Research Article

Evaluation of some global solar radiation models in selected locations in Northwest, Nigeria

Abstract

This study assesses the performance of four global solar radiation models in three selected locations (Gusua, Yelwa and Katsina) in North-western, Nigeria. A new model for estimating global solar radiation which is developed by Olomiyesan and Oyedum is also presented. This model alongside three existing models has been tested and validated for the selected locations using twenty-two years' (1984–2005) meteorological data collected from the Nigerian Meteorological Agency (NIMET). Global solar radiation estimated from the newly developed model was compared with the values obtained from Garcia, Hargreaves-Samani and Angstrom-Prescott models. The accuracy of the models was determined by using mean bias error (MBE), mean percentage error (MPE), root mean square error (RMSE) and coefficient of determination (R^2). Based on the statistical error indices obtained, Olomiyesan and Oyedum model was found to perform best in terms of accuracy, with the least RMSE values in the three locations, and highest coefficient of determination, R^2 values in two of the three locations. Thus, the newly developed model is suitable for estimating global solar radiation in the North-Western region of Nigeria and other locations with similar meteorological and climatic conditions.

Keywords: solar radiation, empirical model, statistical error, meteorological data

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Introduction

Availability of accurate solar radiation data is essential for the design of reliable and efficient solar energy devices in any location of interest. Using inaccurate solar radiation data for the design of solar energy application can affect the performance of such device, while paucity of solar data can hinder the implementation of solar energy application at any required site. Despite the importance of solar radiation data and the promotion of solar energy applications for generation of environmentally friendly energy, solar radiation data are still relatively scarce in many locations, especially in the developing countries.

This may be attributed to the lacks of measuring instruments and/ or relevant techniques, as well as poor maintenance culture, especially in developing countries.[1] For instance, in Nigeria, solar radiation data are mainly measured by Nigerian Metrological Agency (NIMET), mostly at the airports across the country.

The limited coverage of this measurement indicates that solar radiation data are not readily available for most locations in the country; hence the need to employ empirical methods for estimating solar radiation at any required location.[2]

Many articles for estimating monthly average daily global solar radiation have been published and tested based on different models.[3] Some of these models have regression constant(s) that are acclaimed to be universally applicable, while others contain regression coefficients that are site-dependent. However, there is always the need to calibrate empirical coefficients against a set of local data before they are used in locations other than base region.[2] Empirical models for estimation

of global solar radiation can be classified based on the number of input parameters used. Thus, the models can be classified as single-parameter models and multiple-parameter models.

Single-parameter models

These are regression models in which only one meteorological parameter is used as the main input data for the estimation of global solar radiation. The commonly used parameters in this category are sunshine duration, air temperature and cloud cover. Examples of such model include: Angström,[4] Black,[5] Hargreaves and Samani,[6] Bristow and Campbell,[7] Badescu[8] and El-Metwally.[9]

Multiple-parameter models

These are regression models which require two or more types of input data for the estimation of global solar radiation. The required input data for these models are usually a combination of various available meteorological parameters such as: sunshine duration, dew point temperature, soil temperature, relative humidity, cloud cover, precipitation, evaporation, pressure, wind speed, minimum and maximum temperatures. Examples of correlation with two or more input parameters are Swartman and Ogunlade,[10] Chen et al,[11] Ojosu and Komolafe[12] and Okonkwo and Nwokoye.[13]

Although many models have been developed for estimating global solar radiation, research is still on-going to develop new models and to improve the accuracy of the existing ones. Also, there is need to test the suitability of both new and existing models in given locations. Olomiyesan and Oyedum[14] developed a new model for estimating global solar radiation in Nigeria. The model has been tested and found to perform better than some existing models in three locations in the

North-western region of Nigeria. The purpose of this study is therefore to compare the performance of the new model with that of three other existing models in other locations in north-west region of Nigeria.

Studied models

Angstrom–prescott model

Angstrom-Prescott model is a modified version of Angstrom model.[15] It is a single-parameter model (sunshine-based model) that has been widely used for estimating monthly average daily global solar radiation. In Nigeria it was used for the estimation of monthly average daily global solar radiation in Yola, Maiduguri and Minna by Medugu and Yakubu;[16] Musa, Zangina and Aminu[17] and Olomiyesan et al.[18] respectively. The Angstrom-Prescott model is given as:

$$\frac{H}{H_O} = a + b\frac{S}{S_O} \tag{1}$$

where:

H = monthly average daily global radiation on a horizontal surface (MJm^{-2}day^{-1});

H_o = monthly average daily extraterrestrial radiation on a horizontal surface (MJm^{-2}day^{-1});

S = monthly average daily number of hours of bright sunshine;

S_o = monthly average daily maximum number of hours of possible sunshine;

a, b = regression constants.

Hargreaves and samani model

Hargreaves and Samani[6] were the first to propose a procedure to estimate the global solar radiation by using the difference between monthly average of daily maximum and daily minimum air temperature and extraterrestrial irradiation. It is a single-parameter model and can be expressed in the form:

H_o can be calculated using the equation given by[22] as:

$$H_o = \frac{24 \times 3600}{\pi} \times I_{SC}\left[1.0 + 0.033\cos\left(\frac{360dn}{365}\right)\right] \times \left[cos\varnothing cos\delta sin\omega S + \frac{\pi}{180}\omega S sin\delta sin\varnothing\right] \tag{5}$$

where:

ω_s = Sunset hour angle in degree defined as: $\omega_s = \cos^{-1}(-\tan\varnothing \tan\delta)$; $\tag{6}$

$$S_O = \frac{2}{15}\omega_s \tag{7}$$

δ = declination angle given as: $\delta = 23.45 \sin^{360(284 + d^{n)/365}}$; $\tag{8}$

$\varnothing$ = the latitude of the location;

dn = day number of the year starting from the first of January as dn=l;

$$\frac{H}{H_O} = a\left(\Delta T\right)^{0.5} \tag{2}$$

where ΔT is the difference between the monthly average of daily maximum and minimum air temperature (T_{max} - T_{min}). The coefficient a is regression constant. Later, Hargreaves[19] recommended using a = 0.16 for interior regions and a = 0.19 for coastal regions. Hassan and Onimisi[20] employed this model to assess the global solar energy potential at Nigerian Defence Academy (NDA) Permanent Site, Afaka Kaduna, Nigeria.

Garcia model

Garcia proposed a single-parameter model for estimating global solar radiation in 1994. Garcia model is an adaptation of Angstrom-Prescott model with a slight modification that makes it temperature-based type expressed in the form:[21]

$$\frac{H}{H_O} = a + b\frac{\Delta T}{S_O} \tag{3}$$

where a, b are regression constants to be determined and ΔT is the difference between maximum and minimum temperature values. Abdulsalam et al.[21] used this model to estimate the global solar radiation in some selected locations in North-western, Nigeria.

Olomiyesan and oyedum model

A multiple-parameter regression model was developed for the estimation of global solar radiation in 2016. Garcia model was incorporated into Angstrom-Prescott model to obtain a new model with three regression constants. The model has been tested and found suitable for estimating global solar radiation in three locations in Northwest region of Nigeria.[14] The proposed model is of the form:

$$\frac{H}{H_O} = a + b\frac{S}{S_0} + c\frac{\Delta T}{S_O} \tag{4}$$

where a, b, and c are the regression constants to be determined for a given location. Other symbols are as earlier defined.

I_{SC} = Solar constant given as 1367 (Wm^{-2});

Study area

Three locations from the North-Western region of Nigeria selected for this study are Katsina (12.15^{o}N, 7.30^{o}E), Gusau (12.10^{o}N, 6.15^{o}E) and Yelwa (11.80^{o}N, 4.34^{o}E). The climatic condition in this region is typical of the northern part of Nigeria with two major seasons: a long dry season and a short wet season. The dry season extends from October to April, while the wet season covers a relatively shorter period, from May to September. The dry season includes the harmattan, a dry chilly spell that commences in December and lasts

till February, and is associated with lower temperatures, a dusty and hazy atmosphere brought about by the north-easterly winds blowing from the Sahara desert.

Methodology

Data collection

The twenty-two years' (1984–2005) meteorological data consisting of monthly mean daily sunshine duration, minimum and maximum temperatures, and global solar radiation used for this study were collected from the Nigerian Meteorological Agency (NIMET), Oshodi, Lagos. The global solar radiation data were measured in millimetre using Gunn-Bellani radiometer. The Gunn-Bellani solar radiation data were converted to $MJm^{-2}day^{-1}$ using a conversion factor ($1mm = 1.216\ MJm^{-2}day^{-1}$) proposed by.[23]

Data analysis techniques

Microsoft Excel software package was used for the collation of the monthly mean values of the data collected from NIMET and in carrying out other statistical analysis and computation.

The regression constants for the models used (Angstrom-Prescott, Garcia and Olomiyesan-Oyedum models) were obtained using SPSS software. Linear regressions were carried out between the observed monthly clearness index and other meteorological parameters using 15 years data (1984-1998).

Estimated values of global solar radiation for the three sites were compared with the ground measured data to determine their level of accuracy using statistical indicators which include mean bias error (MBE), mean percentage error (MPE), root mean square error (RMSE), coefficient of correlation (R), and coefficient of determination (R^2).

The expressions for the MBE ($MJm^{-2}day^{-1}$), MPE (%) and RMSE ($MJm^{-2}day^{-1}$) as given by[24] are:

$$MBE = \frac{\left[\sum(H_{iest} - H_{imeas})\right]}{n} \tag{9}$$

$$MPE = \frac{\left[\sum\left(\frac{H_{imeas} - H_{iest}}{H_{imeas}} \times 100\right)\right]}{n} \tag{10}$$

$$RMSE = \left[\frac{\sum(H_{iest} - H_{imeas})^2}{n}\right]^{1/2} \tag{11}$$

$$R = \frac{\left[\sum\left(H_{iest} - \bar{H}_{iest}\right)\left(H_{imeas} - \bar{H}_{imeas}\right)\right]}{\sqrt{\sum\left(H_{iest} - \bar{H}_{iest}\right)^2 \sum\left(H_{imeas} - \bar{H}_{imeas}\right)^2}} \tag{12}$$

where $H_{iest},\ H_{imeas,}\ \bar{H}_{iest}$ and $\bar{H}_{imeas}$ are the ith estimated, measured, mean estimated and mean measured values respectively, of global solar radiation, n is the total number of observations.

A low RMSE value is desirable while R and R^2 should approach unity as closely as possible. A positive value of MBE or MPE indicates overestimation, while a negative value indicates underestimation in the calculated values.

Results and discussion

Determination of regression constants

The values of regression constants obtained from the linear regression ana lysis using SPSS were used in equations 1, 2 and 4. The modified equations of Angstrom-Prescott model, Garcia model and Olomiyesan-Oyedum model respectively obtained for each of the locations are presented below.

Modified models equations for Katsina:

$$\frac{H}{H_o} = -0.227 + 1.228\left(\frac{S}{S_o}\right) \tag{13}$$

$$\frac{H}{H_o} = 0.082 + 0.429\left(\frac{\Delta T}{S_o}\right) \tag{14}$$

$$\frac{H}{H_o} = 0.046 + 0.069\left(\frac{S}{S_o}\right) + 0.420\left(\frac{\Lambda T}{S_o}\right) \tag{15}$$

Modified models equations for Gusau:

$$\frac{H}{H_o} = 0.023 + 0.830\left(\frac{S}{S_o}\right) \tag{16}$$

$$\frac{H}{H_o} = 0.311 + 0.226\left(\frac{\Lambda T}{S_o}\right) \tag{17}$$

$$\frac{H}{H_o} = 0.215 + 0.234\left(\frac{S}{S_o}\right) + 0.175\left(\frac{\Lambda T}{S_o}\right) \tag{18}$$

Modified models equations for Yelwa:

$$\frac{H}{H_o} = 0.315 + 0.450\left(\frac{S}{S_o}\right) \tag{19}$$

$$\frac{H}{H_o} = 0.393 + 0.152\left(\frac{\Lambda T}{S_o}\right) \tag{20}$$

$$\frac{H}{H_o} = 0.384 + 0.027\left(\frac{S}{S_o}\right) + 0.146\left(\frac{\Lambda T}{S_o}\right) \tag{21}$$

The global solar radiation for each of the selected locations was estimated using the modified equations of the three models as presented in equations 13-21 and Hargreaves-Samani model (equation 3). The input parameters used in this analysis are presented in Table 1.

A comparison of the monthly mean values of the estimated global solar radiation from the four models with ground-measured data for Yelwa, Katsina and Gusau are respectively shown in Figures 1-3. H_{meas} represents ground measured data, while H_{est1}, H_{est2}, H_{est3} and H_{est4} respectively represent estimated global solar radiation from Angstrom-Prescott model, Garcia model, the Olomiyesan and Oyedum model and Hargreaves-Samani model.

Table 1 Input Parameters of the Models for Gusau, Yelwa and Katsina Figures 1-3 show that Hest2 and Hest3 have better agreement with the measured data than Hest1 and Hest4 in the three locations. However, the estimated global solar radiation from the Olomiyesan-Oyedum model (Hest3) displays the best agreement with the measured data in Yelwa. Angstrom-Prescott model (Hest1) shows the highest level of overestimation and underestimation among the four models used. This indicates that Angstrom-Prescott model is not suitable for predicting the monthly mean global solar radiation in the selected locations. This is in agreement with the result obtained for Sokoto, Kaduna and Kano.[14]

	Gusau			Yelwa			Katsina		
MONTH	**H_o (MJm^{-2}day^{-1})**	**S/S_o**	**$\Delta T/S_o$**	**H_o (MJm^{-2}day^{-1})**	**S/S_o**	**$\Delta T/S_o$**	**H_o (MJm^{-2}day^{-1})**	**S/S_o**	**$\Delta T/S_o$**
Jan	30.83	0.729	1.415	30.98	0.708	1.646	30.81	0.696	1.496
Feb	33.63	0.767	1.400	33.74	0.753	1.572	33.61	0.711	1.431
Mar	36.45	0.653	1.332	36.51	0.736	1.261	36.44	0.615	1.371
Apr	38.01	0.623	1.202	38.00	0.712	1.033	38.01	0.62	1.232
May	38.00	0.654	1.017	37.94	0.668	0.900	38.01	0.666	1.055
Jun	37.57	0.634	0.871	37.48	0.525	0.770	37.58	0.685	0.931
Jul	37.61	0.587	0.741	37.53	0.394	0.693	37.62	0.607	0.808
Aug	37.78	0.532	0.706	37.74	0.327	0.697	37.78	0.580	0.785
Sep	36.88	0.650	0.874	36.91	0.389	0.803	36.87	0.677	0.924
Oct	34.38	0.747	1.243	34.47	0.462	1.092	34.36	0.734	1.241
Nov	31.39	0.770	1.685	31.52	0.653	1.514	31.36	0.757	1.555
Dec	29.90	0.719	1.491	30.05	0.630	1.576	29.87	0.735	1.513
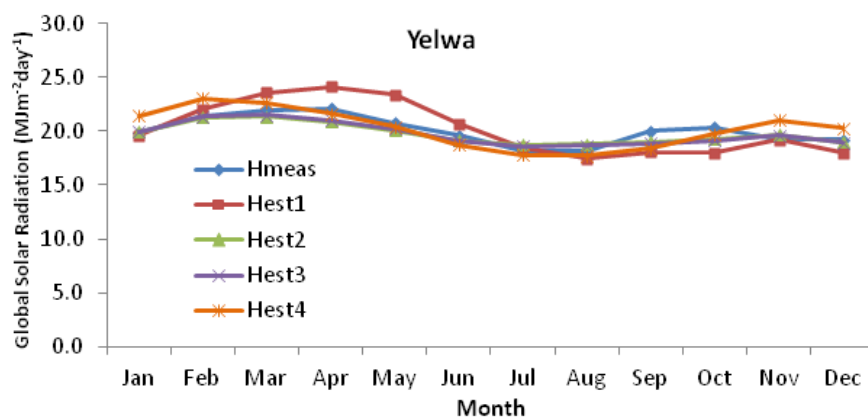
Figure 1 Estimated and Ground Measured Global Solar Radiation for Yelwa.
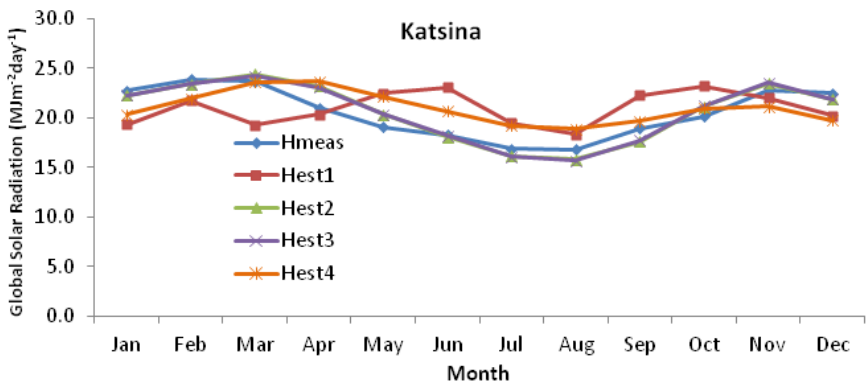
Figure 2 Estimated and Ground Measured Global Solar Radiation for Katsina.
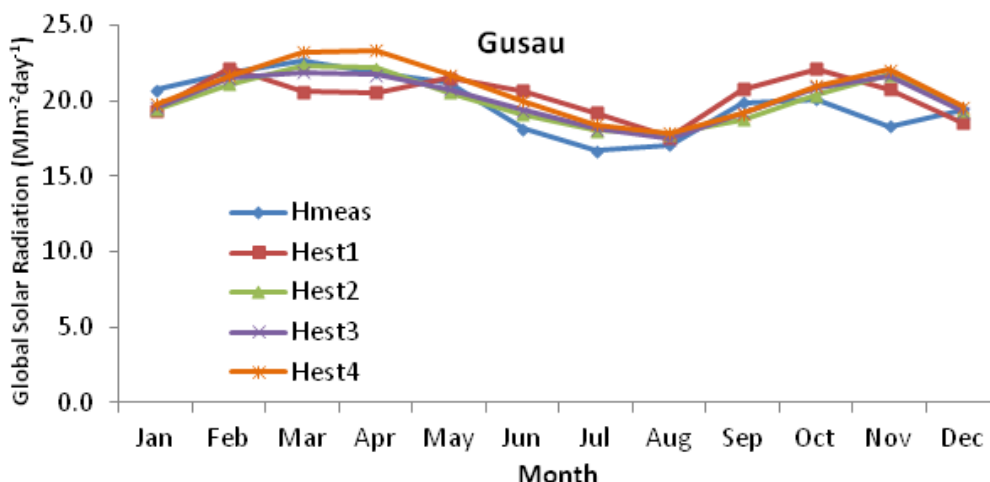
Figure 3 Estimated and Ground Measured Global Solar Radiation for Gusau.

Statistical error indicators of the studied models

The accuracy of the models was evaluated using five statistical indicators (MBE, MPE, RMSE, R and R^2). The calculated values of the error indices of the studied models for the three locations are summarised in Table 2. Angstrom-Prescott model, Garcia model, Olomiyesan-Oyedum model and Hargreaves-Samani model are respectively denoted as Model 1, Model 2, Model 3 and Model 4 in Table 2.

MBE and MPE give an indication of the long-term performance of the models. From Table 2, the MBE and MPE values for the four models vary between slight overestimation and slight underestimation of the estimated global solar radiation.

Table 2 Statistical Error Indicators of the Studied Models

State	Model	MBE (MJm^{-2}day^{-1})	MPE (%)	RMSE (MJm^{-2}day^{-1})	R	R^2
Gusau	Model 1	0.479	-2.976	1.647	0.559	0.313
	Model 2	**0.222**	**-1.501**	1.252	0.752	0.566
	Model 3	0.285	-1.833	**1.240**	0.763	0.582
	Model 4	0.828	-4.490	1.473	**0.772**	**0.596**
Yelwa	Model 1	**0.156**	**-0.567**	1.484	0.837	0.700
	Model 2	-0.300	1.358	0.686	0.886	0.785
	Model 3	-0.303	1.400	**0.659**	**0.891**	**0.793**
	Model 4	0.172	-0.828	1.009	0.781	0.610
Katsina	Model 1	0.418	-3.486	2.965	0.000	0.000
	Model 2	0.094	-0.268	1.018	0.941	0.886
	Model 3	**0.083**	**-0.216**	**0.997**	**0.943**	**0.889**
	Model 4	0.442	-0.313	2.087	0.552	0.305

Root mean square error (RMSE) test: A lower RMSE value indicates a good performance of the model. Olomiyesan and Oyedum model (Model 3) gives the lowest RMSE values in all the locations (1.240 for Gusau, 0.659 for Yelwa and 0.997 for Katsina), while the highest RMSE values were produced by Angstrom-Prescott model in the three selected locations. Garcia model gives the second best RMSE values in all the sites. Since a low RMSE is desirable, the performance of the models can be ranked based on their RMSE values in Table 2 as follows: Model 3 has the highest level of accuracy, Model 2 ranks second, Model 4 ranks third while Model 1 ranks fourth.

Coefficient of determination (R^2) Test: Table 2 shows that Model 2, Model 3 and Model 4 have higher values of coefficient determination (R^2) compared to Model 1. However, Model 3 produced the highest R^2 values in Katsina (0.889), Yelwa (0.793) and the second highest in Gusau (0.582). The R^2 value of 0.889 shows that 88.9% of the clearness index for Katsina is accounted for by model 3. However, the $R^2 = 0$ obtained for Angstrom-Prescott model in Katsina shows that the estimated regression line for the model is perfectly horizontal with a slope of zero. This indicates that the relationship between the clearness index and sunshine ratio is not linear. Since, the best estimation has the highest value of R^2, the statistical results reveal that Model 3 is the best fitting global solar radiation method among the four models under study. Model 2 ranks second, while Model 4 and Model 1 rank respectively third and fourth.

From the result of the above statistical error analysis, it can be deduced that Model 3 (Olomiyesan- Oyedum model) performed better

than Model 2 (Garcia model) and Model 4 (Hargreaves and Samani model), while Model 1 (Angstrom-Prescott model) is not suitable for estimating global solar radiation in the study locations. This result is in agreement with the result obtained for Sokoto, Kaduna and Kano,[14] and also a prove of the stability of Model 3. Moreover, the statistical result shows a close relationship in the values of the statistical error values for model 2 and 3. This indicates that both models are suitable for the estimation of global solar radiation in the study sites. However, it is also noteworthy that the inclusion of air temperature to Angstrom-Prescott model (equation 1) in the proposed model (equation 4) improved the accuracy of the sunshine-based model. Thus, the inclusion of air temperature as input parameter improves the performance of global solar radiation model in areas with high-temperature difference as also observed by.[25]

Conclusion

A multiple-parameter model for estimating global solar radiation developed by Olomiyesan and Oyedum has been validated and tested for three selected locations (Gusua, Yelwa and Katsina) in Northwest, Nigeria. The model has been proved to outperform three other existing models (Hargreaves and Samani model, Garcia model and Angstrom-Prescott model) in terms of the statistical error analysis result in the study area. Based on the statistical error indices, the proposed model was found to have the overall best accuracy with the least RMSE values in all the studied sites as well as highest coefficient of determination, R^2 values. Thus, Olomiyesan-Oyedum model is recommended for estimating the monthly mean daily global solar radiation on the horizontal surface in North-western region of Nigeria and in other locations with similar meteorological climate.

Acknowledgments

Conflicts of interest

The authors declare that there is no conflict of interests about the publication of this paper.

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