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New model to estimate daily global solar radiation over Nigeria

O.O. Ajayi [a,*], O.D. Ohijeagbon [b], C.E. Nwadialo [a], Olumide Olasope [a]

[a] *Mechanical Engineering Department, Covenant University, P.M.B. 1023, Ota, Nigeria*
[b] *Mechanical Engineering Department, University of Lagos, Akoka, Lagos, Nigeria*

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ABSTRACT

This study focussed on developing an appropriate model for estimating daily global solar radiation for any location in Nigeria. Data for the study were obtained from the Nigeria Meteorological Agency, covering 12 sites, spread across the six geopolitical zones, for a period between 1987 and 2010. Various statistical methods were employed to determine the performance and accuracy of the model. A multivariate model that expresses global solar irradiance in terms of location latitude, daily relative sunshine, maximum daily temperature, daily average relative humidity, and cosine of day number was developed. The inclusion of the maximum daily temperature and daily mean relative humidity makes the model much more sensitive to climatic and weather changes. Also, the seasonal fluctuations of the humid tropical region are also well captured in the model. The analysis showed a good agreement between the measured data and computed results. Thus the model can be used to predict the global solar irradiance over Nigeria with minimum error. Further to this, the global solar radiation intensity values produced by this approach can be used in the design and estimation of the performance of solar applications.

Introduction

Over the years energy availability has proved to be a pivotal element to the development of any nation. The challenge of improving existing energy generation modules and also developing new ones has always been a major phenomenon across the globe. The issues of sustainable development as it concerns energy generation and distribution is also a subject of intense debate [1]. This is because the widely used energy generation modules across several countries are those of fossil fuel and nuclear power origin. These sources have been proven to be harmful to both the environment and humans. The present energy shift is basically towards encouraging utilization of renewable energy (RE) resources for power generation. This is due to the fact that they are environmentally friendly, widely available, easily applicable and non toxic [2,3]. One of the major sources of RE is the Solar energy.

Solar energy occupies one of the most significant positions among the various potential alternative energy sources [4]. A precise knowledge of the solar radiation profile at a particular geographical location is of vital importance for the development and performance estimation of most solar energy devices [4]. However, for many developing countries solar radiation measurements are not easily obtainable due to inability to afford the required measuring equipment and poor operating techniques used on the available ones. In Nigeria, barely few stations collect solar radiation data on a regular basis [5].

Moreover, the utilization of solar energy resources for power generation in a given location requires the first step of resource assessment. This is necessary in order to have adequate information on the solar radiation intensity at such location [6,7]. Thus the information on the global solar radiation of different local sites is usually globally required [8–12]. Such knowledge will aid solar energy product marketing and also enhance the development of solar applications [12,13]. It is also required for the determination of the global distribution of thermal load on buildings and to carryout analysis and design of solar-energy collecting systems [10]. Other important areas of application include its use in the development of crop growth models and also to carryout designs of irrigation systems [10].

Therefore since the shift in energy utilization for sustainable growth and development is towards renewable energy such as solar electricity. It is therefore imperative that accurate and precise data is used in the design of various solar power systems. However, solar radiation data obtained through direct measurements are not always readily available for different places across the world. Therefore, various estimation procedures have been developed to evaluate global solar radiation which is the integral of solar irradiance over a time period. This is by way of modelling.

Modelling global solar radiation: previous studies and the case for present work

There have been numerous researches into the estimation of the global solar radiation incident on a horizontal surface. An initial empirical correlation was proposed by Angstrom [14], which

* Corresponding author. +234 8036208899.
E-mail address: oluseyi.ajayi@covenantuniversity.edu.ng (O.O. Ajayi).

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correlated global solar radiation with the ratio of sunshine duration. The Angstrom correlation was adjusted by Prescott [15] and Page [16], and their modifications are being used widely to estimate global irradiance [17].

A study of the world profile of solar radiation was carried out by Lof et al. [18] and attempts at finding common models applicable anywhere in the world are still in progress [19]. More so, attempts at developing models in large domains such as Europe [20] and wet tropical countries [21] have been the focus of some investigators. In addition, the accuracy of the Angstrom correlation and its several derivatives for predicting solar radiation over an entire country has been examined in many countries. Such countries include Canada [22,23] and Australia [24]; South Asian countries such as Sri Lanka [25], India [26] and Pakistan [27]; Caribbean countries such as Guatemala [28], the West Indies [29] and Venezuela [30]. Research has also been undertaken in Middle East countries like Kuwait [31], Iraq [32] and Turkey [33,34]. In South East Asia, studies have been done in Hong Kong [35], Macau [36], Thailand [37], Malaysia [38], Singapore [39], Vietnam [40] and China [41]. On the African continent, countries such as Egypt [42,43], Nigeria [44], Sudan [45] and Lesotho [46] have also modified the correlation.

Moreover, different models exist that correlates different meteorological parameters to evaluate the global solar irradiance (H) of a place. Some of these include those that evaluate H from the correlation of parameters such as maximum and minimum temperatures, amount of cloud cover, extraterrestrial radiation, relative humidity, latitude, elevation, soil temperature, precipitation, evaporation and number of rainy days, [8,10–12,47–60], also parameters such as sunshine duration, maximum air temperature, altitude and location of the place in relation to water surfaces, the solar declination angle, mean daily vapor pressure and mean daily sea level pressure, mean cloudiness, mean precipitation and mean evaporation [47–55] have also been used in creating models.

The model that correlates the global solar radiation to the relative sunshine hours commonly called the Angstrom–Prescott model is given by Eq. (1):

$$K_T = \frac{H}{H_o} = a + b\frac{\bar{n}}{N} \qquad (1)$$

where K_T = clearness index, H_o = extraterrestrial solar radiation, $\bar{n}$ = the monthly average sunshine hours, N = monthly average sunshine duration or day length, a and b are correlation coefficients (or constants). The ratio $\frac{\bar{n}}{N}$ is called the relative sunshine.

Basically, major argument against Eq. (1) or its modifications has been the fact that it is location dependent [8,9,61]. However, it is reported in Ertekin and Yaldiz [62] and Jin et al. [8] that Eq. (1) type models give better accuracy than others and that it is convenient to apply.

For the case of Nigeria, some literatures exists that reported global solar radiation models of the Angstrom–Prescott and other model types. Some of the Angstrom–Prescott type models include the ones of Fagbenle [63]. He developed quadratic models to estimate global solar radiation for Benin City, Samaru and Ibadan, three locations in Nigeria. Akpabio and Etuk [9] developed a linear Angstrom–Prescott type model for Onne, Nigeria while Udo [61] presented a quadratic model for daily data spread over a two year period for Ilorin, Nigeria. In addition, Akpabio et al. [61] presented a modification to the Angstrom–Prescott model using a quadratic model to estimate for Onne, Nigeria. Augustine et al. [77] also created several regression models for 4 cities in southern Nigeria, using location dependent equations for each of the cities, their predictor variables were clearness index, relative sunshine, maximum temperature, cloudiness index, and relative humidity. Also Olayinka [78] estimated global and diffuse solar radiation for 4 selected cities in Nigeria with the same predictor variables as [77] using regression analysis, but the models were also site dependent. Yohanna et al. [74] also created an Angstrom–Prescott type model for Makurdi, Nigeria, the model is also location dependent.

Worthy of note however is the fact that, apart from Fagbenle [63] that estimated for the nation, other few existing reports estimated for specific local sites. However, it is reported that as at 2001, about 25% of the 774 local government areas of Nigeria were not connected to the national electricity grid and as at 2010, more than 80% of these areas were still not connected [64]. Therefore, since employing solar for power generation will be beneficial to these localities, modelling global solar radiation provides a way out to the unavailability of information regarding measured solar radiation in the country. Thus, a national estimation model developed from data for as many sites as are available is a plus.

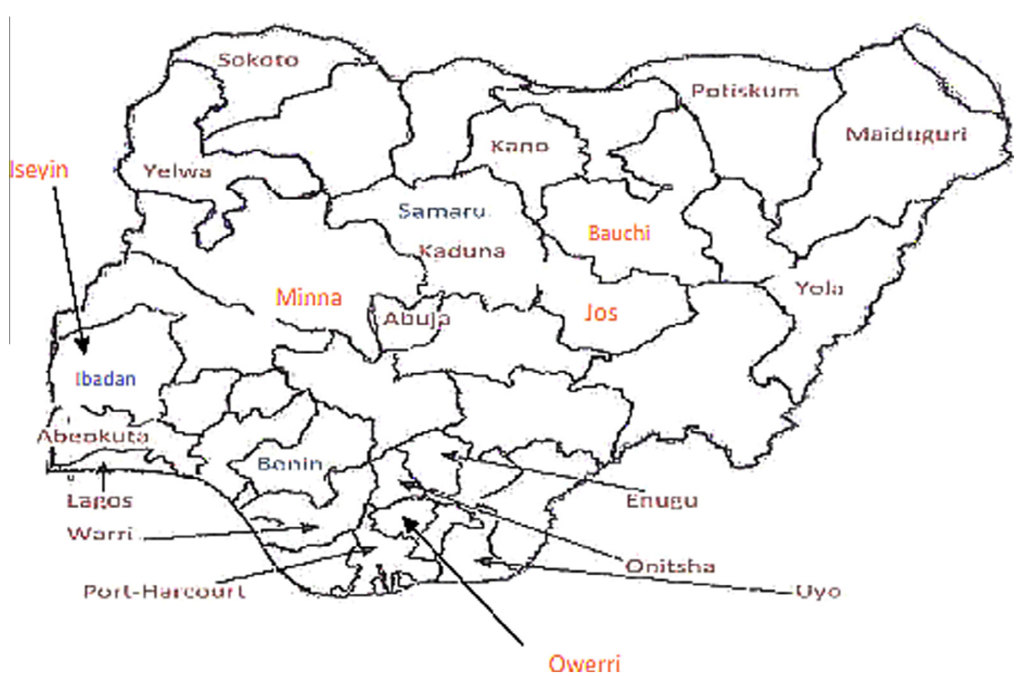

Fig. 1. Map of Nigeria showing the meteorological locations employed in the study. Samaru, Benin and Ibadan are sites employed by Fagbenle [63].

Fagbenle's preliminary work [63] was carried out using three sites (see Fig. 1) with one site each from South-West, South-South and North-Central geopolitical zones of Nigeria. The quadratic model used only two years data to estimate global solar radiation for the whole of Nigeria. Eq. (2) is the result of the study.

$$K_T = 0.376 - 0.138\left(\frac{\bar{n}}{N}\right) + 0.660\left(\frac{\bar{n}}{N}\right)^2 \quad (2)$$

The geographical spread and number of these locations have placed a limitation on the accuracy of the model. The number of years of data employed is another issue. It is very pertinent to note that modelling climatic variables is very important for proper prediction when measured data are not readily available. However such model must be developed from historical data taken over a period of some years for it to be accurate. Furthermore, developing a model that averages for the whole nation required employing data from as many sites scattered across the country. This is in order to have statistically significant correlation. Thus, suggesting a need for the development of a better and more accurate model that will be suitable for analysing and predicting the magnitude of H across the different locations of the country. With this model, the issue of unavailability of measured solar radiation is resolved as the values can be easily estimated.

Some of the shortcomings presently facing solar radiation models in Nigeria include: very limited number of years considered in developing the models [61,63], and also the very few number of stations' data employed in model development [63], and the fact most of them are location dependent [8,9,61,77,78,74].

It is therefore necessary to fill up this gap in Nigeria, by providing a model that will capture the nations' unique climate, and seasonal fluctuations in the tropics. Further to this, this study looks into the possibility of a new relationship between global solar irradiance (i.e. radiation expressed in W/m^2) (H) and some geographical and meteorological parameters for the whole of Nigeria.

This study was therefore used to create a new regression model for Nigeria that:

- better captures differences due to the changes in geographical location This is done by including the location latitude as an additional variable, despite its inclusion in the estimation of extraterrestrial radiation.
- is much more sensitive to climatic and weather changes by the inclusion of the maximum daily temperature, and mean daily relative humidity. These variables are better instantaneous climatic indicators of the amount of global solar radiation that could be captured for that location on a particular day.
- captures the seasonal fluctuations of the humid tropical region by adding to the model the cosine of the day number of the year.

This study therefore combines the location latitude, average daily relative humidity, daily ratio of sunshine duration, daily maximum temperature, and cosine of day number. Five equations were developed and their coefficients deduced. The predicted global solar radiation values, as calculated from the five correlations, were also compared with measured values and values cited in literature.

Present work

Based on the aforementioned, this study was focused on the development of a new multivariate regression model by employing 24 years daily data for more stations spread across the geopolitical zones of Nigeria.

Multivariate regression analysis is used when a relationship exists between a dependent variable and two or more independent variables. This method was chosen because of its better prediction ability, made possible by multiple predictors [66]. Worthy of note is the fact that models that mimic life phenomenon mostly involve multiple independent variables [67]. It is also useful in optimizing combinations of predictors, by carrying out independent correlations between the criterion variable and each predictor beforehand. When multiple independent variables are involved in a model, the examination of more sophisticated research hypotheses are possible than with simple correlations. This is because the independent variables can be numeric or categorical. The interactions between the variables can be incorporated hypothetically and polynomial terms can be included in the study [68].

The equations developed are of the form indicated in Eqs. (3)–(7):

Model 1

$$H = a\cos\phi + b\cos n + cT_{\max} + d\left(\frac{\bar{n}}{N}\right) + e\left(\frac{T_{\max}}{R.H}\right) + f\left(\frac{T_{\max}}{R.H}\right)^2 + g\cos\phi\cdot\cos n + h \quad (3)$$

Model 2

$$H = a\cos\phi + b\cos n + cT_{\max} + d\left(\frac{\bar{n}}{N}\right) + e\left(\frac{T_{\max}}{R.H}\right) + f\left(\frac{T_{\max}}{R.H}\right)^4 + g\cos\phi\cdot\cos n + h\frac{T_{\max}}{\cos\phi} + i \quad (4)$$

Model 3

$$H = a\cos\phi + b\cos n + cT_{\max} + d\left(\frac{\bar{n}}{N}\right) + e\left(\frac{\bar{n}}{N}\right)^3 + f\left(\frac{T_{\max}}{R.H}\right) + g\left(\frac{T_{\max}}{R.H}\right)^2 + h\left(\frac{T_{\max}}{R.H}\right)^3 + i\cos\phi\cdot\cos n + j\left(\frac{T_{\max}}{\cos\phi}\right) + k\cos^2 n + l \quad (5)$$

Model 4

$$H = a\cos\phi + b\cos n + cT_{\max} + d\left(\frac{\bar{n}}{N}\right) + e\left(\frac{\bar{n}}{N}\right)^3 + f\left(\frac{T_{\max}}{R.H}\right) + g\left(\frac{T_{\max}}{R.H}\right)^2 + h\left(\frac{T_{\max}}{R.H}\right)^3 + i\left(\frac{T_{\max}}{R.H}\right)^4 + j\cos\phi\cdot\cos n + k\left(\frac{T_{\max}}{\cos\phi}\right) + l\cos^2 n + m \quad (6)$$

Model 5

$$H = a\cos\phi + b\cos n + cT_{\max} + d\left(\frac{\bar{n}}{N}\right) + e\left(\frac{T_{\max}}{R.H}\right) + f(R.H) + g\cos\phi\cdot\cos n + h\left(\frac{T_{\max}}{\cos\phi}\right) + i\left(\frac{T_{\max}}{R.H}\right)^2 + j\left(\frac{\bar{n}}{N}\right)^2 + k\cos^2 n + l \quad (7)$$

where ϕ = location latitude (°), $\bar{n}$ = the daily sunshine hours, N = maximum sunshine duration or day length, $T_{\max}$ = maximum daily temperature (°C), n = day number in the year, R.H. = daily relative humidity, and a, b, c, d, e, f, g, h, i, j, k, l, m are correlation coefficients (or constants). The ratio $\frac{\bar{n}}{N}$ is called the relative sunshine and H is the daily global solar irradiance value (W/m^2).

Materials and methods

The twenty-four years (1987–2010) daily solar radiation, daily sunshine hour, daily relative humidity and daily maximum temperature data employed for this study were sourced from the Nigeria Meteorological (NIMET) agency, Oshodi, Lagos State, Nigeria. The data covered 12 sites spread across the six geopolitical zones of the nation. All zones were represented by 2 sites each. The distribution of the selected sites is as shown in Fig. 1. This was done in order to have an evenly spread data analysis around the country.

The global instantaneous solar radiation data were measured using Gunn-Bellani radiometer. The instrument provides a time-integrated estimation of radiation incident on a black body by measuring the volume of liquid distilled by the radiation. However, not all NIMET stations measure global solar radiation, thus this study employed data from stations with accurate and well documented databases.

To develop the models therefore, the global solar radiation data measured in millimeters using Gunn-Bellani distillate were converted to useful form (using a conversion factor of 1.1364 proposed by Sambo [69] to (MJ/m^2 day) which was further converted into (W/m^2) by a conversion factor of 11.5741. The collected data from NIMET was also used for quality control as it was used in evaluating the accuracy of the model developed in this study. This was done by comparing the calculated daily global solar radiation (H_{cal}) with that obtained from the NIMET Gun-Bellani apparatus (H_m). Table 1 presents the information regarding the sites.

Estimation of extraterrestrial solar radiation

Eq. (8) was used to estimate the extraterrestrial radiation [23]:

$$H_0 = \frac{24}{\pi} I_{SC}\left(1 + 0.033\cos\frac{360n}{365}\right)\left(\cos\phi\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360} \times \sin\phi\sin\delta\right) \tag{8}$$

where I_{sc} = solar constant = 1367 W/m^2, n = day number in the year, ϕ = location latitude (LAT), δ = declination angle (degrees) and ω_s = sunset hour angle (degrees).

$$\delta = 23.45\sin\left(\frac{360(n+284)}{365}\right) \tag{9}$$

$$\omega_s = \cos^{-1}(-\tan(\delta)\tan(\phi)) \tag{10}$$

$$N = \frac{2}{15}\omega_s \tag{11}$$

Model performance estimation

In order to predict the accuracy of the model and thereby select the best performing model, the Root Mean Square Error (RMSE), Mean Bias Error (MBE), Mean Percentage Error (MPE), Mean Absolute Percentage Error (MAPE), Mean Absolute Bias Error (MABE) and the Nash–Sutcliffe Coefficient of Efficiency (COE) were employed. These are given as [1–3,9,70–72]:

$$RMSE = \sqrt{\left(\sum_{i=1}^{n}(H_m - H_{cal})^2\right)/k} \tag{12}$$

$$MBE = \left(\sum_{i=1}^{n}(H_m - H_{cal})\right)/k \tag{13}$$

$$MPE = \frac{\left[\sum_{i=1}^{k}\left(\frac{H_m - H_{cal}}{H_m}\right) \times 100\right]}{k} \tag{14}$$

$$COE = 1 - \frac{\sum_{i=1}^{k}(H_{cal} - H_m)^2}{\sum_{i=1}^{k}(H_{cal} - \bar{H}_m)^2} \tag{15}$$

$$MAPE = \frac{\left[\sum_{i=1}^{k}\left|\left(\frac{H_m - H_{cal}}{H_m}\right)\right| \times 100\right]}{k} \tag{16}$$

$$MABE = \left(\sum_{i=1}^{n}|H_m - H_{cal}|\right)/k \tag{17}$$

where k = number of data points, $\bar{H}_m$ = mean of all the measured global solar radiation obtained from NIMET. The NIMET data were therefore employed together with Eqs. (8)–(11).

Results and discussion

The constants of Eqs. (3)–(7) were determined using the least square statistics. The corresponding results are presented in Table 2 below.

Determination of the best model fit

In order to determine the best model of Eqs. (3)–(7) that adequately fits the data set for the nation, it was necessary to determine the level of performance of the models. This was evaluated using Eqs. (12)–(17) and presented in Table 3.

Table 3 shows the values of RMSE was same for models 1, 2 and 3, with models 4 and 5 showing a considerable difference.

Based on the values of MBE and MPE, Table 3 indicates that models 1, 2, and 3 also have the same values, which shows better performance than both model 4 and 5. It is worthy of note, that the reported values of MBE and MPE (Table 3), contains some negative and positive results which neutralized out in the average. In order therefore to have a proper classification of the models, the MABE and MAPE statistics were computed and the trend of the degree of performance of the models, based on the values of MABE and MAPE, was found to be similar to that of RMSE. The results of MABE and COE gave model 3 as the best performing model. From all the results of analysis, model 3 is found to be the best performing model overall.

Further to this, the models were employed for each site in order to determine that which best fits the site specific data set. Table 4 presents the results of performance of all the models with site specific data for all the twelve sites. The results showed that with the

Table 1
The location of the meteorological sites employed in the study.

Geopolitical Zone	State	Latitude (*N*)	Longitude (*E*)
North–West	Sokoto	13.0833°	5.2500°
	Kano	12.0031°	8.5288°
North–East	Maiduguri	11.8333°	13.1500°
	Bauchi	10.5000°	10.0000°
North–Central	Jos	9.9167°	8.9000°
	Minna	9.6167°	6.5500°
South–West	Iseyin	7.9667°	3.6000°
	Ibadan	7.3907°	3.8923°
South–East	Enugu	6.4500°	7.5000°
	Owerri	5.4833°	7.0333°
South–South	Port-Harcourt	4.7833°	7.0000°
	Benin City	6.3176°	5.6145°

Table 2
Results of determined constants for the five developed models in this study.

Coefficients	Model 1	Model 2	Model 3	Model 4	Model 5
a	0.5175	−1.1515	−3.0811	−1.1718	−3.6889
b	19.219	18.0974	27.8746	28.161	29.309
c	5.513	5.6835	6.22147	7.0114	7.6652
d	125.757	123.143	51.4537	110.16	57.524
e	−21.683	−9.0768	92.9025	30.619	7.9618
f	5.634	0.19745	0.06058	−184.1	0.6421
g	−2.693	−2.5541	−6.4363	154.08	−3.6827
h	−33.15	−3.4211	1.88823	−52.038	−8.855
i	0	−14.276	−3.7365	6.048	0.499
j	0	0	−6.2588	−3.2879	91.308
k	0	0	−3.8329	−5.0832	−2.9855
l	0	0	15.8587	−0.0348	−61.702
m	0	0	0	13.852	0

Table 3
Results of error and performance analyses of the different models developed in the study.

Error term	Model 1	Model 2	Model 3	Model 4	Model 5	Minimum	Maximum
RMSE	0.117	0.117	0.117	0.176	0.137	0.117	0.176
MBE	0.012	0.012	0.012	0.12	0.063	0.012	0.12
MABE	0.084	0.083	0.082	0.136	0.097	0.082	0.136
MPE(×100%)	0.012	0.012	0.012	0.12	0.063	0.012	0.12
MAPE (×100%)	0.014	0.014	0.014	0.031	0.019	0.014	0.031
COE	0.649	0.652	0.658	0.333	0.587	0.333	0.658
Multiple *R* (%)	80.534	80.764	81.126	81.861	82.045	80.534	82.045
R-squared (%)	64.857	65.227	65.814	67.012	67.314	64.857	67.314

Table 4
Results of performance of all models of this study with site specific data for 12 sites.

Error Term	Location	Model 1	Model 2	Model 3	Model 4	Model 5
RMSE	Owerri	0.052854	0.054612	0.050925	0.122521	0.042588
MBE		0.0007	−0.0039	0.0003	0.106363	0.001145
MPE		0.0682	−0.3883	0.0303	10.63632	0.11455
MAPE		4.0639	4.2822	4.1527	10.6363	3.2885
RMSE	Iseyin	0.044041	0.045891	0.050483	0.134118	0.043815
MBE		3.96E-05	0.009398	0.00569	0.117513	−0.00291
MPE		0.003961	0.939806	0.569044	11.75128	−0.29146
MAPE		4.061	4.428	4.5719	11.751	3.533
RMSE	Port Harcourt	0.052996	0.041448	0.048503	0.152889	0.053366
MBE		0.042847	0.028125	0.030911	0.148112	0.043518
MPE		4.284692	2.812526	3.091133	14.81117	4.351762
MAPE		2.81	3.036	3.971	14.811	5.024
RMSE	Sokoto	0.081814	0.075376	0.069299	0.155916	0.076647
MBE		0.054185	0.044728	0.035545	0.143318	0.059101
MPE		5.41854	4.472793	3.554535	14.33185	5.910128
MAPE		7.298	6.676	5.933369	14.332	7.284
RMSE	Maiduguri	0.09258	0.091559	0.093619	0.09932	0.100443
MBE		−0.05205	−0.05258	−0.03644	0.05005	−0.05914
MPE		−5.2049	−5.25824	−3.64355	5.004969	−5.91417
MAPE		6.886	6.493	6.886	9.013	7.425
RMSE	Benin City	0.1501	0.147656	0.14521	0.071673	0.14692
MBE		−0.13626	−0.13438	−0.13343	−0.03278	−0.1324
MPE		−13.6258	−13.4376	−13.3428	−3.2782	−13.2401
MAPE		13.626	13.438	13.343	5.846	13.24
RMSE	Enugu	0.136483	0.137395	0.134852	0.177526	0.136149
MBE		0.020298	0.025089	0.025548	0.117836	0.022286
MPE		2.029799	2.508887	2.554837	11.78358	2.22856
MAPE		10.335	10.274	10.138	12.813	10.454
RMSE	Ibadan	0.236253	0.244078	0.242927	0.36993	0.232904
MBE		0.194003	0.203117	0.200541	0.331866	0.18891
MPE		19.40033	20.31168	20.05413	33.18664	18.89103
MAPE		19.4	20.312	20.054	33.187	18.89103
RMSE	Bauchi	0.058886	0.055824	0.054057	0.116091	0.051809
MBE		−0.01267	−0.00852	−0.01591	0.09565	−0.01252
MPE		−1.26693	−0.85215	−1.59053	9.565016	−1.25233
MAPE		5.645	5.431	5.0115	9.923	4.227
RMSE	Kano	0.060793	0.064259	0.072447	0.099436	0.094725
MBE		−0.03401	−0.03752	−0.04226	0.076165	−0.01674
MPE		−3.40148	−3.75237	−4.22601	7.616506	−1.67378
MAPE		5.265	5.528	6.175	7.617	7.928
RMSE	Minna	0.159724	0.159296	0.150296	0.269902	0.133941
MBE		0.094865	0.09793	0.093793	0.222832	0.097603
MPE		9.486507	9.793043	9.379328	22.28319	9.760296
MAPE		11.657	11.441	10.964	22.283	9.76
RMSE	Jos	0.135813	0.127495	0.129899	0.137978	0.121204
MBE		−0.08405	−0.07804	−0.09056	0.026322	−0.10553
MPE		−8.40482	−7.80396	−9.05616	2.632185	−10.5526
MAPE		11.062	10.401	9.813	12.263	10.579

exception of model 4, the remaining models performed very well with best performance by model 3 and closely followed by model 5. This shows that the model 3 can also be employed for each of the sites with minimal error.

Comparison of the model 3 to other national and international models

As was discussed earlier, various models of the different variations of the Angstrom type-model have been developed by

Table 5
Results of comparing the model 3 from this study with other models to determine the model with best fit.

Error term	Model 3	Fagbenle [63]	Akpabio et al. [61]	Udo (Akpabio et al. [61]	Akinoglu and Ecevit (Akpabio et al. [61]	Ertekin and Yaldiz [62]	Akinoglu and Ecevit [73]	Yohanna et al. [74]	Minimum	Maximum
RMSE	0.117	0.497	0.294	0.457	0.493	0.367	0.498	0.522	0.117	0.522
MBE	0.012	0.487	0.28	0.451	0.484	0.244	0.489	0.51	0.012	0.51
MPE	1.2	−2219	−1370	−2067	−2203	−922	−2225	−2303	1.2	−2303
MAPE	8.23	2219	1381	2067	2203	1532	2225	2303	8.23	2303
COE	0.658	0.0028	−0.006	0.0024	0.0028	0.013	0.0028	0.0031	−0.006	0.658

Table 6
Results of comparing model 3 from this study with other latitude-based models to determine the model with best fit.

Error term	Model 3	Gopinathan [75]	Rietveld [76]	Glower and McCulloch [75]	Minimum	Maximum
MBE	0.012	1.307	0.396	1.842	0.012	1.842
RSME	0.117	1.336	1.211	1.921	0.117	1.921
MPE	1.2	8.3	5.9	11	1.2	11

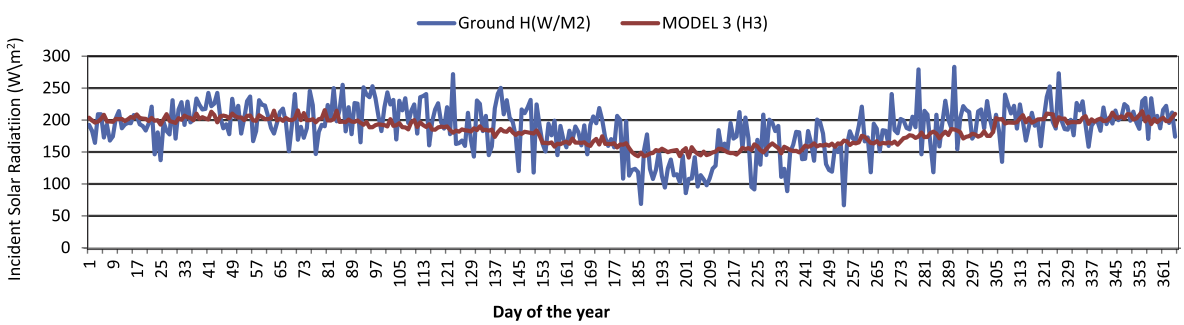

Fig. 2a. Comparison of estimated and actual H (Owerri).

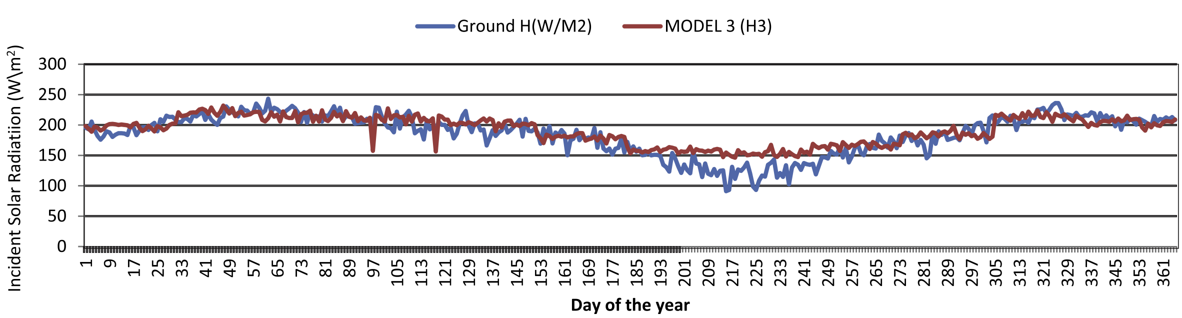

Fig. 2b. Comparison of estimated and actual H (Iseyin).

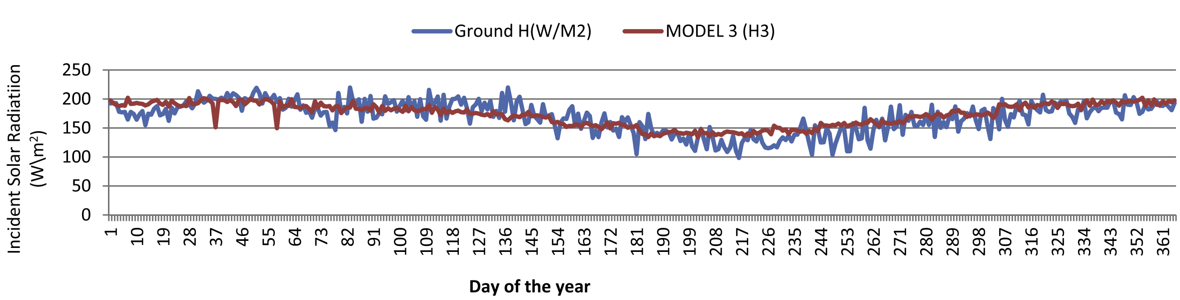

Fig. 2c. Comparison of estimated and actual H (Port-Harcourt).

different researchers. These correlate the clearness index to relative sunshine for specific local sites across the globe and in Nigeria. Of these models, seven were selected for comparison. These include models developed by Fagbenle [63], Akpabio et al. [61], Udo [61], Akinoglu and Ecevit [61], Ertekin and Yaldiz [62], Akinoglu and Ecevit [73] and Yohanna et al. [74]. Table 4 presents the results of error analyses and performance estimations of the models. The models are given as Eqs. (2), (18)–(23) respectively:

$$K_T = 0.147 + 1.125\left(\frac{\bar{n}}{N}\right) - 1.416\left(\frac{\bar{n}}{N}\right)^2 \quad (18)$$

$$K_T = 0.053 + 1.280\left(\frac{\bar{n}}{N}\right) - 0.830\left(\frac{\bar{n}}{N}\right)^2 \quad (19)$$

$$K_T = 0.145 + 0.845\left(\frac{\bar{n}}{N}\right) - 0.280\left(\frac{\bar{n}}{N}\right)^2 \quad (20)$$

$$K_T = -2.4275 + 11.946\left(\frac{\bar{n}}{N}\right) - 16.745\left(\frac{\bar{n}}{N}\right)^2 + 7.9575\left(\frac{\bar{n}}{N}\right)^3 \quad (21)$$

$$K_T = 0.145 + 0.845\left(\frac{\bar{n}}{N}\right) - 0.280\left(\frac{\bar{n}}{N}\right)^2 \quad (22)$$

$$K_T = 0.17 + 0.68\left(\frac{\bar{n}}{N}\right) \quad (23)$$

$$K_T = \left[\left[0.539\cos\phi - 0.0693Z\left(\frac{\bar{n}}{N}\right) - 0.309\right]\left[-1.027\cos\phi + 0.0926Z + 0.359\left(\frac{\bar{n}}{N}\right) + 1.527\right]\left(\frac{\bar{n}}{N}\right)\right] \quad (24)$$

$$K_T = 0.29\cos\phi + 0.52\left(\frac{\bar{n}}{N}\right) \quad (25)$$

$$K_T = 0.18 + 0.62\left(\frac{\bar{n}}{N}\right) \quad (26)$$

where Z is site altitude (in km).

Table 5 reveals that, in terms of the magnitude of the error analyses, model 3 developed in this study performs better than all the other models. This means that, Eq. (5) can be employed to predict the global solar radiation of Nigeria with minimal error. It can also be employed for the same purpose for other locations in Nigeria. Table 6 also compares model 3 with results from two other latitude-based models of Gopinathan [75] and Glower and McCulloch [76], and one Angstrom–Prescott model of Rietveld [75], given as Eqs. (24)–(26). These models were developed and tested with data from 14 cities around the globe. The cities include

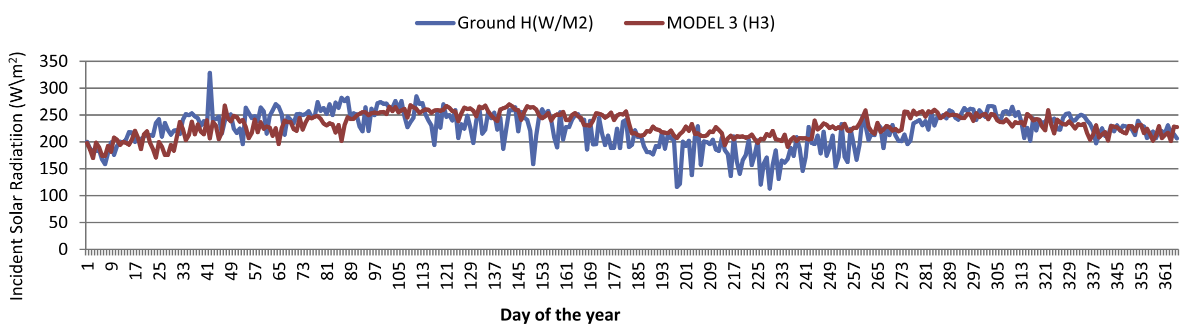

Fig. 2d. Comparison of estimated and actual H (Sokoto).

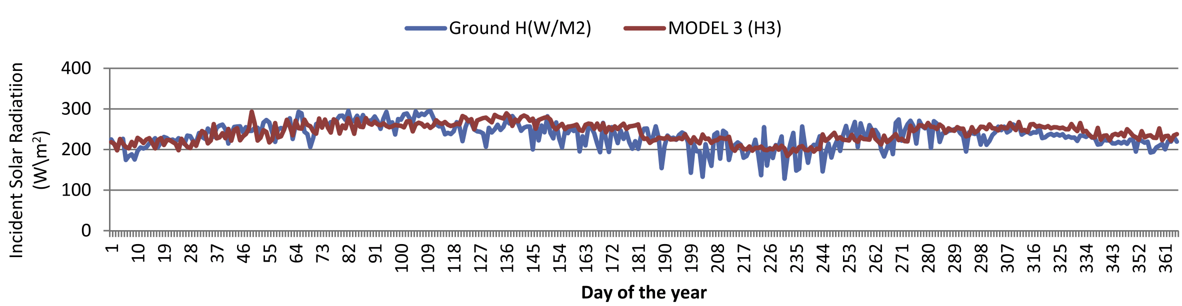

Fig. 2e. Comparison of estimated and actual H (Maiduguri).

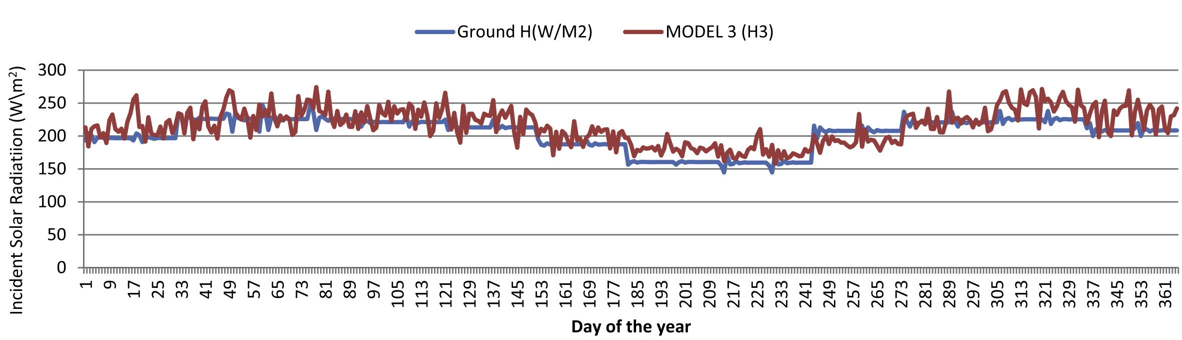

Fig. 2f. Comparison of estimated and actual H (Minna).

Ibadan in Nigeria. Table 6 therefore shows the result of comparing model 3 with these models. It reveals that Eq. (5) performed better and gave more accurate results for Nigeria. Further to this, when the mode performance was compared with other site specific models [77,78,74] to predict the sites reveal that the model Eq. (5) performed better.

Figs. 2a–2f shows comparison between estimated and actual values for six of the 12 stations modelled.

Conclusions

The development of an estimation model for the global solar radiation incident on a horizontal Nigerian surface was carried out in this study. Since the previous models with regard to Nigeria do not include the latitude, their accuracy and applications were limited to the sites from which the models were developed. This study therefore developed a new regression model for Nigeria that is much less site dependent and able to capture the differences due to changes in geographical locations. The inclusion of the maximum daily temperature and mean daily relative humidity makes the model much more sensitive to climatic and weather changes. More so, the variables are better instantaneous climatic indicators of the amount of global solar radiation that could be captured for that location on a particular day. The seasonal fluctuations of the humid tropical region are also well captured in the model. This is because the cosine of the day number of the year makes possible a global H distribution that is symmetrical about the middle of the year when the rainy season peaks, with an increasing global solar radiation profile towards December, and backwards towards January. Based on the aforementioned, the model fit that best approximates the global solar radiation over Nigeria is given as Eq. (5). Further to this, since the model is latitude based, it may be employed for estimating daily global solar radiation of other locations outside Nigeria with similar climatic conditions, especially those within the same latitude range.

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