Empirical Models for the Correlation of Global Solar Radiation with Meteorological Data for Enugu, Nigeria.

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ABSTRACT

A number of multilinear regression equations were developed to predict the relationship between global solar radiation with one or more combinations of the following meteorological parameters: fraction of sunshine, maximum temperature, cloudiness index and relative humidity for Enugu for seventeen years (1990 – 2007). Using the Angstrom model as the base, other regression equations were developed by modifying the Angstrom equation. 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) statistical techniques. The values of the correlation coefficient (R) and coefficient of correlation (R^2) were also determined for each equation. The equation with the highest values of R, R^2 and least values of MBE, RMSE and MPE is given as:

$$\frac{\overline{H}_P}{\overline{H}_O} = -0.627 + 0.452\frac{\overline{n}}{\overline{N}} - 0.283\frac{\overline{c}}{\overline{C}} + 0.0171T_M + 0.468\frac{R}{100}$$

The developed model can be used for estimating global solar radiation in Enugu and other locations with similar climatological characteristics.

(Keywords: sunshine, maximum temperature, cloudiness index, relative humidity, 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). A global study of the world distribution of global solar radiation requires knowledge of the radiation data in various countries and for the purpose of world wide marketing, the designers and manufacturers of solar equipment will need to know the mean global solar radiation available in different and specific regions (Ibrahim, 1985).

Obviously, the best solar radiation information is that obtained from experimental measurements of the global and diffuse components of the solar insolation at the location in question. Unfortunately, there are few meteorological stations conducting such measurements. Therefore, it is rather important to develop models to estimate the solar radiation using whatever weather parameters available. Several empirical models have been developed to calculate the solar radiation using various parameters. Such models include that of Sambo(2005), Awachie and Okeke (1990), Akpabio et al. (2004), Badamus and Momoh (2005), Hussaini et al. (2005), Iheonu (2001), Arinze and Obi (1983), Falayi and Rabiu (2005), El- sabaii et al. (2005), Babatunde et al. (1990), and Burari et al. (2001) to mention but a few.

This work tried to investigate the suite of empirical models used in the estimation of the global solar radiation from the meteorological parameters in Enugu and its environs.

METHODOLOGY

The monthly mean daily sunshine duration, maximum temperature, cloudliness index and relative humidity, were obtained from the Archives of Nigerian Meteorological Agency, Oshodi, Lagos. The monthly mean global solar radiations were collected from the Nigerian Meteorological Agency, Akanu Biam Airport, Enugu. The data obtained , covered a period of seventeen years

(1990 – 2007) for Enugu Located at latitude 7.55^{0}N and longitude 6.45^{0}E and it has an altitude of 141.5m above sea level. The monthly mean daily data processed in preparation for the correlations are presented in Table1.

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

The liner regression model used in correlating the measured global solar radiation data $\frac{\overline{H}_M}{\overline{\overline{H}}_O}$ with fraction of sunshine $\frac{\overline{n}}{\overline{\overline{N}}}$ is given after Angstrom (1924) and later modified by Prescott (1940):

$$\frac{\overline{H}_M}{\overline{\overline{H}}_O} = a + b\frac{\overline{n}}{\overline{\overline{N}}} \quad (1)$$

Where a and b are regression constants, $\overline{H}_M$ is the measured monthly mean daily global radiation, $\overline{H}_O$ is the monthly mean extraterrestrial solar radiation on horizontal surface, given by Iqbal (1983) as follows:

$$\overline{H}_O = \frac{24}{\pi} I_{sc} E_O \left(\frac{\pi}{180} W_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin w_s \right) \quad (2)$$

Where I_{sc} is the solar constant, E_O is the eccentricity correction factor, ϕ is the latitude, δ is the solar declination and W_s is the hour angle. The expressions for I_{sc}, E_O, δ and W_s are given by Iqbal (1983) :

$$I_{sc} = \frac{1367 X 3600}{1000000} \text{ (MJm}^{-2}\text{day}^{-1}\text{)} \quad (3)$$

$$E_O = 1 + 0.033 COS\left(\frac{360N}{365}\right) \quad (4)$$

$$\delta = 23.45 Sin\left[\frac{360(N+284)}{365}\right] \quad (5)$$

$$W_s = Cos^{-1}(-\tan\phi \tan\delta) \quad (6)$$

Where N is the day number ranging from N = 1 on 1st January to N = 365 on 31st December.

Table 1: Meteorological Data and Global Solar Radiation for Enugu.

MONTH	$\frac{\overline{n}}{\overline{\overline{N}}}$	$\overline{T}_M$ (ºC)	$\frac{\overline{c}}{\overline{\overline{C}}}$	R/100	$\overline{H}_M$ (MJ/m^2/day)	$\overline{H}_O$ (MJ/m^2/day)	$\overline{K}_T = \overline{H}_M / \overline{H}_O$
JAN	0.5484	35.81	0.18	0.46	14.25	35.82	0.3978
FEB	0.5579	37.69	0.28	0.49	15.65	37.01	0.4229
MAR	0.5013	37.30	0.34	0.61	14.77	37.54	0.3934
APR	0.5296	35.57	0.38	0.71	14.27	36.44	0.4916
MAY	0.5247	34.07	0.39	0.77	14.85	34.41	0.4316
JUN	0.4294	32.65	0.40	0.80	13.61	33.15	0.4106
JUL	0.3113	31.62	0.42	0.82	11.65	34.85	0.3343
AUG	0.3088	31.14	0.42	0.83	10.80	35.47	0.3044
SEPT	0.3702	31.96	0.41	0.82	12.26	36.95	0.3318
OCT	0.5038	32.91	0.39	0.78	15.18	37.73	0.4023
NOV	0.6459	34.93	0.32	0.65	16.51	35.83	0.4608
DEC	0.6005	35.49	0.23	0.52	15.42	35.22	0.4378

The various meteorological data are related to global solar radiation. Multiple linear regression and correlation analysis of four parameters ($\frac{\bar{n}}{\bar{N}}$, T_M, $\frac{\bar{c}}{\bar{C}}$ and R) were employed to estimate the global solar radiation. Where $\frac{\bar{n}}{\bar{N}}$ is the fraction of sunshine duration, T_M is the maximum temperature, $\frac{\bar{c}}{\bar{C}}$ is the Cloudiness index and R is the relative humidity (Table 1).

SPSS Computer Software Program was used in evaluating model parameters. The values of the regression coefficients obtained for Enugu are found to be different from values for Maiduguri, Bauchi, Ilorin, Nsukka, Onne, and Sokoto obtained by Hussain (2005), Bala (2001), Burari et al. (2001), Awachie and Okeke (1990), Akpabio et al. (2002), and Badamus et al. (2005), respectively. These differences suggests that regression coefficients associated with sunshine hours and other metrological data changes with latitude and atmospheric condition.

The accuracy of the estimated values were tested by calculating the Mean Bias Error (MBE), Root Mean Square Error (RMSE), and Mean Percentage Error (MPE). The expressions for the MBE ($MJm^{-2}day^{-1}$), RMSE ($MJm^{-2}day^{-1}$), and MPE (%) is stated by El – Sebaii et al. (2005) as follows:

$$\mathrm{MPE} = \left[\sum\left(\bar{H}_{i,cal} - \bar{H}_{i,meas}\right)\right]/n \qquad \textbf{(7)}$$

$$RMSE = \left[\sum\left(\bar{H}_{i,cal} - \bar{H}_{i,meas}\right)^2/n\right]^{\frac{1}{2}} \qquad \textbf{(8)}$$

$$\mathrm{MPE} = \left[\sum\left(\frac{\bar{H}_{i,meas} - \bar{H}_{i,cal}}{\bar{H}_{i,meas}} X100\right)\right]/n \qquad \textbf{(9)}$$

Where $\bar{H}_{i,cal}$ and $\bar{H}_{i,meas}$ is the ith calculated (predicted) and measured values and n is the total number of observations. Iqbal (1983), Halouani (1993), Almorox (2005) and Che et al. (2007) have recommended that a zero value for MBE is ideal and a low RMSE is desirable. The RMSE test provides information on the short-term performance of the studied model as it allows a term – by – term comparism of the actual deviation between the calculated values and the measured values. The MPE test gives long term performance of the examined regression equations, a positive MPE values provide the averages amount of overestimation in the calculated values, while the negative values gives underestimation. A low value of MPE is desirable by Akpabio et al. (2002).

RESULTS AND DISCUSSION

The values for the fraction of sunshine duration, maximum temperature, cloudiness index, relative humidity, and clearness index are presented in Table 1. Table 2 contains summaries of various linear regression analysis, obtained from the application of Equation (1) to the monthly mean values for the four variables under study.

Figure 1 shows the comparison between the measured and predicted values of correlation equations. It is clear that the correlation coefficient R, coefficient of determination R^2, MBE ($MJ/m^2/day$), RMSE ($MJ/m^2/day$) and MPE (%) vary from one variable to another variable.

ONE VARIABLE CORRELATION

The correlation coefficient of 0.857 exists between the clearness index and monthly mean daily fraction of sunshine and coefficient of determination of 0.735 implies that 73.5% of clearness index can be accounted using fraction of sunshine.

$$\frac{\bar{H}_P}{\bar{H}_O} = 0.191 + 0.433\frac{\bar{n}}{\bar{N}} \qquad \textbf{(10)}$$

The correlation coefficient of 0.648 exists between the clearness index and monthly mean daily maximum temperature and coefficient of determination of 0.42 implies that 42% of clearness index can be accounted using maximum temperature.

$$\frac{\bar{H}_P}{\bar{H}_O} = -0.152 + 0.016\bar{T}_M \qquad \textbf{(11)}$$

Table 2: Regression Equations and Statistical Indicators.

Eqauations	R	R^2	MBE	RMSE	MPE
$\frac{\overline{H}_P}{\overline{H}_O} = 0.191 + 0.433\frac{\overline{n}}{\overline{N}}$	0.857	0.735	0.3080	0.6920	-2.2000
$\frac{\overline{H}_P}{\overline{H}_O} = -0.152 + 0.016\overline{T}_M$	0.648	0.42	0.1266	1.2660	1.5000
$\frac{\overline{H}_P}{\overline{H}_O} = 0.493 - 0.264\frac{\overline{c}}{\overline{C}}$	0.38	0.144	0.3020	1.4030	-3.2000
$\frac{\overline{H}_P}{\overline{H}_O} = 0.526 - 0.18\frac{R}{100}$	0.453	0.205	0.3290	1.3690	-3.2900
$\frac{\overline{H}_P}{\overline{H}_O} = 0.212 + 0.446\frac{\overline{n}}{\overline{N}} - 0.0008\overline{T}_M$	0.857	0.735	0.3342	0.6222	-1.4758
$\frac{\overline{H}_P}{\overline{H}_O} = 0.0286 + 0.571\frac{\overline{n}}{\overline{N}} + 0.275\frac{\overline{c}}{\overline{C}}$	0.904	0.818	0.3058	0.7229	-2.1295
$\frac{\overline{H}_P}{\overline{H}_O} = 0.0327 + 0.561\frac{\overline{n}}{\overline{N}} + 0.140\frac{R}{100}$	0.891	0.794	0.2117	0.8036	-1.5677
$\frac{\overline{H}_P}{\overline{H}_O} = -0.0953 + 0.528\frac{\overline{n}}{\overline{N}} + 0.310\frac{\overline{c}}{\overline{C}} + 0.0039\overline{T}_M$	0.909	0.826	0.3442	0.7829	-2.5839
$\frac{\overline{H}_P}{\overline{H}_O} = -0.394 + 0.490\frac{\overline{n}}{\overline{N}} + 0.253\frac{R}{100} + 0.011\overline{T}_M$	0.915	0.837	-0.0483	0.9339	-0.1869
$\frac{\overline{H}_P}{\overline{H}_O} = 0.0439 + 0.561\frac{\overline{n}}{\overline{N}} - 0.0654\frac{R}{100} + 0.375\frac{\overline{c}}{\overline{C}}$	0.906	0.820	0.1067	0.9179	-0.8769
$\frac{\overline{H}_P}{\overline{H}_O} = -0.627 + 0.452\frac{\overline{n}}{\overline{N}} - 0.283\frac{\overline{c}}{\overline{C}} + 0.0171\overline{T}_M + 0.468\frac{R}{100}$	0.916	0.840	0.0212	0.1118	0.0442

The correlation coefficient of 0.38 exists between the clearness index and monthly mean daily cloudiness index and coefficient of determination of 0.144 implies that 14.4% of clearness index can be accounted using cloudiness index.

$$\frac{\overline{H}_P}{\overline{H}_O} = 0.493 - 0.264\frac{\overline{c}}{\overline{C}} \qquad \textbf{(12)}$$

The correlation coefficient of 0.453 exists between the clearness index and monthly mean daily relative humidity and coefficient of determination of 0.205 implies that 20.5% of clearness index can be accounted using relative humidity.

$$\frac{\overline{H}_P}{\overline{H}_O} = 0.526 - 0.18\frac{R}{100} \qquad \textbf{(13)}$$

TWO VARIABLES CORRELATIONS

The correlation coefficient of 0.857 exists between the clearness index, monthly mean daily fraction of sunshine duration and maximum temperature, also coefficient of determination of 0.735 implies that 73.5% of clearness index can be accounted using fraction of sunshine and maximum temperature.

$$\frac{\bar{H}_P}{\bar{H}_O} = 0.212 + 0.446\frac{\bar{n}}{\bar{N}} - 0.0008\bar{T}_M \qquad \textbf{(14)}$$

The correlation coefficient of 0.904 exists between the clearness index, monthly mean daily fraction of sunshine duration and cloudiness index, also coefficient of determination of 0.818 implies that 81.8% of clearness index can be accounted using fraction of sunshine and cloudliness index.

$$\frac{\bar{H}_P}{\bar{H}_O} = 0.0286 + 0.571\frac{\bar{n}}{\bar{N}} + 0.275\frac{\bar{c}}{\bar{C}} \qquad \textbf{(15)}$$

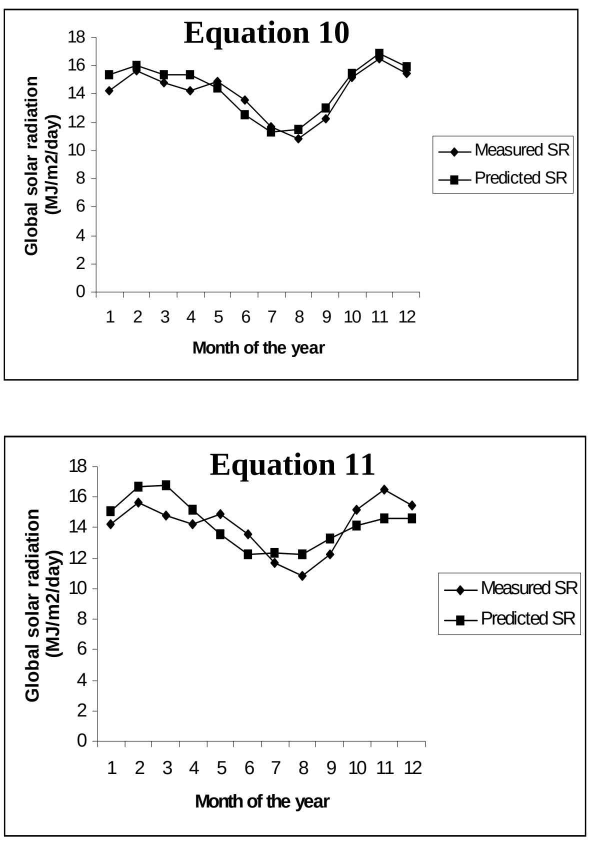

Figure 1 (Equation 10-11): Comparison Between the Measured and Predicted Values of Correlation Equation.

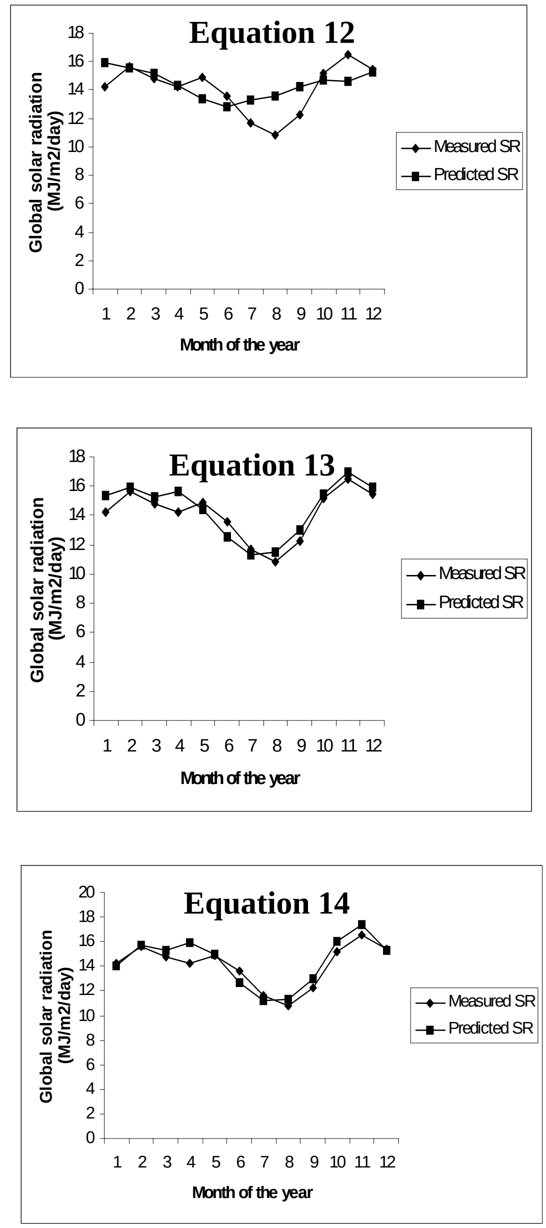

Figure 1 (Equation 12 – 14): Comparison Between the Measured and Predicted Values of Correlation Equation.

The correlation coefficient of 0.891 exists between the clearness index, monthly mean daily fraction of sunshine duration and relative humidity, also coefficient of determination of 0.794 implies that 79.4% of clearness index can be accounted using fraction of sunshine and relative humidity.

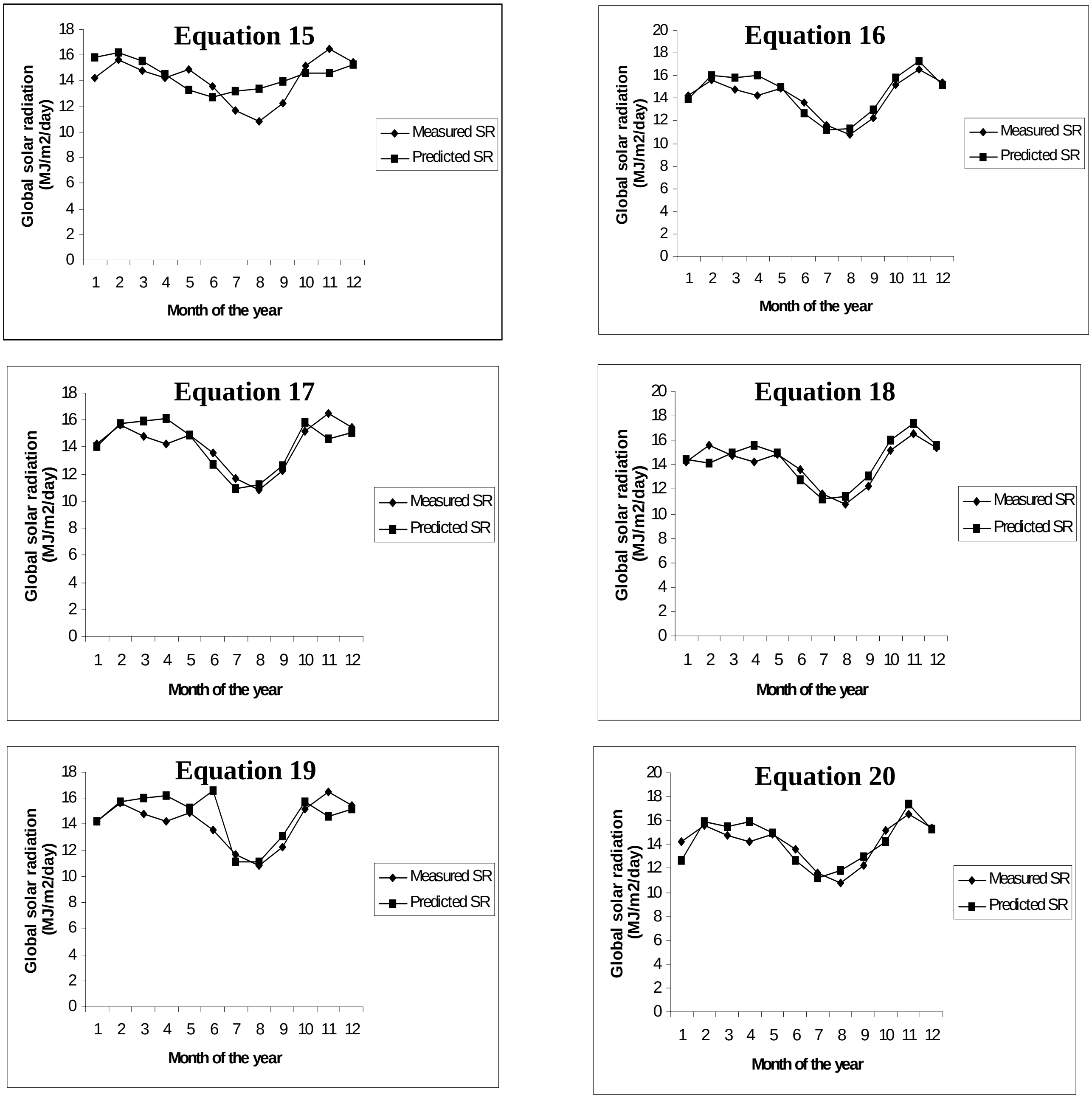

Figure 1 (Equation 15 - 20): Comparison Between the Measured and Predicted Values of Correlation Equation.

$$\frac{\overline{H}_P}{\overline{H}_O} = 0.0327 + 0.561\frac{\overline{n}}{\overline{N}} + 0.140\frac{R}{100} \quad \textbf{(16)}$$

THREE VARIABLES CORRELATIONS

The Equations (14) – (16) can be modified by incorporating extra parameters to the set of correlation equations for two variables.
The correlation coefficient of 0.909 exists between the clearness index, monthly mean daily

fraction of sunshine duration, cloudiness index and maximum temperature, also coefficient of determination of 0.826 implies that 82.6% of clearness index can be accounted using fraction of sunshine, cloudiness index and maximum temperature.

$$\frac{\overline{H}_P}{\overline{H}_O} = -0.0953 + 0.528\frac{\overline{n}}{\overline{N}} + 0.310\frac{\overline{c}}{\overline{C}} + 0.0039\overline{T}_M \quad \textbf{(17)}$$

The correlation coefficient of 0.915 exists between the clearness index, monthly mean daily fraction of sunshine duration, relative humidity and maximum temperature, also coefficient of determination of 0.837 implies that 83.7% of clearness index can be accounted using fraction of sunshine, relative humidity and maximum temperature.

$$\frac{\overline{H}_P}{\overline{H}_O} = -0.394 + 0.490\frac{\overline{n}}{\overline{N}} + 0.253\frac{R}{100} + 0.011\overline{T}_M \quad \textbf{(18)}$$

The correlation coefficient of 0.906 exists between the clearness index, monthly mean daily fraction of sunshine duration, relative humidity and cloudiness index, also coefficient of determination of 0.820 implies that 82% relative humidity and cloudliness index.

$$\frac{\overline{H}_P}{\overline{H}_O} = 0.0439 + 0.561\frac{\overline{n}}{\overline{N}} - 0.0654\frac{R}{100} + 0.375\frac{\overline{c}}{\overline{C}} \quad \textbf{(19)}$$

FOUR VARIABLES CORRELATION

Equations (17) – (19) can be modified by incorporating extra parameters to the set of correlation equations for three variables.

The correlation coefficient of 0.916 exists between the clearness index, monthly mean daily fraction of sunshine duration, cloudiness index, maximum temperature and relative humidity, also coefficient of determination of 0.840 implies 84% of clearness index can be accounted using fraction of sunshine, cloudiness index , maximum temperature and relative humidity.

$$\frac{\overline{H}_P}{\overline{H}_O} = -0.627 + 0.452\frac{\overline{n}}{\overline{N}} - 0.283\frac{\overline{c}}{\overline{C}} + 0.0171T_M + 0.468\frac{R}{100} \quad \textbf{(20)}$$

For better analysis the developed correlation will be considered that has high values of correlation coefficient R and coefficient of correlation R^2: Equations (10), (11), (12), (13), (14), (15), (16), (17), (18), (19), and (20). Equations (10), (14), (15), (16), (17), (18), (19), and (20) have the highest values of correlation coefficient and coefficient of determination , while the others have low values of correlation coefficient and coefficient of determination. Furthermore, there is a remarkable agreement between the observed and the predicted values of global solar radiation for seventeen years from our correlation (Table 2).

From Table 2, based on the highest values of correlation coefficient, coefficient of determination and least values of MBE, RMSE and MPE, Equation (20) is the best regression equation suitable for estimating solar radiation in Enugu and its environs.

CONCLUSION

The monthly mean daily global solar radiation, fraction of sunshine duration, maximum temperature, cloudiness index and relative humidity have been employed in this study to develop several correlation equations. Four variables have been developed with different types of equations obtained. It was observed that Equation (20) has the highest value of correlation coefficient and coefficient of determination, which gives good results when considering statistical indicators that is, MBE, RMSE, and MPE. The equation could be employed in the estimation of global solar radiation in Enugu and other similar locations.

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