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Estimation of Global Solar Radiation in Port Harcourt, Nigeria Using Some Measured Meteorological Parameters

Akpan, U. E.
Department of Physics, University of Uyo, Nigeria
email: udosenakpan@yahoo.com

Osu, A. D.
Department of Physics, University of Uyo, Nigeria
email: azuanosu@gmai.com

Abstract: **The global solar radiation received from horizontal surface has been estimated for Port Harcourt, Nigeria using some meteorological parameters including sunshine duration, maximum and minimum temperature, relative humidity, and rainfall. Data for ten years collected from the Nigerian Meteorological Agency were used to correlate between measured and estimated values of the global solar radiation. The results showed a good agreement between measured and estimated values particularly when parameterised with sunshine duration, temperature and rainfall. The performance of different models constructed was determined using MBE, MPE, NSE and t-statistics tests. The minimum values of average radiation were obtained in the month of July for all the models used while maximum values were obtained in the month of December.**

Keywords: **Estimation, Meteorological Parameters, Port Harcourt, Shuttleworth Equation, Solar Radiation.**

I. INTRODUCTION

Renewable energy offers a good alternative source of energy in Nigeria to the currently celebrated fossil fuel. Solar energy as one of the renewable energy seems to be the most effective alternative source of energy which apart from supplying an uninterrupted energy flow is very much economical and environmental friendly. Nigeria has adequate solar energy potential to support its enormous energy demand if it is properly harnessed. Solar radiation data are the necessary inputs for solar energy application. In order to design, optimize, and evaluate solar technologies for a particular location, solar radiation data are required. Unfortunately, in Nigeria like other developing countries, solar radiation measurements are scarcely available. To this end, it becomes necessary to evolve a method of estimating solar radiation based on readily available meteorological data.

Various models have been proposed to estimate global solar radiation on horizontal surfaces using several meteorological data such as sunshine hours, ambient temperature, relative humidity and rainfall. El-sebaii [1] used first, second and third Angstrom type of correlation between global solar radiation and bright sunshine hours for five locations in Egypt. Mehreen [2] used sunshine duration in Meteorological Radiation Model (MRM) and cloud cover Cloud Cover Radiation Model (CRM) to estimate horizontal global, diffuse and beam solar radiation on horizontal surface. El-sebaii [3] estimated global and diffuse solar radiation on horizontal surface for Jeddah using measured data of bright sunshine hours, temperature, relative humidity and amount of cloud cover that were averaged over twelve years. Al-Salihi [4] used five years average maximum temperature, sun shine duration and relative humidity to estimate global solar radiation received on horizontal surfaces for three locations representing different weather conditions of Iraq. Udo [5] in his contribution developed a correlation relation of Angstrom-Prescott model for estimation of global solar irradiation at Ilorin, Nigeria using two years monthly averages of clearness index and sunshine hours. Medugu [6] used four years average data of daily sunshine hours to estimate global solar radiation at Yola, Nigeria. Muzathik [7] estimated global solar radiation on horizontal and inclined surfaces in Malaysia using sunshine hours averaged over four years fitted on linear exponential model as a modification of Angstrom and Prescott model. A total of twelve models including linear, quadratic, cubic, exponential and power forms using only sunshine hours, latitude, and altitude were developed by Kang [8] to estimate global solar radiation at Plateau Zone, China.

This work is aimed at estimating global solar radiation on horizontal surfaces in Port Harcourt, using Angstrom-Prescott model with four meteorological parameters which include temperature, sunshine hours, relative humidity, and rainfall. The model with best estimation performance will be determined.

II. METHODOLOGY

Data of daily global solar radiation on horizontal surface (H), number of bright sunshine hours (S), maximum and minimum temperatures (T_{max}, T_{min}) , relative humidity (Rh), and rainfall (Rf) for Port Harcourt for a period of ten years (2002 to 20011) were collected from Nigeria Meteorological Agency, Port Harcourt. The data were averaged to obtain monthly mean daily values. The mean daily values for each month were then averaged over the ten years. The data were subjected to linear and multiple regressions to obtain the values of empirical constants a to e in (1) to (6). The correlations to which the measured data were fitted were as follows:

$$\frac{R}{R_o} = a + b\frac{S}{S_o} \quad (1)$$

$$\frac{R}{R_o} = a + bT + c\frac{S}{S_o} \quad (2)$$

$$\frac{R}{R_o} = a + bT + cRH + d\frac{S}{S_o} \quad (3)$$

$$\frac{R}{R_o} = a + bRH + c\frac{S}{S_o} \quad (4)$$

$$\frac{R}{R_o} = a + bRF + c\frac{S}{S_o} \quad (5)$$

$$\frac{R}{R_o} = a + bRH + cT + dRF + e\frac{S}{S_o} \quad (6)$$

Where a, b, c, d and e are empirical constants from the regression analysis.

R is the monthly average daily global solar radiation ($MJm^{-2}day^{-1}$), Ro is the monthly average extraterrestrial solar radiation ($MJm^{-2}day^{-1}$), S is the sunshine duration (h), So is the maximum possible sunshine duration (h), T is the average temperature (^oC), Rh is the relative humidity (%), and Rf is the rainfall (mm).

Ro and So were calculated by equation obtained from Iqual (1983) as follows;

$$Ro = \frac{24}{\pi} I_{sc}\left[1 + 0.033\cos\left(\frac{360N}{365}\right)\right]. \begin{bmatrix} \cos\varphi \cos\varphi\delta \sin\omega_s + \\ \left(\frac{2\pi\omega_s}{360}\right) \sin\varphi \sin\delta \end{bmatrix} \quad (7)$$

Where I_{sc} is the solar constant ($1367Wm^{-2}$, φ is the latitude of the site, δ sun declination and ω_s is the mean sunrise hour angle for the given month. δ, ω_s and So are computed by the following equations:

$$\delta = 23.45\sin\left[360\left(N + \frac{284}{365}\right)\right] \quad (8)$$

Where N is the day number of the year

$$\omega_{s= \cos^{-1}}(-\tan\varphi \tan\delta) \quad (9)$$

$$S_o = \frac{2\omega_s}{15} \quad (10)$$

The Excel mathematic editor was used to obtain the values of R_o and S_o in (7) and (10). The measured data were used for linear and multiple regression analysis to obtain the values of the empirical constants in (1) to (6).

The relative ability of the different models to predict the global radiation on horizontal surfaces was examined. This was done by determining the performance of individual models using statistical methods. In this work, the accuracy of the solar radiation estimated from the model are tested using mean bias error (MBE), root mean square error (RMSE), mean percentage error (MPE), the correlation coefficient (r) and the coefficient of determination (R^2). The MBE, MPE and RMSE estimators should be closer to zero for a good estimation, and correlation coefficient, r which tests the linear relationship between estimated and measured values, should approach to 1; and R^2 which is an index of the future prediction reliability should approach also to 1. The Nash-Sutcliffe equation (NSE) was also used to evaluate the models. The model is more efficient when NSE is closer to 1 as observed in [7]. It should be observed that the estimated errors do not objectively indicate whether the estimates from the models are statistically significant or not. In order to test whether the predicted values from the models are statistically significant, t-test was carried out.

The t-statistic allows models to be compared and at the same time its indicates whether or not a model is significant at a particular confidence level. The MBE test provides information on the long term performance of a model. A low MBE is desired. The negative value of MBE indicates the average amount of underestimation in the calculated value and the positive gives the average amount of overestimation. The MBE is given by the equation:

$$MBE = \frac{\sum_{i=1}^{N}(R_{i,est} - R_{i,mea})}{N} \quad (11)$$

Where $R_{i,\ est}$ is the estimated ith value of global solar radiation, $R_{i,\ mea}$ is the measured ith value and N is the total number of observation.

$$MPE\ (\%) = \frac{\sum_{i=1}^{N}\left(\frac{R_{i,\ est} - R_{i,\ mea}}{R_{i,\ mea}}\right)}{N} \quad (12)$$

A percentage error between -10% and +10% is considered acceptable (Robaa, 2008)

$$RMSE = \left[\frac{\sum_{i=1}^{N}(R_{i,\ est} - R_{i,\ mea})^2}{N}\right]^{\frac{1}{2}} \quad (13)$$

The RMSE gives information on the short-term performance of the correlation by allowing a term-by-term comparison of the deviation between the predicted and the measured values. The smaller the value, the better is the model's performance as noted by Glover [9].

$$NSE = 1 - \frac{\sum_{i=1}^{N}(R_{i,\ mea} - R_{i,\ est})^2}{\sum_{i=1}^{N}(R_{i,\ mea} - \bar{R}_{i,\ mea})^2} \quad (14)$$

Where $\bar{R}_{i,\ mea}$ is the mean measured global solar Radiation. The NSE represents a measure of the precision of the model results. Chen[10] noted that a model is more efficient when NSE is closer to 1.

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2}\right]^{1/2} \quad (15)$$

The smaller the value of t is, the better the performance of the model. For the model estimate to be considered statistically significant at the (1 – α) confidence level, the calculated t value must be less than the critical value at (n -1) degree of freedom as observed in Iqbal [11]. For this study $t_{critical}$ = 1.796 at 95% confidence level. The correlation coefficient, r, is used to determine the linearity relationship between the measured and the estimated values..

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III. RESULTS AND DISCUSSION

The measured data for Port Harcourt were used to obtain regression equations of H/H_o with respect to meteorological variables. From the equations, the values of the regression constants (a, b, c, d, e), MBE, MPE, RMSE, NSE, t, and regression coefficients r, were obtained and listed in table 1. The values of measured and estimated global solar radiation on horizontal surface as predicted from (1) to (6) are presented in table 2. Fig. 1 to Fig. 6 shows the corresponding graphical representation of the relationship between the measured and predicted values.

Table 1. Different models with statistical parameters to test predictive ability

Model	Model No.	R	R^2	MBE	RMSE	MPE	NSE	T
$R/R_O = 0.155 + 0.545 S/S_O$	1	0.958	0.918	-0.003	0.528	0.181	0.907	0.016
$R/R_O = -0.194 + 0.014T + 0.459 S/S_O$	2	0.969	0.940	0.029	0.442	0.312	0.935	0.222
$R/R_O = 0.229 + 0.007T - 0.003RH + 0.403 S/S_O$	3	0.978	0.957	-1.422	1.490	-11.611	0.262	10.632
$R/R_O = 0.461 - 0.003RH + 0.422 S/S_O$	4	0.976	0.953	0.309	0.526	2.678	0.908	2.405
$R/R_O = 0.216 - 0.001RF + 0.435 S/S_O$	5	0.990	0.979	-0.167	0.401	-1.579	0.946	1.521
$R/R_O = 0.347 - 0.002RH + 0.002T - 0.001RF + 0.365 S/S_O$	6	0.997	0.994	-0.470	0.619	-4.198	0.873	3.874

Table 2. Measured and estimated global solar radiation from different models

Month of the year	R (measured) $MJm^{-2}day^{-1}$	R(estimated) $MJm^{-2}day^{-1}$					
		Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
January	13.49	13.02	12.97	12.48	14.07	13.25	13.53
February	14.48	13.91	14.31	13.18	14.65	13.88	13.99
March	13.75	13.49	14.24	12.77	14.2	13.62	13.68
April	14.5	13.24	14.64	12.82	14.41	14.42	14.1
May	13.15	13.45	13.09	11.47	13.43	13.61	13.04
June	11.12	10.93	10.98	9.39	11.2	10.78	10.37
July	9.85	9.5	9.48	8.04	9.96	9.35	8.99
August	9.45	10.75	10.51	8.91	10.94	8.56	8.02
September	10.74	10.32	10.31	8.73	10.68	10.93	10.51
October	12.38	12.27	12.15	10.38	12.21	12.19	11.61
November	13.41	14.05	13.92	12.15	13.76	13.62	13.02
December	14.25	14.61	14.31	13.17	14.77	14.34	14.08

It is observed that the coefficient of determination R^2 ranges from 0.918 to 0.994. This shows that the models can give a future reliable prediction of the global solar radiation. Looking at the MBE value of the models, models (1), (3), (5) and (6) give underestimated values of the solar radiation with negative values of MBE, while models (2) and (4) give overestimated values with positive values of MBE. However, the least underestimation is given by model (1) having MBE of -0.003, while the least overestimated is provided by model (2) with MBE value of 0.029. The RMSE values range from 0.401 to 1.490, while NSE values range from 0.2690 to 0.9464. These are all acceptable values of indices of good prediction except for model (5) .The model is said to be a good predictor when RMSE is small and NSE is closer to 1.The t-statistics shows that at the critical value of 1.796 and at 0.96 level of confidence, model (1), (2) and (5) with the values of 0.016, 0.222, and 1.521 respectively are stat-iscally significance, while models (3), (4) and (6) are not statistical significant since their calculated t-values are higher than the critical value of t-statistics. Generally, it is observed that models (1), (2) and (4) have satisfied all the statistical tests of reliability, approximation and sig-nificance for good estimation of global solar radiation. It is further observed that in inclusion of relative humidity as a parameter for estimation reduces the acceptability of the model. This observation is not in tandem with the findings made by [3] which held relative humidity as a good predictor of global solar radiation using Jeddah meteorological data.

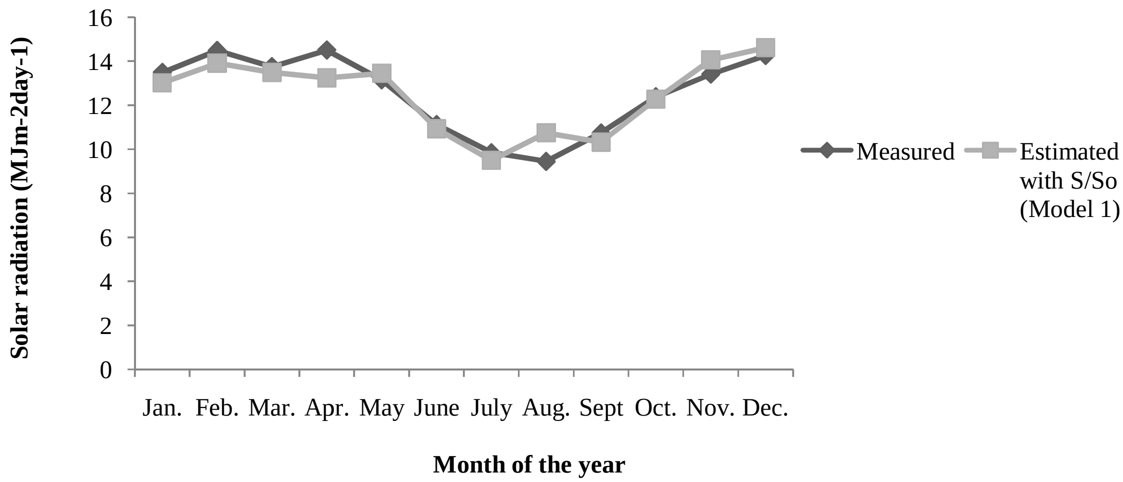

Fig.1. Estimation of solar radiatiojn with sunshine hours

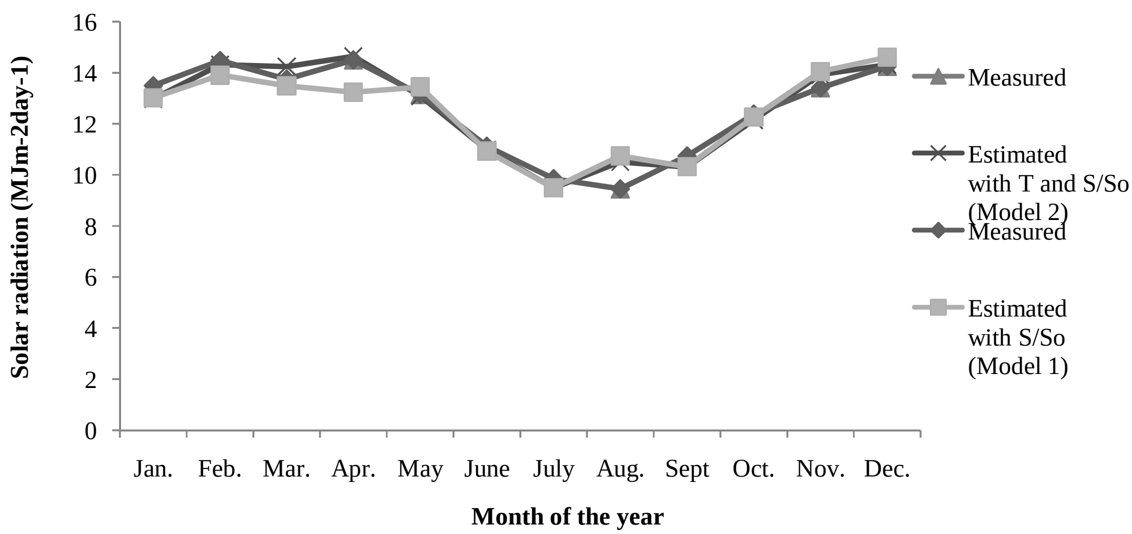

Fig. 2. Estimation of solar radiation with temperature and sunshine hours.

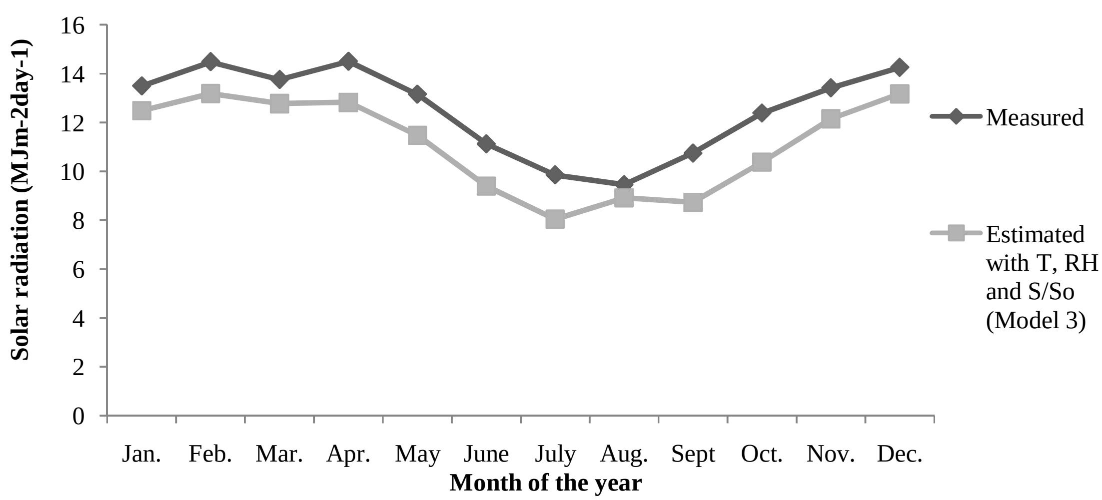

Fig. 3: Estimation of solar radiation with temperature, relative humdity and sunshine hpors.

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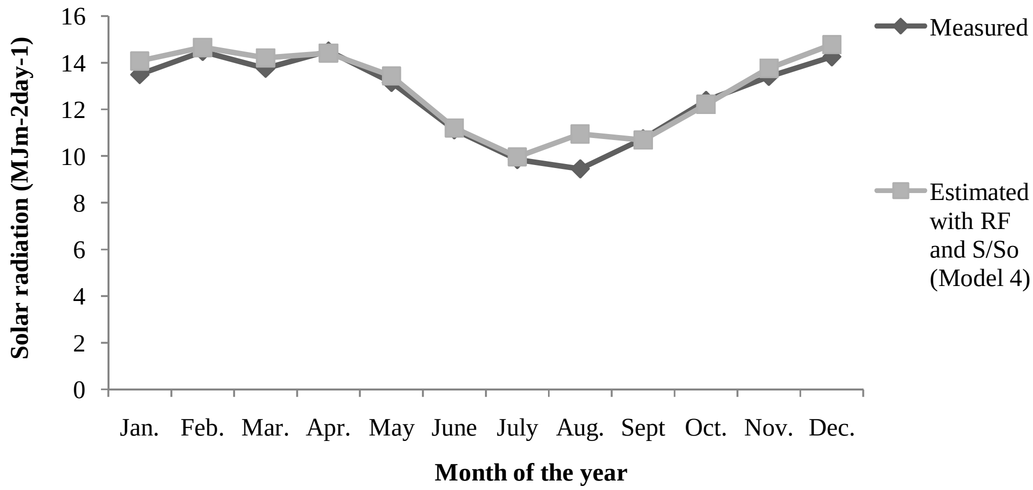

Fig. 4: Estimation of solar radiation with relative humidity and sunshine hours.

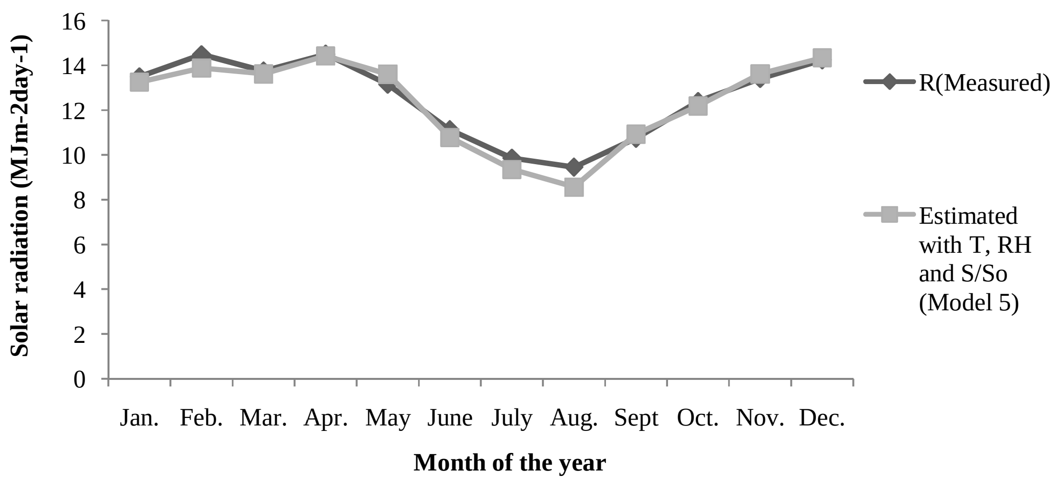

Fig.5: Estimation of solar radiation with relative rainfall and sunshine hours.

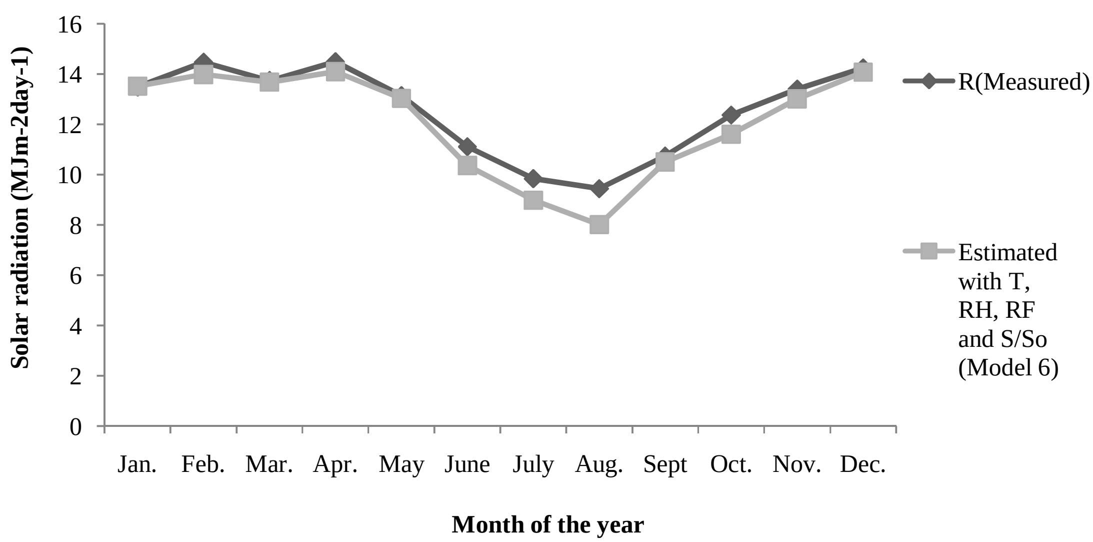

Fig. 6: Estimation of solar radiation with temperature, rainfall, relative humidity and sunshine hours.

IV. Conclusion

From the regression results and the statistical test, we conclude that daily global radiation models with sunshine duration, temperature and rainfall show more accurate result than those that include relative humidity. Consequently, models 1, 2 and 5 may be used to estimate global solar radiation on horizontal surface in location with similar meteorological parameters with Port Harcourt, Nigeria.

V. References

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Author's Profile

Dr. Udosen E. Akpan holds a Ph.D degree in Physics with specialization in Atmospheric Physics. He has been a University Lecturer for the past twenty four years. He has published more than twenty five articles in both national and International journals. He has also attended many national and International conferences. Presently, he is a Senior Lecturer in the Department of Physics, University of Uyo, Nigeria.
email: udosenakpan@yahoo.com

Azuanamibebi Derikuma Osu, born at Kolo town in 1978 graduated in Physics department from University of Ibadan, Nigeria in 1998. Presently he is pursuing his postgraduate program in Atmospheric Physics under the supervision of Dr. Udosen Akpan at the University of Uyo, Uyo, Akwa Ibom State, Nigeria. He had guided over 20 undergraduate students, published over 10 research papers in journals of repute and had attended many local and international conferences. His career goal is to become an atmospheric science professor with a focus on teaching. His research interest is in the field of Estimation of solar radiation.
email: azuanosu@gmai.com