Communications in Applied Sciences
ISSN 2201-7372
Volume 1, Number 1, 2013, 25-37

Estimation of Global Solar Radiation in Onitsha and Calabar Using Empirical Models

M. N. Nnabuchi, J. E. Ekpe and G. F Ibeh

Department of Industrial Physics, Ebonyi State University, Abakaliki, Nigeria

Corresponding author: G. F Ibeh, Department of Industrial Physics, Ebonyi State University, Abakaliki, Nigeria

ABSTRACT

Understanding solar radiation data is essential for modelling solar energy systems. The purpose of the present study was to estimate global solar radiation on horizontal surface using meteorological parameters for a period of eleven years (1996 – 2006). Monthly average global solar radiation, H has been estimated for Onitsha and Calabar, Nigeria using predicting models generated by simple linear and multiple regression analyses. The models included a one variable model with relative humidity as the independent variable and two three-variable models correlating H with relative humidity and each of average temperature, cloudiness index and number of sunshine hours. The values of the global solar radiation estimated by the models and the measured solar radiation were tested using the mean bias error (MBE), root mean square error (RMSE) and mean percentage error (MPE) statiscal techniques. The values of the correlation coefficient (CC) were also determined for each model. The model that indicate a good agreement between the measured and estimated values for Onitsha and Calabar are $H = 11.166 + 0.0176R + 0.000455R^2$ and $H = -7.704 + 0.705\ T_{av}$ respectively. The developed models can be used for estimating global solar radiation in Onitsha and Calabar and other locations with similar climatic factors.

Keywords: Sunshine, average temperature, relative humidity, cloudiness, global solar radiation

Introduction

Knowledge of the global solar radiation is of fundamental importance for all solar energy conversion systems. Information on global solar radiation received at any site (preferably gained over a long period) should be useful not only to the locality where the radiation data is collected but also for the wider world community (Massaquoi, 1988).

Practically, solar radiation data are easily obtained using the relevant equipment. Pyrheliometer and pyranometer can be used readily to obtain the diffused component of the radiation and the global solar radiation respectively. Weather stations have been used mostly for this purpose. However, there are a few of such stations across the globe and worse still in the developing nations. In an effort to generate radiation data, researchers had extrapolated values from one location for application in a different location. Hence solar radiation prediction from estimation models has been widely utilized globally to generate solar radiation database for various locations of the world.

The development of the solar radiation data base for various Nigeria locations has been an on-going task for researchers in the field for many years now. With the very few meteorological stations, the option of using estimating models has been widely adopted in Nigeria for predicting solar radiation at specific location and at a regional scale (Agbo, et al 2007).

RESEARCH METHODOLOGY

The data such as sunshine hours, average temperatures, cloud cover, relative humidity and global solar radiation data for Onitsha and Calabar used for this study were obtained from the Nigeria meteorological Agency, Federal ministry of Aviation Oshodi, Lagos, Nigeria. The data collected covered a period of eleven years (1996-2006) for Onitsha (Latitude $5^o 45' N$, Longitude $6^o 45' E$, and altitude 56 metres above sea level) and Calabar (Latitude $4^o 48' N$, Longitude $8^o 25' E$ and altitude 58 metres above sea level). These values were obtained by the use of GPS (general position satellite) equipment.

DATA ANALYSIS

The monthly data processed in preparation for the correlation are presented in Tables 1 and 2 for Onitsha and Calabar respectively.

Table 1: Monthly mean value of climatic parameters for Onitsha 1996-2006

S/N	MONTH	T_{av}(°C)	R%	S/N	c/C	H(MJ/m²/day)
1	JAN	34.336	67.546	0.542	0.564	14.25
2	FEB	35.527	69.727	0.525	0.564	15.65
3	MAR	34.809	75.364	0.516	0.600	14.77
4	APR	33.555	79.182	0.582	0.629	14.27
5	MAY	32.236	81.727	0.581	0.611	14.85
6	JUN	31.027	84.546	0.491	0.631	13.61
7	JULY	29.545	87.000	0.345	0.644	11.65
8	AUG	29.364	88.182	0.274	0.649	10.80
9	SEPT	30.436	85.636	0.342	0.647	12.26
10	OCT	31.364	82.818	0.428	0.630	15.18
11	NOV	33.500	75.909	0.580	0.625	16.51
12	DEC	33.836	71.273	0.552	0.576	15.42
Total	$\sum$ =	389.535	948.91	5.758	7.360	169.22

Table 2: Monthly mean values of climatic parameters for Calabar (1996-2006)

S/N	MONTH	T_{av}(°C)	R%	S/N	c/C	H(MJ/m²/day)
1	JAN	32.348	76.364	0.489	0.609	14.00
2	FEB	33.809	76.455	0.449	0.613	16.37
3	MAR	32.718	82.636	0.355	0.625	15.45
4	APR	31.955	84.273	0.411	0.626	16.36
5	MAY	31.509	84.000	0.403	0.626	15.14
6	JUN	30.164	86.818	0.341	0.633	13.09
7	JULY	28.164	90.000	0.241	0.645	11.64
8	AUG	28.127	91.636	0.139	0.647	12.29
9	SEPT	29.155	89.000	0.212	0.642	13.49
10	OCT	30.018	87.000	0.293	0.630	14.13
11	NOV	31.056	85.273	0.436	0.631	14.34
12	DEC	31.909	80.455	0.538	0.612	13.26
Total	$\sum$ =	371.711	1013.91	4.307	7.539	169.56

T_{av} = monthly average daily temperature

R (%) = Relative humidity @ 9 hours

H = value of measured average daily solar radiation on the horizontal surface.

c/C = The cloudiness index

S/N = The monthly average daily relative sunshine duration.

To develop the model, the global solar radiation measured using Gun-Bellini distillate were converted to useful form (MJM^2/day) using a conversion factor of 1.1364 proposed by (Sambo, 1985).

Professional modellers have proposed correlation that should be used to estimate the global solar radiation. The first correlation proposed for estimating the monthly mean global solar radiation on the horizontal surface H (MJ/m^2/day) using the sunshine duration data was done by (Angstrom, 1924). (Prescott, 1940) has put the Angstrom correlation in more convenient form as:

$$\frac{H}{H_o} = a + b\left(\frac{n}{N}\right) \quad (1)$$

Where H is the measured monthly mean daily global solar radiation, H_o is the monthly mean extraterrestrial solar radiation on horizontal surface, n is the monthly mean daily bright sunshine hours. N is the maximum possible monthly mean daily sunshine hour or the day length, $\frac{H}{H_o}$ is the clearness index, $\frac{n}{N}$ is the fraction of sunshine hours, a and $b$is regression constants.

A number of correlations which include more meteorological parameters such as ambient temperature, the total precipitation, relative and specific humidity, amount of total cloud cover etc. have been developed by different workers (Attili and Abdalla, 1993).

The above equation has been found to be very convenient to a large number of locations and most widely used correlation.

The extraterrestrial solar radiation on horizontal surface is given by (Igbal, 1983) as written below:

$$H_o = \frac{24}{\pi} I_{sc} E_o \left[\frac{\pi}{180} \omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s \right] \quad (2)$$

Where I_{sc} is the solar constant, E_o is the eccentricity correction factor, ϕ = latitude, δ =solar declination, ω_s = hour angle.(Igbal ,1983) gave the expressions for I_{sc},E_o, ϕ ,δ ω_s as follows:

$$I_{sc} = \frac{1367 \ x\ 3600}{1000000}$$

$$E_o = 1 + 0.033 \cos\left(\frac{360\ N}{365}\right)$$

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

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

$$N = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta)$$

Where N is the characteristic day number for each month

$$a + bX = Y \quad 3$$

$$a + bX + cX^2 = Y \quad 4$$

where a and b are constants which can be determined, Y is being replaced as Hm and it is a dependent variable and X is the independent variable which can replace any of the meteorological data like average temperate, T_{av} and relative humidity, R. Equations (3) and (4) are equations of least square line and least square parabola or first and second order regressions respectively (Murray, 1961).To execute the regression analysis of the first order, both sides of equation (3) has to be multiply by '1' and X successively and summing both sides to obtain

$$aN + b\sum X = \sum Y \quad 5$$

$$a\sum X + b\sum X^2 = \sum XY \quad 6$$

If we apply our variables like (T_{av} and R) as the independent variable in eqn. (3.1), we have these equations:

$$a_1 + b_1 Tav = H_1 \quad 7$$

$$a_2 + b_2\ R = H_2 \quad 8$$

At this point, applying average temperature, T_{av} as our independent variable in equations (5) and (6) we have:

$$a_1 N + b_1 \sum T_{av} = \sum H \qquad 9$$

$$a_1 \sum T_{av} + b_1 \sum T^2_{av} = \sum HT_{av} \qquad 10$$

Equations (9) and (10) will be used to evaluate the regression constants a and b The basic equation for second order regression analysis is known as least square parabola. To obtain these equations we have to multiply equation (3.2) by 1, X and X^2 successively, and adding them to obtain equations (11), (12) and (13).

$$a_1 N + b_2 \sum X + c_3 \sum X^2 = \sum Y \qquad 11$$

$$a_1 X + b_2 \sum X^2 + c_3 \sum X^3 = \sum XY \qquad 12$$

$$a_1 X^2 + b_2 \sum X^3 + c_3 \sum X^4 = \sum X^2 Y \qquad 13$$

Applying these equations to solve our problem, that is using our variables, such as average temperature and relative humidity we have

$$H_3 = a_3 + b_3 T_{av} + c_3 T_{av}{}^2 14$$

$$H_4 = a_4 + b_4 R + c_4 R^2 15$$

Then substituting T_{av} as our independent variable in equations (11), (12) and (13), we obtain the equation outlined below:

$$a_3 N + b_3 \sum T_{av} + c_3 \sum T^2_{av} = \sum H \qquad 16$$

$$a_3 \sum T_{av} + b_3 \sum T^2_{av} + c_3 \sum T^3_{av} = \sum HT_{av} \qquad 17$$

$$a_3 \sum T^2_{av} + b_3 \sum T^3_{av} + c_3 \sum T^4_{av} = \sum HT^2_{av} \qquad 18$$

$$a_4 N + b_4 \sum R + c_4 \sum R^2 = \sum H \qquad 19$$

$$a_4 \sum R + b_4 \sum R^2 + c_4 \sum R^3 = \sum HR \qquad 20$$

$$a_4 \sum R^2 + b_4 \sum R^3 + c_4 \sum R^4 = \sum HR^2 \qquad 21$$

To further buttress the analysis, the multiple correlation analysis was also applied to evaluate for H_5, H_6, and H_7. In this case, the multiple variables such as average temperature, T_{av} and relative humidity, R are used which lead to the equation written below.

$H_5 = a_5 R + b_5 T_{av}$ 22

Where a and b are coefficients. If we take X_1 = H, X_2 =R and H_3 = T_{av}, we can now employ regression equation of X_1 on X_2 and X_3 and carry out a correlation analysis on equation (22) written below as

$Z = a + bX + cY$ 23

By multiplying both sides of equation (23) by 1, X_2 and X_3 successively and adding them to obtain the outlined equations:

$$aN + b\sum X_2 + c\sum X_3 = \sum X_1 \quad 24$$

$$a\sum X_1 + b\sum X_2^2 + c\sum X_2 X_3 = \sum X_1 X_2 \quad 25$$

$$a\sum X_3 + b\sum X_2 X_3 + c\sum X_3^2 = \sum X_1 X_3 \quad 26$$

Substituting our variables in the last two equations we arrive as;

$$a_5\sum R^2 + b_5\sum RT_{av} = \sum HR \quad 27$$

$$a_5\sum RT_{av} + b_5\sum T_{av}^2 = \sum HT_{av} \quad 28$$

Equation 27 and 28 were used to evaluate for H_5.

Similarly, H_6we be estimated by using R-S combination, that is relative humidity and sunshine hours which leads to:

$$H_6 = a_6 R + b_6 S \quad 29$$

The same procedure used in obtaining equations 27 and 28 were applied to arrived at equations 30 and 31.

$$a_6\sum R^2 + b_6\sum RS = \sum HR \quad 30$$

$$a_6\sum RS + b_6\sum S_6^2 = \sum HS \quad 31$$

Under this we can also estimate H by using R and C in combination.

$$a_7R + b_7C = H_7 \quad 32$$

Hence, in carrying out the correlation analysis in equations (27) and (28) we obtain:

$$a_7\sum R^2 + b_7\sum RC = \sum HR \quad 33$$

$$a_7\sum RC + b_7\sum C^2 = \sum HC \quad 34$$

The accuracy of the predicted values was tested by calculating the Mean Bias Error (MBE), the Root Mean Square Error (RMSE), the Mean Percentage Error (MPE) and the coefficient of correlation CC.

Results

Table 3: Measured and Predicted Solar Radiation for Onitsha, (1996-2006)

S/N	Month	$H_{meas.}$ MJ/M²/day	H_1 MJ/M²/day	H_2 MJ/M²/day	H_3 MJ/M²/day	H_4 MJ/M²/day	H_5 MJ/M²/day	H_6 MJ/M²/day	H_7 MJ/M²/day
1	JAN	14.25	15.335	16.111	14.004	14.131	14.804	14.810	11.516
2	FEB	15.65	16.117	15.732	15.200	15.105	15.925	14.565	12.543
3	MAR	14.77	16.646	14.751	14.225	14.925	14.966	14.664	13.902
4	APR	14.27	14.823	14.086	14.800	14.945	14.248	16.243	14.657
5	MAY	14.85	13.958	13.643	14.350	14.425	14.255	16.352	16.504
6	JUN	13.61	13.165	13.153	13.195	13.875	13.910	14.608	14.610
7	JULY	11.65	12.193	12.726	11.915	11.915	11.125	11.672	11.425
8	AUG	10.80	12.074	12.520	10.425	10.839	10.320	10.243	10.620
9	SEPT	12.26	12.777	12.963	12.615	12.100	12.125	11.539	12.225
10	OCT	15.18	13.386	13.454	15.300	15.715	15.115	13.199	15.205
11	NOV	16.51	14.787	14.656	16.895	16.675	16.195	16.034	13.259
12	DEC	15.42	15.007	15.463	15.900	15.925	15.200	15.210	12.839

Table 4: Measured and Predicted Solar Radiation for Calabar, (1996-2006)

S/N	MONTH	$H_{meas.}$ MJ/M²/day	H_1 MJ/M²/day	H_2 MJ/M²/day	H_3 MJ/M²/day	H_4 MJ/M²/day	H_5 MJ/M²/day	H_6 MJ/M²/day	H_7 MJ/M²/day
1	JAN	14.00	15.099	15.221	14.825	11.502	15.140	12.968	15.045
2	FEB	16.37	16.131	15.204	16.015	11.528	15.927	15.895	15.243
3	MAR	15.45	15.362	14.029	15.150	13.407	15.137	14.875	14.408
4	APR	16.36	14.824	13.718	16.250	13.929	14.666	16.375	14.067
5	MAY	15.14	14.509	13.770	15.400	13.841	14.432	15.000	14.133
6	JUN	13.09	13.562	13.235	13.550	14.761	13.605	13.215	13.836
7	JULY	11.64	12.703	12.630	11.225	15.835	12.835	11.625	13.727
8	AUG	12.29	12.126	12.319	12.255	16.402	12.333	12.286	13.441
9	SEPT	13.49	12.850	12.820	13.880	15.493	12.982	13.525	13.804
10	OCT	14.13	13.459	13.200	14.005	14.821	13.188	14.215	13.627
11	NOV	14.34	14.191	13.528	14.345	14.253	14.143	13.925	14.099
12	DEC	13.26	14.792	14.444	13.925	12.728	14.767	13.315	14.210

Table 3 and 4 show the comparison between the measured global solar radiation and the predicted one. A plot of the measured global solar radiation with the predicted values gave rise to figure's 1 and 2 for Onitsha and Calabar respectively, which scientifically agree well with Table 3 and 4 graphically.

GRAPHICAL REPRESENTATION OF THE MEASURED AND PREDICTED VALUES OF SOLAR RADIATION

When the measured and predicted values of solar radiation obtained from model equations were plotted, they showed almost the same curve. This revealed that the model equations can be used to predict the solar radiation of any part of the world that possessessimilar climatological factors like that of Onitsha and Calabar. The following plotted graphs illustrated these points better.

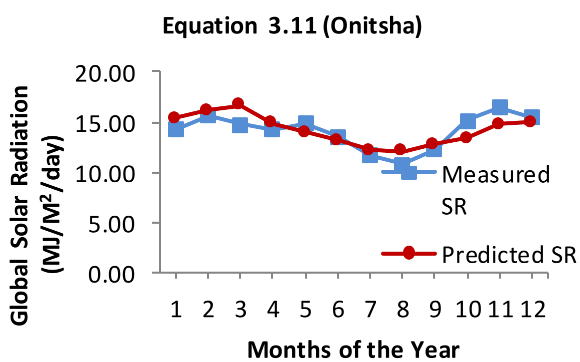

Fig 1a: Comparison between the measured and predicted values of correlation equation for Onitsha (1996 – 2006)

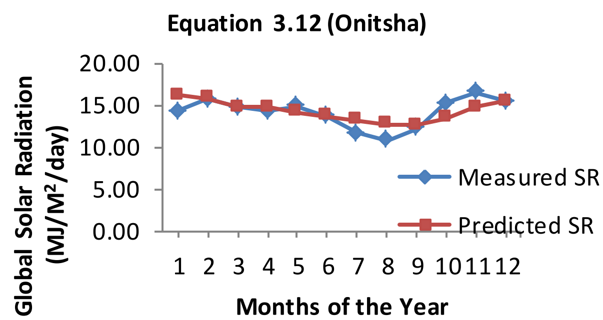

Fig 1b: Comparison between the measured and predicted values of correlation equation for Onitsha (1996 – 2006)

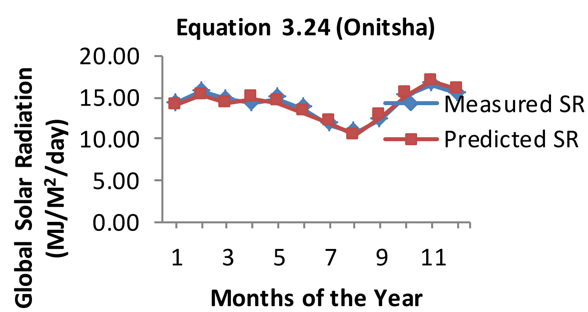

Fig 1c: Comparison between the measured and predicted values of correlation equation for Onitsha (1996 – 2006)

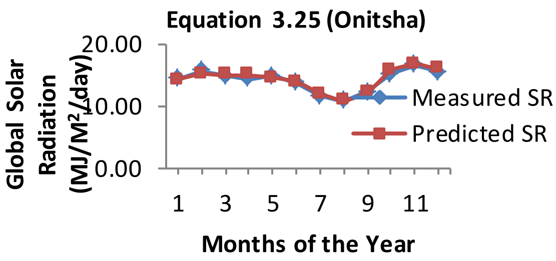

Fig 1d: Comparison between the measured and predicted values of correlation equation for Onitsha (1996 – 2006)

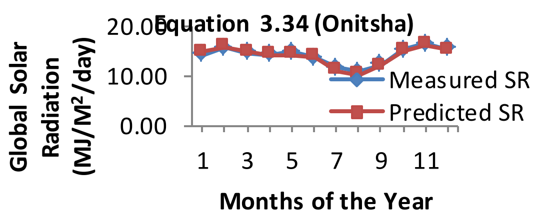

Fig 1e: Comparison between the measured and predicted values of correlation equation for Onitsha (1996 – 2006)

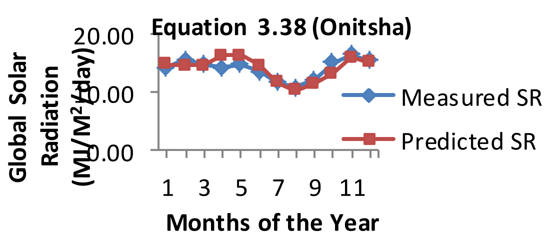

Fig 1f: Comparison between the measured and predicted values of correlation equation for Onitsha (1996 – 2006)

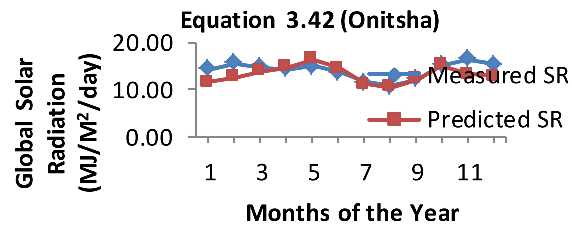

Fig 1g: Comparison between the measured and predicted values of correlation equation for Onitsha (1996 – 2006)

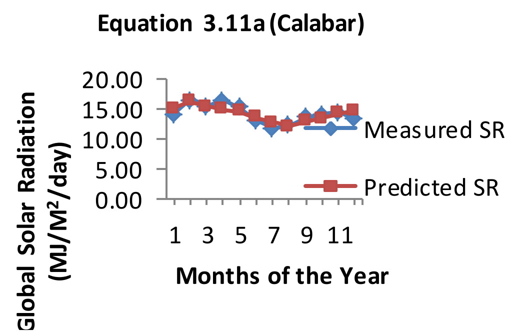

Fig 2a: Comparison between the measured and predicted values of correlation equation for Calabar (1996 – 2006)

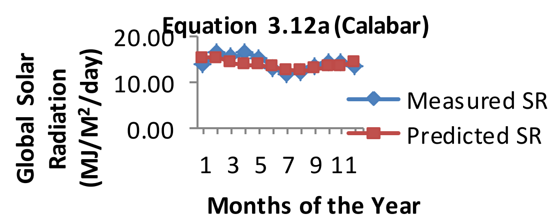

Fig 2b: Comparison between the measured and predicted values of correlation equation for Calabar (1996 – 2006)

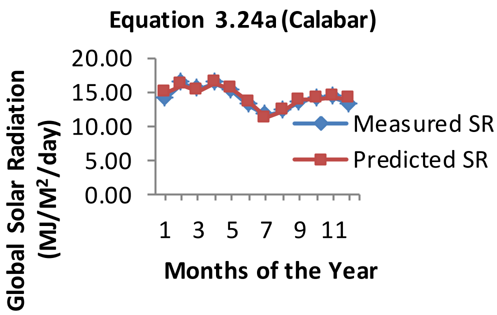

Fig 2c: Comparison between the measured and predicted values of correlation equation for Calabar (1996 – 2006)

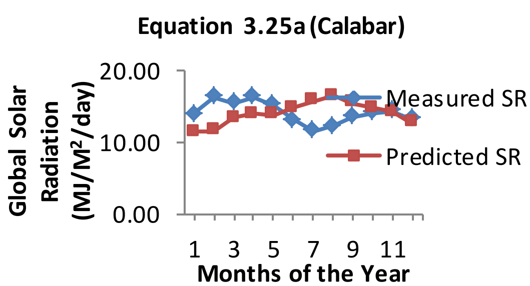

Fig 2d: Comparison between the measured and predicted values of correlation equation for Calabar (1996 – 2006)

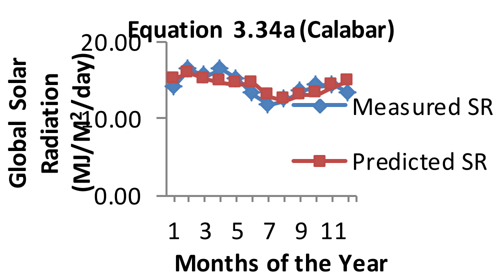

Fig 2e: Comparison between the measured and predicted values of correlation equation for Calabar (1996 - 2006)

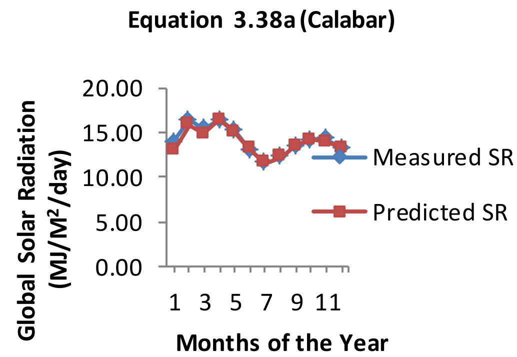

Fig 2f: Comparison between the measured and predicted values of correlation equation for Calabar (1996 – 2006)

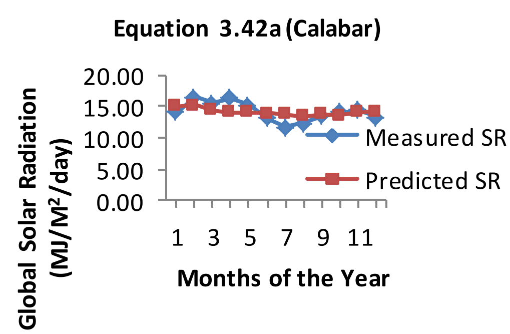

Fig 2g: Comparison between the measured and predicted values of correlation equation for Calabar (1996 – 2006)

CONCLUSION

The proposed model equations for Onitsha and Calabar can be used for estimating the monthly average solar radiation on horizontal surface for any location in the country with absolute values of the MPE less than 8%

and other places outside the country which have the same values of the maximum clearness index.

Therefore, from the above results, it can be concluded that the following simple first order Angstrom type correlation can be used for the estimation of global solar radiation H on a horizontal surface at the locations under study

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