16e	3	6	3	6	6	3	3	30
Eqn.16f	2	3	1	3	4	1	1	**15**
Eqn.16g	1	8	8	8	8	8	7	48
Eqn.16h	6	7	7	7	7	7	8	49

Table 7a and 7b summarizes the different statistical validation indicators utilized in this study and the ranking of the temperature dependent models for Owerri. Based on the R^2 the result indicated that the proposed model developed in this study, equation 16g (Quadratic exponential 2) temperature dependent model has the highest values with 94.2 %. The Garcia model has the lowest MBE and t – test values with underestimation of 0.0010 $MJm^{-2}day^{-1}$ in its estimated value and 0.0035 respectively. The proposed model, equation 16f (Quadratic exponential 1) temperature dependent model have the lowest RMSE value of 0.5304 $MJm^{-2}day^{-1}$ and highest NSE and IA values of 94.0147 % and 98.5253 % respectively. The Hargreaves and Samani (HS) model has the lowest MPE with overestimation of 0.0144 % in its estimated value. The results revealed that despite the observed overestimation and underestimation exhibited by some of the existing and proposed models they all fall within the acceptable range ($MPE \leq \pm 10\%$)except for the proposed models, equation 16g (Quadratic exponential 2) and equation 16h (multiple linear). The $t_{cal} < t_{critical}$ values for all the models under consideration are significant at 95% and 99% confidence levels, except for the models, equation 16g (Quadratic exponential 2) and equation 16h (multiple linear) that is not significant at both confidence levels while the model, equation 16e (Quadratic logarithmic) is not significant at 95% confidence level.

The total ranks acquired by the different models (Table 7b) were in the range 15 to 49, based on the overall results for Owerri; the proposed empirical quadratic exponential 1 temperature dependent model given in equation 16f was found more accurate for estimating global solar radiation in this location as compared to other evaluated temperature dependent models.

3.2 Correlation between the measured and estimated temperature dependent models

Fig. 2a shows the comparison between measured and estimated temperature dependent global solar radiation models for Akure. The estimated temperature dependent models underestimated the measured global solar radiation in the month of October and November and overestimated the measured in the month of February. The existing temperature dependent models (Chen, HS and Garcia models) including the model equation 12h overestimated the measured and other estimated models in the month of July and August. The model equation 12h also overestimated the measured and other estimated models in the month of February and March. The Garcia model underestimated the measured and other estimated models in the month of April and May.

Fig. 2b shows the comparison between measured and estimated temperature dependent global solar radiation models for Ogoja. The estimated temperature dependent models underestimated the measured global solar radiation in the month of June and overestimated the measured in the month of January, July and August. The existing temperature dependent models (Chen, HS and Garcia models) including the model equation 12h overestimated the measured and other estimated models in the month of July and August.

Fig. 2c shows the comparison between measured and estimated temperature dependent global solar radiation models for Ikeja. The estimated temperature dependent models underestimated the measured global solar radiation in the month of April and May. It is obvious that the model equation 14e underestimated the measured and other estimated models throughout the period under investigation except in the month of September and October where it has almost similar value with the measured. The Garcia model overestimated the measured and other estimated models in the month of January, July and August, so also is the model equation 14g in the months from October to December.

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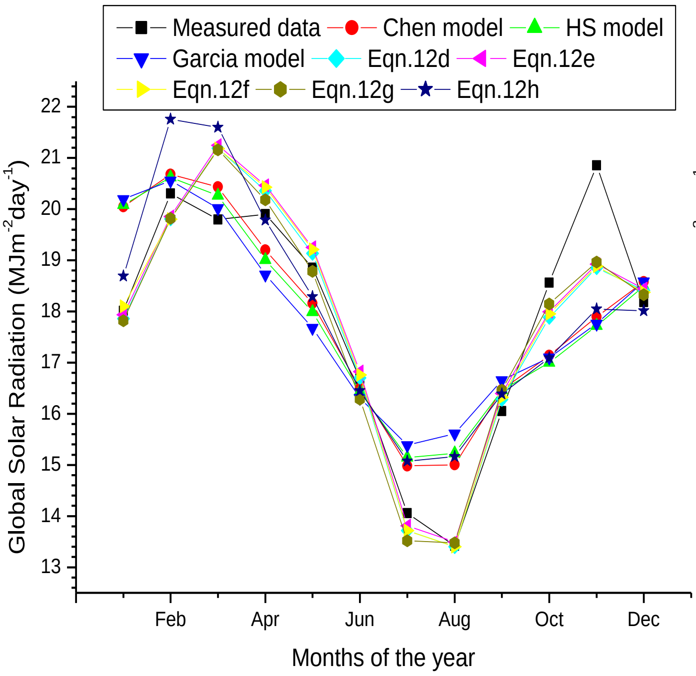
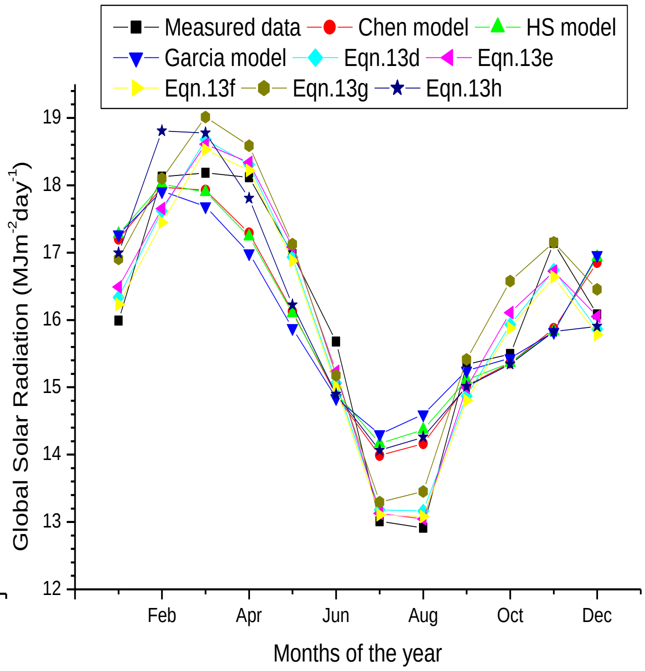
Fig. 2d shows the comparison between measured and estimated temperature dependent global solar radiation models for Benin. The estimated temperature dependent models underestimated and overestimated the measured global solar radiation in the month of November and January respectively. The existing temperature dependent models (Chen, HS and Garcia models) overestimated the measured and other estimated models in the month of August while the model equation 15h underestimated the measured and other estimated models in the same month and in the months of June, July, October and December. The Garcia model overestimated the measured and other estimated models in the months of January, February, July, August and September and underestimated same from March to May.

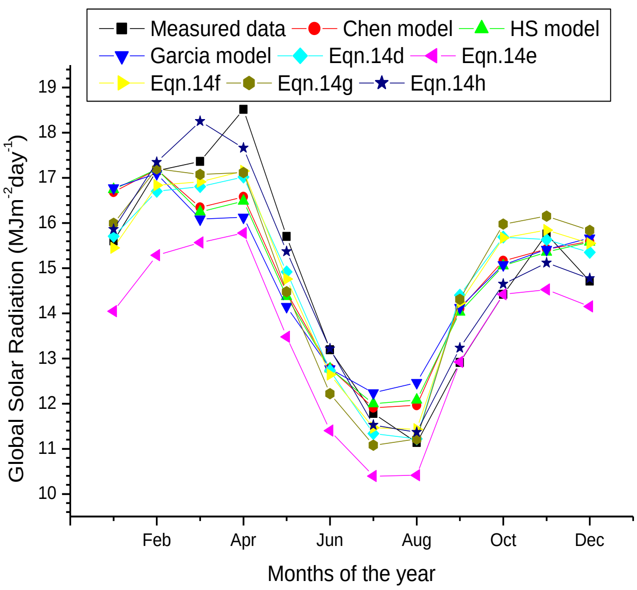
Fig. 2e shows the comparison between measured and estimated temperature dependent global solar radiation models for Owerri. It is obvious that there is remarkable overestimation and underestimation in the estimated values of the models equation 16g and 16h as compared to the measured and other estimated models throughout the months under investigation.



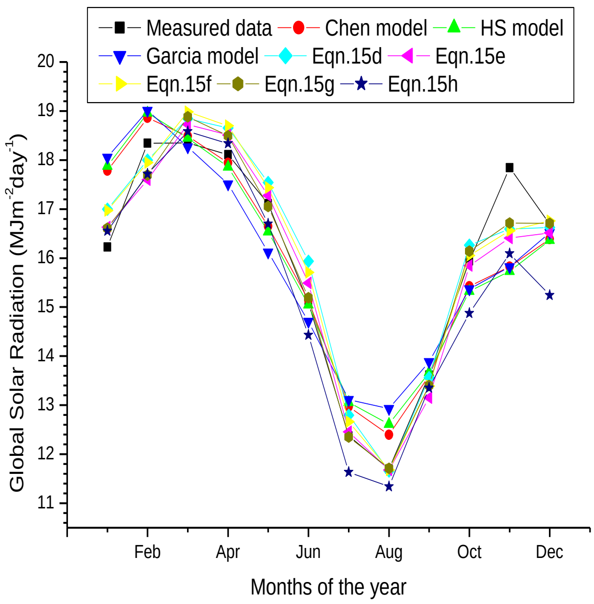
(a)



(b)



(c)



(d)

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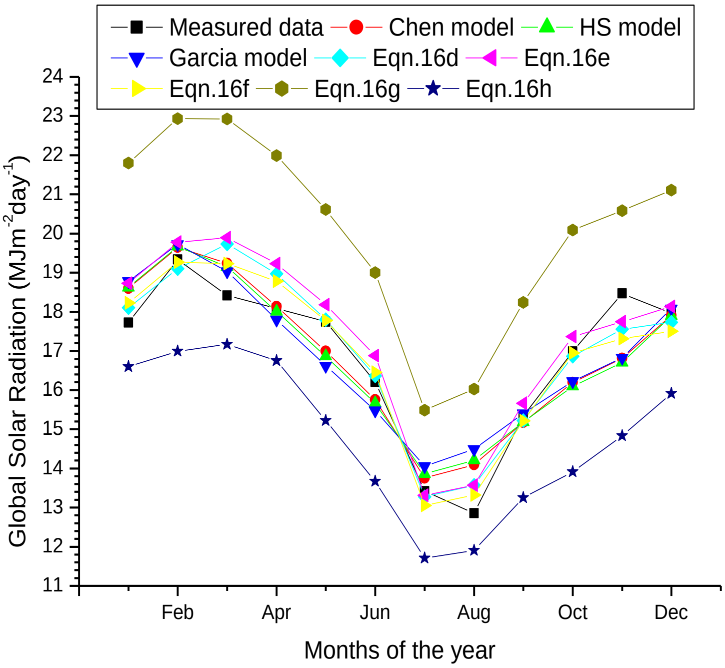

(e)

Fig. 2: Comparison between the measured and estimated global solar radiation for Coastal region (a) Akure (b) Ogoja (c) Ikeja (d) Benin (e) Owerri .
Eqn. 12d, 13d, 14d, 15d, 16d – Linear exponential, Eqn. 12e, 13e, 14e, 15e, 16e – Quadratic logarithmic, Eqn. 12f, 13f, 14f, 15f, 16f – (Quadratic exponential 1), Eqn. 12g, 13g, 14g, 15g, 16g – Quadratic (exponential 2), Eqn. 12h, 13h, 14h, 15h, 16h – Multiple linear .

4. CONCLUSION

This study evaluates eight different temperature dependent models; five proposed (linear exponential, quadratic logarithmic, quadratic exponential 1, quadratic exponential 2 and multiple linear) and three existing (Chen, HS and Garcia) using monthly average daily global solar radiation, maximum and minimum temperature data during the period of thirty one (1980 – 2010) years. The most accurate model for estimating global solar radiation in each of the studied areas (Akure, Ogoja, Ikeja, Benin and Owerri) located in the Coastal climatic zone of Nigeria was determined using coefficient of determination (R^2), Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), t – test, Nash – Sutcliffe Equation (NSE) and Index of Agreement (IA). The results showed that in Akure, Ogoja, Ikeja, Benin and Owerri; the proposed quadratic logarithmic, linear exponential, multiple linear, quadratic (exponential 2) and quadratic (exponential 1) temperature dependent models respectively were found to be most suitable and can be used in locations with comparable weather condition. The variation of the regression coefficients given in the temperature dependent models indicates that they are site – dependent; therefore when use in locations other than where they are developed, the empirical coefficients should be calibrated against the local data, even though the models are to be used in the same climatic zone. The results showed that the accuracy of each evaluated temperature dependent model varies significantly from one location to another in the coastal climatic zone of Nigeria; notably is the quadratic logarithmic temperature dependent model that was found most accurate in Akure performed poorly in Ikeja. The evaluated HS and Garcia temperature dependent models for Ikeja in this study performed better than those found in literature based on statistical validation indicators. The most accurate models were found to have the best fitting as compared to other estimated temperature dependent models when correlated with the measured global solar radiation data.

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