www.ijecs.in
International Journal Of Engineering And Computer Science ISSN: 2319-7242
Volume 4 Issue 10 Oct 2015, Page No. 14677-14685

Comparison of Empirical Models in the Estimation of Global Solar Radiation over Nigeria

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ABSTRACT--- *The performance of both temperature and Sunshine dependent models were evaluated for the estimation of global solar radiation over Nigeria using relative sunshine duration, mean monthly minimum and maximum air temperature and extraterrestrial solar radiation (R_o). The monthly global solar radiation was estimated for 10 years (2001-2010). The Angstrom-Prescott (1924), Hargreaves and Sammani (1982) and Garcia (1994) models were used. Sokoto, Enugu, Port Harcourt and Oyo were chosen for the study. New Armstrong –type equations were formulated for each city with new coefficient constants.*

From the models compared, the improved Angstrom-Type models performed best with a RMSE of 0.00000241, 0.00028, 0.0127, and 0.000935 for Enugu, Oyo, Port Harcourt and Sokoto respectively. This was closely followed by the Hargreaves and Sammani Model and the Angstrom-Prescott model. The Garcia model performed least.

Sokoto recorded the highest global solar radiation in Nigeria with the month of April having 21.598MJ/M^2/ day, While Oyo has the least with 8.630 MJ/M^2/ day during the month of August. Consequently the developed Angstrom-type models can be used with confidence for each of the cities in Nigeria and other locations with similar latitudinal variations

Keywords--- temperature, sunshine duration, global solar radiation

INTRODUCTION

Solar radiation is the energy given off by the sun. It is the main driving force for the processes in the atmosphere as well as in the biosphere. Knowledge of solar radiation is indispensible to many solar energy related applications. Modern technology has led to the design and construction of modern facilities such as solar cookers, solar dryers, solar heaters, photovoltaic cells, and many other solar electronics. (Audu, 2013). Comprehensive knowledge of global solar radiation of a particular location is useful in the study and design of the economic viability of devices that depend on use of solar energy (Isikwue et al, 2012). The trends of energy indicate that oil production will reach peak and start a long downward slide when the fossil fuel and gas would have been consumed. These studies on new and renewable energy sources are encouraged because energy resources used today are rapidly decreasing and also cause environmental pollution. Solar radiation is the largest renewable energy source and it has been studied recently due to its importance. The knowledge of the dwindling level of these resources and their related environmental challenges is generating the necessity to shift emphasis from use of fossil fuel to renewable energy resources such as solar radiation.

The utilization of solar radiation in Nigeria will play an important role in the near future. Nigeria is blessed with abundant amount of sunshine with an estimated 3,000 hours of annual sunshine (Burari and Sambo, 2001). Detailed information of the availability of solar radiation on the surface of the earth is essential in understanding many physical and biological processes. The amount of solar radiation which reaches the earth's surface varies from one place to another owing to the attenuation properties of the atmosphere and the diverse geographical characteristics of the earth surface. Hence detailed study of global solar radiation under local climate conditions here in Nigeria is essential. Obviously the best way of knowing the amount of global solar radiation at a place or site is to install measuring devices such as Pyranometers at many locations to record the day-to-day components of the global and diffuse components of the solar radiation. Unfortunately for most developing countries like Nigeria, there are very few stations that measure solar radiation directly.

Meteorological stations often record only precipitation, surface pressure, relative hours of bright sunshine, relative humidity, minimum and maximum temperature and air temperature data. Empirical models which express global solar radiation as a function of these variables have been proposed by various researchers. Their suitability for a particular location would largely depend on validation against actual measurements. It is therefore imperative that we compare some of these models to find out which best suits various parts of Nigeria.

2. METHODOLOGY AND DATA

The monthly mean daily measured global solar radiation, the minimum and maximum air temperature, and the sunshine duration data for a period of ten years was obtained from the International Institute for Tropical Agriculture (IITA) Ibadan.

The most widely used correlation for predicting solar radiation was developed by Angstrom (1924). Prescott (1940) reconsidered this model in order to make it possible to calculate monthly average of daily global solar radiation MJ/M^2/day on a horizontal surface.

$$\frac{R_s}{R_0} = a + b\left(\frac{n}{N}\right) \qquad (1)$$

R_s is the monthly mean daily global solar radiation in $MJm^{-2}day^{-1}$ on a horizontal surface while R_o is the monthly mean daily extraterrestrial solar radiation in $MJm^{-2}day^{-1}$ and it is expressed as by Duffie and Beckman (1991) as

$$R_o = \frac{24(60)}{\pi} G_{sc} dr[W_s \sin\Phi \sin\delta + \cos\Phi \cos\delta \sin W_s] \qquad (2)$$

G_{sc} is the solar constant = $0.0820 MJm^{-2}min^{-1}$. The inverse relative earth sun distance dr [rad] is given by Liou (1980) as

$$dr = 1 + 0.033\cos\left[\frac{2\pi J}{365}\right] \qquad (3)$$

Where, J is the number of the day of the year between January 1st and December 31st (365).

N is the daylight hour given as

$$N = \frac{24Ws}{\pi} \qquad (4)$$

Where W_s is the hour angle and is expressed by Fayadh and Ghazi (1983) as

$$W_s = arc\cos[-\tan\Phi\tan\delta] \quad (5)$$

Φ and δ are the latitude and declination angles respectively. The declination measured in degrees is given by Cooper(1969) as

$$\delta = 0.409\sin\left(\frac{2\pi J}{365} - 1.39\right) \quad (6)$$

The regression constants a and b are 0.25 and 0.50 respectively.

The Hargreaves and Sammani Model

Hargreaves and Sammani (1982) proposed this empirical equation expressed in the form of a linear regression between the clearness index and the square root of ΔT is given as

$$\frac{R_s}{R_o} = a + b\Delta T^{0.5} \quad (7)$$

ΔT is the difference between the minimum and maximum temperature values. The Hargreaves and Sammani radiation model is adjusted and validated at several weather stations in a variety of climate conditions becomes

$$R_s = R_o(K_{rs})\sqrt{T_{max} - T_{min}} \quad (8)$$

Where,

T_{max} is the maximum temperature (^{0}C).

T_{min} is the minimum temperature (^{0}C).

K_{rs} is the adjustment coefficient (0.16 - 0.19)

The adjustment coefficient K_{rs} is empirical and differs for interior or coastal regions, K_{rs} = 0.162 for interior and K_{rs} = 0.19 for coastal regions.

The Garcia Model

Garcia (1994) model is an adaptation of Angstrom- Prescott model with a slight modification described as follows

$$\frac{R_s}{R_0} = a + b\frac{\Delta T}{N} \quad (9)$$

Where all the terms assume their usual meanings as already explained above. Each of these above mentioned models will be tested and the results obtained will be compared with observed data for consistencies and to ascertain the best model for each of the four cities.

Improved Angstrom models

Improvements were made on the Angstrom-Prescott equations by obtaining better regression coefficients for each city from relationships given by Tiwari and Sangeeta (1997) as

$$a = 0.110 + 0.235\cos\emptyset + 0.323\frac{n}{N} \quad (10)$$

$$b = 1.449 - 0.553\cos\emptyset - 0.694\frac{n}{N} \quad (11)$$

3.RESULTS

The input parameters used in this analysis are given in table 1-4. Fig 1-4 shows comparison between the measured and estimated solar radiation using the four models. The new regression constants for each city were also obtained

Table 1: Monthly mean measured and estimated global solar radiation over Sokoto

Months	n (hr)	N (hr)	Ro (MJ/m^2/day)	R(mea) (MJ/m^2/day)	R(ang) (MJ/m^2/day)	R(hag) (MJ/m^2/day)	R(gar) (MJ/m^2/day)	R(dev) (MJ/m^2/day)
Jan	**8.87**	11.237	29.471	**18.231**	**19.004**	**17.923**	**26.256**	**18.235**
Feb	**8.43**	11.586	33.402	**19.078**	**20.513**	**19.953**	**28.293**	**19.044**
Mar	**8.86**	11.919	36.193	**20.727**	**22.509**	**20.982**	**28.810**	**21.051**
Apr	**8.94**	12.298	37.965	**19.280**	**22.992**	**22.429**	**30.487**	**21.589**
May	**8.80**	12.604	38.371	**19.598**	**22.990**	**22.576**	**30.290**	**20.962**
Jun	**8.92**	12.762	38.164	**17.484**	**22.886**	**20.654**	**28.563**	**20.876**
Jul	**9.04**	12.694	38.053	**15.375**	**23.059**	**21.523**	**29.693**	**18.196**
Aug	**8.84**	12.157	35.946	**18.539**	**21.993**	**22.678**	**31.639**	**20.485**
Sep	**8.55**	12.063	36.657	**19.143**	**22.148**	**23.643**	**33.429**	**20.325**
Oct	**8.71**	11.696	34.158	**19.373**	**21.251**	**21.239**	**30.361**	**19.902**
Nov	**8.66**	11.383	31.100	**18.452**	**19.609**	**18.975**	**27.737**	**18.541**
Dec	**8.87**	11.237	29.471	**18.231**	**19.004**	**17.923**	**26.256**	**18.235**

Table 2: Monthly mean measured and estimated global solar radiation over Enugu

months	n (hr)	N (hr)	Ro (MJ/m^2/day)	R(mea) (MJ/m^2/day)	R(ang) (MJ/m^2/day)	R(hag) (MJ/m^2/day)	R(gar) (MJ/m^2/day)	R(dev) (MJ/m^2/day)
Jan	**5.320**	**11.663**	**33.476**	**16.081**	**16.004**	**16.004**	**21.537**	**16.144**
Feb	**5.934**	**11.797**	**35.661**	**16.941**	**17.885**	**16.552**	**21.888**	**14.902**
Mar	**6.615**	**11.960**	**37.354**	**15.749**	**19.669**	**16.245**	**21.288**	**16.212**
Apr	**6.249**	**12.146**	**37.642**	**16.269**	**19.093**	**17.288**	**22.539**	**15.208**
May	**4.992**	**12.297**	**36.667**	**16.186**	**16.609**	**17.167**	**22.242**	**15.736**
Jun	**4.645**	**12.374**	**35.800**	**15.368**	**15.669**	**15.854**	**20.837**	**15.614**
Jul	**5.518**	**12.340**	**36.037**	**14.791**	**17.066**	**16.188**	**21.042**	**12.688**
Aug	**6.732**	**12.210**	**36.979**	**14.057**	**16.439**	**15.379**	**22.768**	**14.604**
Sep	**7.435**	**12.031**	**37.231**	**14.741**	**17.612**	**16.341**	**22.878**	**16.032**
Oct	**6.685**	**11.851**	**35.974**	**15.103**	**19.139**	**16.468**	**21.957**	**15.926**
Nov	**6.865**	**11.697**	**33.864**	**14.591**	**18.404**	**15.837**	**21.238**	**15.603**

Dec	**5.182**	**11.626**	**32.703**	**15.227**	**14.736**	**15.549**	**20.808**	**16.368**

Table 3: Monthly mean measured and estimated global solar radiation over Port-Harcourt

nonths	**n** (hr)	**N** (hr)	**Ro** (MJ/m^2/ day)	**R(mea)** (MJ/m^2/ day)	**R(ang)** (MJ/m^2/ day)	**R(hag)** (MJ/m^2/ day)	**R(gar)** (MJ/m^2/ day)	**R(dev)** (MJ/m^2/ day)
Jan	6.540	11.753	34.222	16.744	18.077	18.920	20.367	15.030
Feb	6.165	11.851	36.175	17.059	18.453	20.847	23.324	15.860
Mar	5.219	11.971	37.547	17.430	17.572	20.799	22.866	15.950
Apr	4.469	12.107	37.457	17.155	16.277	20.459	22.488	15.600
May	5.363	12.218	36.201	18.027	16.996	19.999	21.861	16.110
Jun	6.346	12.274	35.206	19.080	17.903	19.438	21.312	17.980
Jul	7.353	12.250	35.499	20.327	19.529	19.112	20.973	17.800
Aug	6.992	12.154	36.674	18.927	19.717	18.707	20.502	18.630
Sep	6.586	12.023	37.278	18.920	19.530	19.288	21.113	18.090
Oct	4.468	11.891	36.380	19.037	15.930	19.962	22.094	16.750
Nov	4.806	11.778	34.550	17.081	15.687	19.021	21.896	17.080
Dec	5.639	11.725	33.505	17.176	16.434	16.212	18.996	17.760

Table 4: Monthly mean measured and estimated global solar radiation over Oyo

Months	**n** (hr)	**N** (hr)	**Ro** (MJ/m^2/ day)	**Rs(mea)** (MJ/m^2/ day)	**Rs(ang)** (MJ/m^2/ day)	**Rs(hag)** (MJ/m^2/ day)	**Rs(gar)** (MJ/m^2/ day)	**R(dev)** (MJ/m^2/ day)
Jan	6.899	11.580	32.760	13.336	17.949	18.719	26.310	15.325
Feb	7.282	11.729	34.917	14.735	19.575	19.387	25.714	16.994
Mar	6.379	11.913	36.708	15.816	18.996	18.784	24.327	15.436
Apr	7.140	11.689	34.080	14.475	18.820	18.502	24.981	16.348
May	6.925	11.728	34.616	14.591	18.835	18.848	25.333	16.050
Jun	6.076	12.467	36.328	14.377	17.935	16.477	20.801	15.921
Jul	6.783	11.851	34.902	14.555	18.685	18.453	24.578	15.714
Aug	2.733	12.263	37.233	10.638	13.458	13.695	17.860	8.630
Sep	4.109	12.038	37.158	12.870	15.631	16.143	19.961	10.027
Oct	6.194	11.814	35.569	13.898	18.217	15.853	20.066	14.652
Nov	7.939	11.622	33.203	14.278	18.942	16.382	21.902	17.776
Dec	8.000	11.533	31.936	14.012	18.761	17.117	23.576	17.368

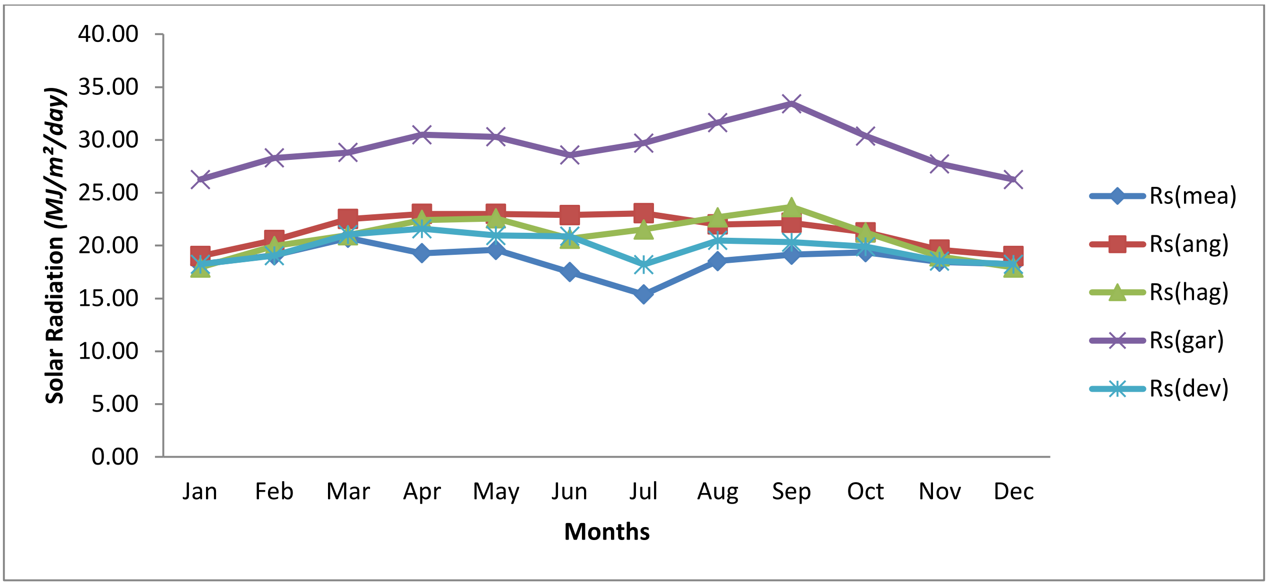

Fig 1: Comparison between measured and estimated global solar radiation over Sokoto using the four models.

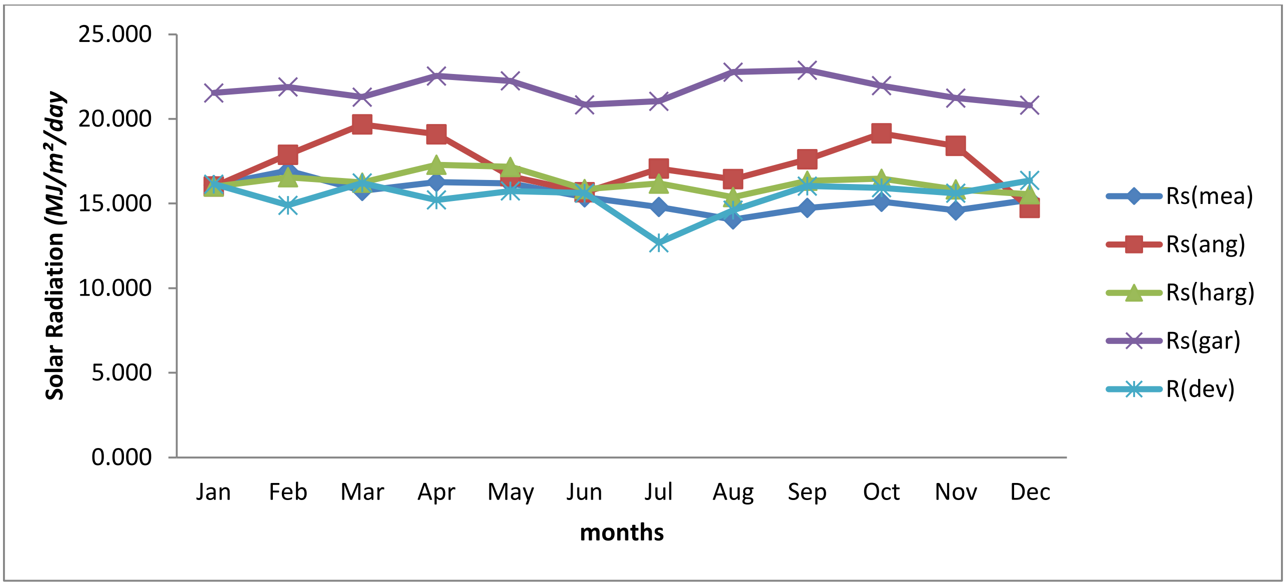

Fig 2: Comparison between measured and estimated global solar radiation over Enugu using the four models.

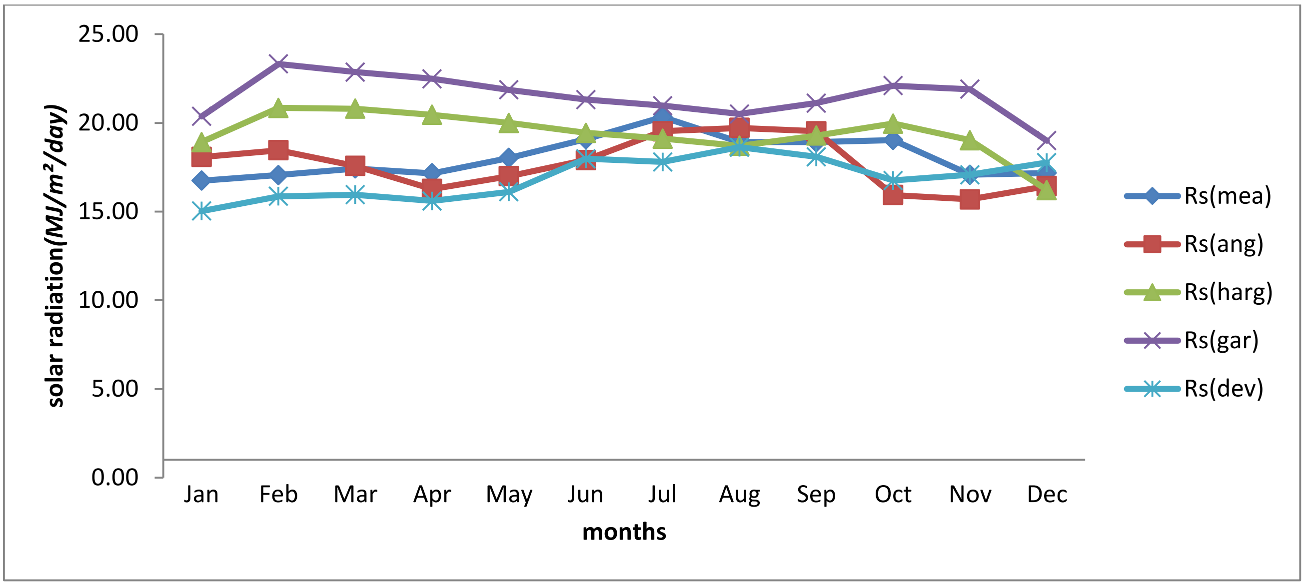

Fig 3: Comparison between measured and estimated global solar radiation over Port-Harcourt using the four models.

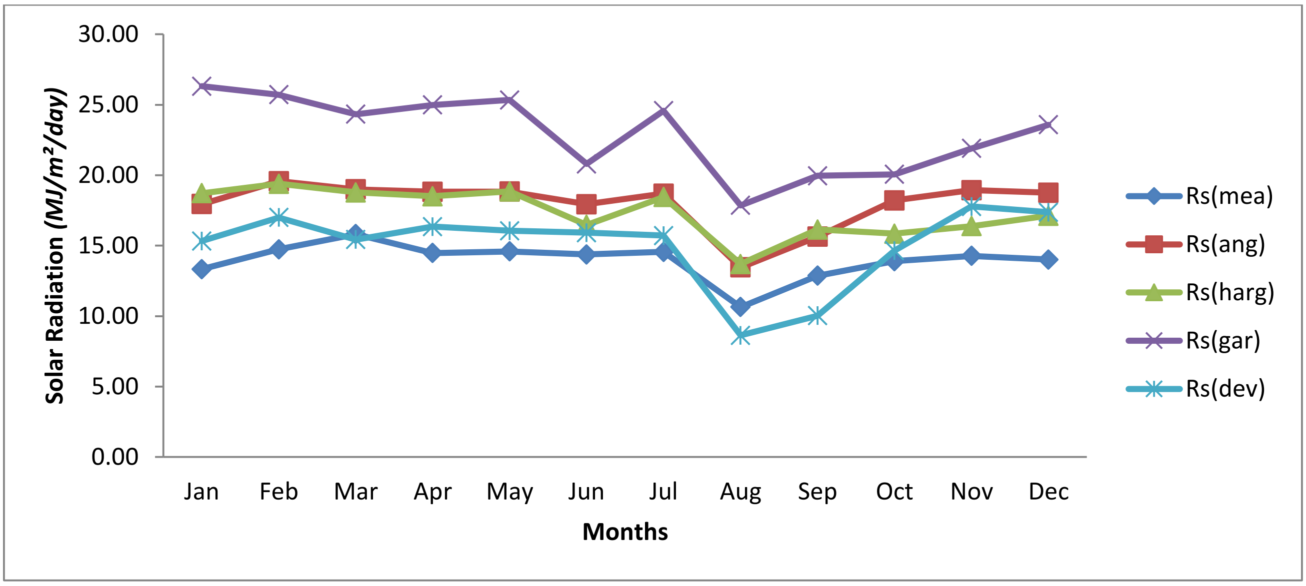

Fig 4: Comparison between measured and estimated global solar radiation over Oyo using the four models.

4. DISCUSSION

Table 1-4 show the performance of the models presented. Table 1 shows that for Sokoto, the solar radiation is relatively high due to the high temperature experienced in Sokoto and the intense sunshine recorded there. This could also be due to vast arid land with little vegetation and relatively lower rainfall received there than most other parts of the country. All the four models show agreement between the measured and estimated values with the month of July having the least global solar radiation of 18.196 MJ/m^2/day. The improved Angstrom-Type model presents the best estimation of global solar radiation over Sokoto, with MBE between the measured and estimated global solar radiation of 0.0966.

Figure 2 shows the performance over Enugu, the Garcia model exhibits overestimation of the global solar radiation. The improved model exhibits underestimation for the months of April, May and June respectively. But the new model still performs best with a RMSE of 0.0000024.

For the city of Port-Harcourt there is an overestimation by all the four models involved, however the new model and the Angstrom-Prescott model still gives the closest values of estimation to the actual measured global solar radiation. The highest value of 16.38 MJ/m^2/day was recorded for the dry season in the months of (Dec-Jan) while (July-August) had the least value of 12.688 MJ/m^2/day for the rainy season. This could be attributed to the rain bearing clouds and high relative humidity present in the skies during this period. It could as well be as a result of the industrialized nature of Port-Harcourt which is home to a good number of industries releasing a lot of pollutants in the atmosphere on a daily basis.

Oyo on the other hand has a relatively low global solar radiation. All the four models still exhibited an overestimation except for the months of June and September where the new model exhibited underestimations. The dry season has the highest global solar radiation of 16.993 MJ/m^2/day while the rainy season recorded a mere 8.630 MJ/m^2/day for the month of August. The relatively low global solar radiation in Oyo could be attributed to the presence of forests and crowded vegetation which reduces the amount of sunshine reaching the ground.

The range of global solar radiation values estimated across the four Nigerian cities is in agreement with the correlation model developed for Makurdi by Audu, and also with the model developed for Bauchi by Burari and Sambo.

The Hargreaves-Sammani and the Garcia model both exhibit similar variations; this could be due to the fact that both the Hargreaves-Sammani and the Garcia models are temperature dependent models and follow the increase and decrease trend in temperature.

The accuracy of the developed models was tested by applying the Mean Bias Error (MBE), Root Mean Square Error (RMSE) and the Mean Percentage Error (MPE) statistical methods. The RMSE test gives us knowledge on the short-term performance of the models hence it is a term by term comparison of the actual deviation between the calculated value and the measured value. The test of MBE provides information on the long-term performance of studied model.

Most of the models indicate an overestimation, however in terms of the Root Mean Square Error (RMSE) and the Mean Bias Error (MBE) the improved Angstrom Type models developed in the present study has the least value which makes it ideal for the estimation of global solar radiation over Nigeria in the absence of measured data.

5. CONCLUSION

New improved Angstrom-Type models for estimating the monthly mean daily global solar radiation on a Horizontal surface over Nigeria have been developed.

The new models are compared with already existing models and are found to fit adequately with the radiation data obtained from (IITA) Ibadan. New regression constants are obtained for the selected cities. Thus, the new Angstrom-Type correlation equations developed for estimating global solar radiation are given as equation (12-15)

Sokoto $$\frac{R_S}{R_0} = 0.138 + 0.642\left(\frac{n}{N}\right) \qquad 12$$

Port Harcourt $$\frac{R_S}{R_0} = 0.202 + 0.775\left(\frac{n}{N}\right) \qquad 13$$

Oyo $$\frac{R_S}{R_0} = 0.236 + 0.548\left(\frac{n}{N}\right) \qquad 14$$

Enugu $\frac{R_s}{R_0} = 0.428 + 0.572\left(\frac{n}{N}\right)$ 15

6. RECOMMENDATION

It is hereby recommended that:

- More attention is given to the design and construction of solar devices and appliances since solar energy is natural, renewable and environmentally friendly.
- More awareness is created on the solar energy potentials of our great country Nigeria.

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