

MODELS FOR PREDICTION OF GLOBAL SOLAR RADIATION ON HORIZONTAL SURFACE FOR AKURE, NIGERIA

OLUMIDE OLUFEMI AKINNAWO, JAMES SAMUEL OLADUNJOYE OLUDOTUN, ABEL GIWA USIFO AND SAMUEL OLUYEMI ADEJUWON

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ABSTRACT

The estimation of global solar radiation continues to play a fundamental role in solar engineering systems and applications. This paper compares various models for estimating the average monthly global solar radiation on horizontal surface for Akure, Nigeria, using solar radiation and sunshine duration data covering years 1981 to 1995. The analysis was performed using Angstrom models, two dimensional principal component analysis (PCA) and adaptive neuro-fuzzy inference system (ANFIS). The performance of the models were tested using statistical indicators such as mean bias error (MBE), mean percentage error (MPE), root mean square error (RMSE) and correlation coefficient (CC). The results indicated that ANFIS and linear regression analysis provide relatively higher degree of prediction, with the performance of ANFIS slightly better.

KEYWORDS: Angstrom model, fuzzy logic system, principal component analysis, regression analysis, solar radiation, sunshine duration.

INTRODUCTION

Global solar radiation (GSR) measurements play a fundamental role in the design of solar engineering projects and in evaluation of system performance. Nigeria is currently focusing on solar energy for power generation especially in remote villages that are not yet connected to the grid system to make electricity available to rural dwellers. The data for the average solar radiation are not readily available for many locations due to a number of factors among which are cost and maintenance of the measuring equipment (Paltineanu et al. 2002; Muzathik et al. 2011). The alternative approach to obtaining the measurement is to correlate it with other meteorological parameters such as temperature, sunshine duration, relative humidity, etc., measured at the study location (Fagbenle 1990; Falayi and Rabi 2005). The most commonly used parameter for this estimation by many researchers however, is the sunshine duration (Akpabio and Etuk 2003; El-Sebaei and Trabea 2005). The models derived from these parameters may then be used to estimate the global solar radiation values for places where the data are not available having similar geographical features.

Angstrom (1924) proposed the first linear regression model for estimating global solar radiation using sunshine duration data. The model was later modified by Prescott (1940) by comparing the clearness

index, H/H_o to the relative sunshine index, n/N which gives information about the atmospheric condition of the study area. The equation is defined in (1):

$$H/H_o = a + b(n/N) \quad \text{----- (1)}$$

The clearness index is the ratio of the solar radiation at the Earth surface (H) to extraterrestrial radiation (H_o), while the relative sunshine index or cloudless index is the ratio of the actual sunshine hour (n) to the monthly average daily maximum number of hours of possible sunshine (N). The empirical constants a and b have been shown to have seasonal and latitudinal variability (Srivastava and Pandey, 2013). On a cloudless day the relative sunshine duration is unity, and thus the clearness index is equal to $(a + b)$. On a cloudy day however, the value of the clearness index is equal to a .

Sen (2008) carried out a comprehensive review on linear and non-linear energy models for estimation of GSR on horizontal surfaces using single predictor variable. Among these models are the principal component analysis (PCA) and fuzzy logic system.

The present study aims to determine model coefficients using the Angstrom-PreScott formula through regression analysis, two-dimensional PCA and adaptive neuro-fuzzy inference system (ANFIS) for estimating GSR on horizontal surface. Statistical

Olumide Olufemi Akinnowo, Department of Physical and Earth Sciences, Crawford University, Igbesa, Ogun State, Nigeria.

James Samuel Oladunjoye Oludotun, Department of Physical and Earth Sciences, Crawford University, Igbesa, Ogun State, Nigeria.

Abel Giwa Usifo, Department of Physical and Earth Sciences, Crawford University, Igbesa, Ogun State, Nigeria.

Samuel Oluyemi Adejuwon, Department of Mechanical Engineering, Polytechnic of Ibadan, Oyo State, Nigeria.

analysis will then be used to compare the estimated monthly average GSR with the measured value.

Data and methods of estimation

Data used in this analysis is obtained from the Nigerian Meteorological Agency (NIMET), Lagos, for Akure (7.25° N, 5.20° E), a tropical location. The mean monthly values of sunshine duration and GSR for a period of fifteen years (1981 – 1995) were used.

In order to use the Angstrom-type formula, the average monthly global solar radiation, obtained using Gun–Bellani radiometer measured in *mI* had to be converted to *MJ m⁻²* using the conversion factor of 1.357±0.176 (Folayan, 1988). The extraterrestrial radiation, *H₀* and the monthly average daily maximum number of hours of possible sunshine, *N* were determined (Iqbal, 1986) as in (2):

$$H_0 = \frac{24}{\pi} G_0 \left(\cos\phi \cos\delta \sin w_0 + \frac{\pi}{180} w_0 \sin\phi \sin\delta \right) \text{----- (2)}$$

$$\text{and } N = \left(\frac{2}{15} \right) w \text{----- (3)}$$

where,

$$G_0 = 1367 \left(1 + 0.033 \cos \left(\frac{360N_d}{365} \right) \right) \text{----- (4)}$$

$$\delta = 23.45 \sin \left(\frac{360(284+N_d)}{365} \right) \text{----- (5)}$$

w is the sunset hour given as:

$$w = \cos^{-1}(-\tan\phi \tan\delta) \text{----- (6)}$$

N_d = Julian day number, *φ* = Latitude, *δ* = declination angle.

The paper considers three different approaches. The first approach uses the Angstrom-PreScott formula for first, second and third-order regression models. The model coefficients of the first order Angstrom-PreScott formula type equation were obtained using linear regression analysis. The scatterplot for the clearness index versus relative sunshine index for the station is obtained for all the months in a period of 15 years, between 1981 and 1995 and the model coefficients determined. The second and third order equations were evaluated using the MATLAB intrinsic function *nlintool* (Hejase and Assi,2011). The form of the three different models is as shown in Table 1. For the models, *b*, *x* and *y* represent the model coefficients, sunshine duration index and clearness index respectively.

Table 1: Angstrom-PreScott type models

S/No	Model	Model type
1	$y = b^1 + b^2 x$	Linear
2	$y = b^1 + b^2 x + b^3 x^2$	Quadratic
3	$y = b^1 + b^2 x + b^3 x^2 + b^4 x^3$	Cubic

The second approach uses two-dimensional PCA to construct orthogonal-mutually uncorrelated principal components. The method employs centralization of the data by removing the average value from each variable such that the new data set produce a zero mean. The covariance matrix was then obtained from the two variables of the newly reconstructed data set. Finally, the eigenvalues and eigenvectors of the covariance matrix were obtained. The eigenvectors corresponding to the biggest eigenvalues (maximum variance in the data) were used to fit a straight line to the original data set. The straight line is the major principal axis corresponding to the first principal component. The other smaller eigenvalues give the minimum variance in the data and correspond to the second principal component. The covariance for the *x* and *y* data is defined as:

$$Cov(x, x) = \frac{\sum_{i=1}^n (x_i - \bar{x})(x_i - \bar{x})}{(n-1)} \text{----- (7)}$$

$$Cov(x, y) = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{(n-1)} \text{----- (8)}$$

and the covariance matrix [S] is defined as:

$$[S] = \begin{pmatrix} Cov(x, x) & Cov(x, y) \\ Cov(y, x) & Cov(y, y) \end{pmatrix} \text{----- (9)}$$

where the leading diagonal corresponds to the individual variances of the *x* and the *y* data and the other gives their joint variance (Wilks, 2011). The PCA model is defined in (10):

$$y_{pca} = b_1 + b_2x \text{ ----- (10)}$$

where, b , x and y_{pca} represent the PCA model parameters, sunshine duration index and clearness index respectively.

The final approach uses ANFIS in the estimation of GSR for Akure. ANFIS is a class of adaptive multi-layer network that combines the learning ability of artificial neural network and fuzzy logic principles. The Sugeno style inference system of the Matlab® toolbox was used in the study. This system uses a single spike for representing the membership function of the rule consequent and a weighted average techniques for its defuzzification (Demiccio and Klir, 2003).

Statistical analyses were performed on the estimated and measured values using parameters like mean bias error (MBE), root mean square error (RMSE), Mean Percentage Error (MPE) and correlation coefficient (CC):

$$MBE = \sum_{i=1}^n \frac{(H_{cal} - H_{obs})}{n} \text{ ----- (11)}$$

$$RMSE = \left\{ \frac{\sum_{i=1}^n (H_{cal} - H_{obs})^2}{n} \right\}^{1/2} \text{ ----- (12)}$$

$$MPI = \frac{1}{n} \sum_{i=1}^n \left(\frac{H_{obs} - H_{cal}}{H_{obs}} \right) 100 \text{ ----- (13)}$$

$$CC = \frac{\sum_{i=1}^n (H_{cal} - \bar{H}_{cal})(H_{obs} - \bar{H}_{obs})}{\left\{ \left[\sum_{i=1}^n (H_{cal} - \bar{H}_{cal})^2 \right] \left[\sum_{i=1}^n (H_{obs} - \bar{H}_{obs})^2 \right] \right\}^{1/2}} \text{ ----- (14)}$$

where, H_{cal} and H_{obs} stand for the predicted and measured values respectively, and n is the total number of observations. The RMSE is always positive and has ideal value equal to zero while the ideal values for the MBE and correlation coefficient should be zero and one respectively (Iqbal, 1986).

RESULTS AND DISCUSSION

The correlation between the clearness index and the relative sunshine index for Akure using mean monthly values are shown in Fig. 1-3. Fig. 1, represents the scatterplot obtained by using both the first order linear regression method and the two-dimensional PCA. The regression method deals with averaging without a consideration of variability within the data while the PCA considers both averaging and variability of the data set (Sen, 2008). From Fig. 1, we obtained the least square regression equation as:

$$H/H_o = 0.1981 + 0.5182(n/N) \text{ ----- (15)}$$

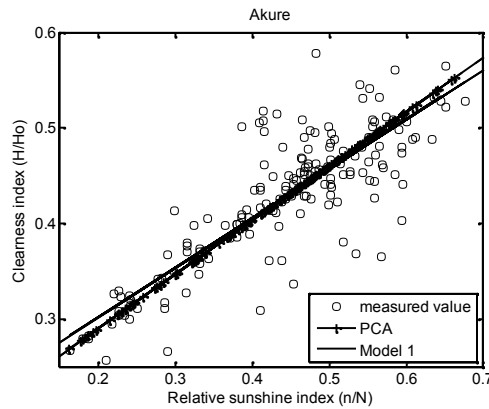


Fig. 1: Correlation between H/H_o and n/N for Akure using mean monthly values.

The model constants obtained from Eq. (15) found a to be 0.1981 and b to be 0.5182. So, the transmissivity of the atmosphere, translate to the clearness index on a cloudless day and was found to be 0.7163. This value lies between 0.68-0.75 as indicated by many researchers for a humid tropical climate (Akpabio and Etuk, 2003; Muzathik et. al, 2011). Also, from the figure, the PCA, yields the linear equation:

$$H_{pca}/H_o = 0.1768 + 0.5667(n/N) \text{ ----- (16)}$$

The model constants obtained from Eq. (16) found a to be 0.1768 and a high value for b to be 0.5667. In this case, the clearness index for a cloudless day yields 0.7435.

Figures 2 and 3 show the second and third orders Angstrom-Preecott type models respectively. The regression equations for these were:

$$H/H_o = 0.1280 + 0.8307(n/N) - 0.3862(n/N)^2 \text{ --- (17)}$$

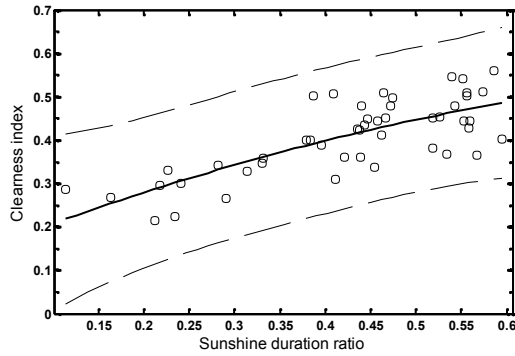


Fig. 2: Regression model with quadratic function between clearness index and sunshine duration ratio

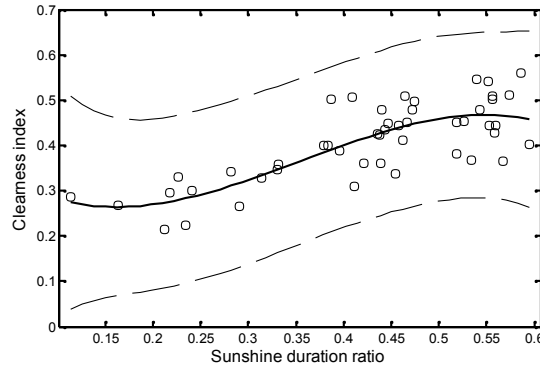


Fig. 3: Regression model with cubic function between clearness index and sunshine duration ratio

$$H_i/H_o = 0.3987 - 1.8543(n/N) + 7.4482(n/N)^2 - 7.0005(n/N)^3 \text{ ---- (18)}$$

Figures 4 and 5 show the plots for the variation of the measured, against the predicted GSRs obtained from all the models for 1982 and 1983 respectively. These figures show two minima with the first minimum occurring between February and March and the more

enhanced second minimum occurring at August. Also from the figure, there exists corresponding two maxima with the first maximum occurring between January and February and the second maximum occurring at November. This phenomenon for Nigeria has been reported by other researchers (Akpabio and Etuk, 2003).

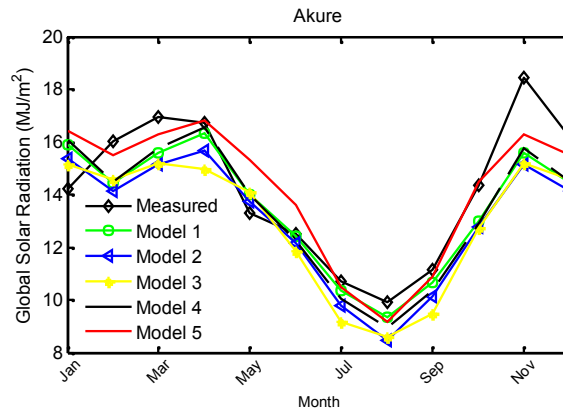


Fig. 4: Comparison of GSR for 1982 in Akure

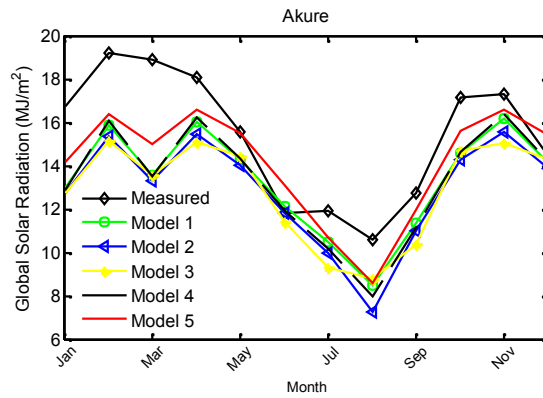


Fig. 5: Comparison of GSR for 1983 in Akure

The values obtained from the regression models, PCA and Fuzzy inference system on the horizontal surface are given in Tables 2 and 3 for 1982 and 1983 respectively. Also the comparisons of the GSR

measured values for the years are given in Tables 4 and 5 respectively. The calculated PE, MPE, MBE, RMSE and CC are shown at the bottom of the tables.

Table 2: Values of Sunshine duration and GSRs for year 1982

Months	Sunshine Duration (Hour)	GSR measured ($MJ m^{-2} day^{-1}$)	GSR Model 1 (Eq. 15) ($MJ m^{-2} day^{-1}$)	GSR Model 2 (Eq. 16) ($MJ m^{-2} day^{-1}$)	GSR Model 3 (Eq. 17) ($MJ m^{-2} day^{-1}$)	GSR Model 4 (Eq. 18) ($MJ m^{-2} day^{-1}$)	GSR Model 5 ANFIS ($MJ m^{-2} day^{-1}$)
January	6.5	14.22	15.885	15.354	15.162	16.077	16.4
February	5.5	16.04	14.431	14.146	14.559	14.488	15.5
March	6.3	16.95	15.594	15.128	15.181	15.759	16.3
April	6.8	16.723	16.321	15.68	14.974	16.554	16.8
May	5.2	13.31	13.995	13.747	14.1	14.011	15.3
June	4.1	12.514	12.396	12.141	11.861	12.262	13.6
July	2.7	10.693	10.362	9.769	9.18	10.037	10.5
August	2	9.897	9.344	8.446	8.597	8.925	9.15
September	2.9	11.148	10.652	10.13	9.47	10.355	10.9
October	4.5	14.334	12.978	12.751	12.736	12.898	14.5
November	6.3	18.429	15.594	15.128	15.181	15.759	16.3
December	5.5	16.154	14.431	14.146	14.559	14.488	15.5

Table 3: Values of Sunshine duration and GSRs for year 1983

Months	Sunshine Duration (Hour)	GSR measured ($MJ\ m^{-2}\ day^{-1}$)	GSR Model 1 (Eq. 15) ($MJ\ m^{-2}\ day^{-1}$)	GSR Model 2 (Eq. 16) ($MJ\ m^{-2}\ day^{-1}$)	GSR Model 3 (Eq. 17) ($MJ\ m^{-2}\ day^{-1}$)	GSR Model 4 (Eq. 18) ($MJ\ m^{-2}\ day^{-1}$)	GSR Model 5 ANFIS ($MJ\ m^{-2}\ day^{-1}$)
January	4.5	16.723	12.978	12.751	12.736	12.898	14.2
February	6.5	19.225	15.885	15.354	15.162	16.077	16.4
March	4.9	18.884	13.559	13.332	13.555	13.534	15
April	6.6	18.088	16.03	15.465	15.122	16.236	16.6
May	5.4	15.585	14.286	14.015	14.417	14.329	15.5
June	3.9	11.831	12.106	11.825	11.421	11.945	13.1
July	2.8	11.945	10.507	9.951	9.319	10.196	10.7
August	1.4	10.58	8.472	7.238	8.809	7.971	8.6
September	3.4	12.741	11.379	11.001	10.368	11.15	12
October	5.6	17.178	14.577	14.276	14.689	14.647	15.6
November	6.7	17.292	16.175	15.574	15.059	16.395	16.6
December	5.3	14.448	14.141	13.882	14.264	14.17	15.4

From Table 4, the calculated CC are strongly correlated and approximately equal to each other. Consequently we rely on the RSME values which give better results of 1.164 for the ANFIS model, 1.334 for the model 1 and 1.349 for the PCA model. The MPE

gives better results for the ANFIS model and the model 1. The same trend is observed for the values in Table 5, hence, the models that give better performance for the estimation of GSR at the study site were the ANFIS, the linear and the PCA models respectively in that order.

Table 4: Values of calculated PE, MPE, MBE RMSE and CC for year 1982

Months	PE				
	Model 1	Model 2	Model 3	Model 4	ANFIS
January	-11.707	-7.978	-6.627	-13.060	-15.331
February	10.030	11.807	9.234	9.679	3.368
March	8.001	10.752	10.436	7.027	3.836
April	2.404	6.233	10.456	1.009	-0.462
May	-5.149	-3.287	-5.938	-5.266	-14.952
June	0.936	2.978	5.213	2.007	-8.682
July	3.104	8.645	14.157	6.136	1.809
August	5.587	14.665	13.134	9.826	7.549
September	4.451	9.133	15.052	7.116	2.229
October	9.460	11.040	11.149	10.015	-1.160
November	15.384	17.914	17.623	14.488	11.553
December	10.664	12.428	9.873	10.315	4.048
MPE	4.430	7.861	8.647	4.941	-0.516
MBE	-0.702	-1.154	-1.238	-0.733	0.028
RMSE	1.334	1.608	1.652	1.349	1.164
CC	0.903	0.905	0.909	0.903	0.898

Table 5: Values of calculated PE, MPE, MBE RMSE and CC for year 1983

Months	PE				
	Model 1	Model 2	Model 3	Model 4	Model 5
January	22.394	23.749	23.842	22.870	15.086
February	17.377	20.135	21.134	16.376	14.696
March	28.198	29.402	28.219	28.331	20.568
April	11.377	14.501	16.398	10.238	8.226
May	8.336	10.073	7.494	8.062	0.546
June	-2.322	0.055	3.466	-0.960	-10.726
July	12.038	16.695	21.981	14.639	10.421
August	19.921	31.582	16.741	24.658	18.712
September	10.691	13.659	18.626	12.489	5.817
October	15.143	16.895	14.490	14.735	9.185
November	6.455	9.935	12.909	5.185	3.999
December	2.125	3.912	1.271	1.922	-6.593
MPE	12.644	15.883	15.548	13.212	7.495
MBE	-2.035	-2.488	-2.467	-2.081	-1.235
RMSE	2.517	2.898	2.858	2.547	1.896
CC	0.858	0.855	0.868	0.858	0.865

CONCLUSION

In this study, the regression equations, that is, first order, second order and third order Angstrom- Prescott formula have been used for the estimation of global solar radiation in Akure. The two-dimensional PCA and fuzzy interference system were also considered for the GSR estimation. The statistical tests carried out on the predicted results show that the fuzzy inference system is slightly more efficient than the linear regression model and relatively far better than other methods in terms of performance. Consequently, the fuzzy inference system and linear regression model are suitable for GSR estimation for Akure and its environ.

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