Estimation of Solar Radiation using Air Temperature and Geographical Coordinates over Nigeria.

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ABSTRACT

In this paper, monthly mean surface data of solar radiation and air temperature for the period 1970 - 1995 were obtained from the archives of the Nigerian Meteorological Agency (NIMET) for fourteen (14) stations selected across all climatic regions of Nigeria. The data of 1970 -1990 were used to developed monthly models from where solar radiation data can be evaluated over Nigeria. The monthly latitudinal distribution of solar radiation over Nigeria was observed using contour method. It was found that solar radiation increases with latitude. The Multivariate linear regression models were developed relating solar radiation to the air temperature, latitude and longitude of the selected stations. The efficiency of the model was verified by validating it with 1991-1995 surface data of air temperature together with the latitude and longitude of the selected locations. Results have shown that all the developed models were statistically significant and could explain most of the monthly variability of solar radiation. The coefficients of determination ($p < 0.05$) varied in the range of 0.6017 - 0.9170 for monthly models and 0.4145 for annual models. The developed models can be used reasonably to predict solar radiation received on horizontal surfaces in the selected stations and their proximate cities in Nigeria.

(Keywords: solar radiation, contour, correlation, variability, regression)

INTRODUCTION

Solar radiation data has been considered as an essential requirement to conduct feasibility studies for solar energy systems. Technology for measuring solar radiation is costly and has instrumental hazards (Alam et al., 2005). Thus, alternative methods for estimating these data are required. One of these methods is the use of empirical models. Accurate modeling depends on the quality and quantity of the measured data used, and is a good tool for generating solar radiation at locations where measured data are not available (Al-Salihi et al., 2010).

Meanwhile, the importance of solar radiation in power generation and precision agriculture has been established in many literatures. Knowledge of spatial distribution of climatic data is an essential tool for the management of natural resources and the prediction of climatic data is very useful in a wide number of scientific disciplines (e.g. Agronomy, Geography, Ecology, etc.). The act of fossil fuel burning and deforestation on climatic change raises the awareness for the development of adequate and reliable prediction models of solar radiation around the world. Hence, there is the need for the development of national models from which the values of solar radiation can be predicted for a given location in Nigeria.

Several models have been proposed to estimate global solar radiation. Angstrom (1924) was the first scientist known to suggest a simple linear relationship to estimate global solar radiation. Badescu (1999) studied existing relationships between monthly mean clearness index and the number of bright sunshine hours using the data obtained from Romania.

Trabea and Shaltout (2000) studied the correlation between the measurements of global solar radiation and some meteorological parameters using mean daily maximum temperature, mean daily relative humidity, mean daily sea level pressure, mean daily vapor pressure, and hours of bright sunshine data obtained from different parts of Egypt; while Sfetsos and Coonock (2000) used artificial intelligence techniques to forecast hourly global solar radiation. Okogbue and Adedokun (2002) estimated the global solar radiation at Ondo, Nigeria, while Ulgen and Hepbasli (2002) correlated the ratio of monthly average hourly diffuse solar radiation to monthly average hourly global solar radiation with the monthly average hourly clearness index in form of polynomial relationships for the city of Izmir, Turkey. Several investigations for instance, Akpabio et al. (2004) and Falayi and Rabiu (2005) have demonstrated the predictive ability of the Angstrom type model by correlating the global solar radiation to relative sunshine duration in a simple linear regression form.

Kaplanis (2006) described a computationally efficient and intuitively simple model to estimate hourly global solar radiation on a horizontal surface. Bamiro (1983) investigated various empirical models from the viewpoint of obtaining appropriate empirical model to determine solar radiation in Ibadan. Akpabio et al. (2004) developed a multiple linear regression model with ten variables to estimate monthly average daily global solar radiation for Onne, Nigeria.

The aim of the present study is to develop multiple linear models for estimating monthly and annual mean solar radiation using mean temperature and the geographical coordinates (latitude and longitude) of fourteen (14) stations distributed across Nigerian. This will be useful in the development and the applications of solar energy technology in Nigeria.

METEOROLOGY OF THE STUDY AREA

Nigeria is a tropical country that lies within the latitudinal range from 4^0N to 13^0N (Figure 1). The country can be divided into four climatic zones namely: Coastal/Tropical Rainforest, Derived Savannah, Guinea Savanna, and Sahel/Arid (Olaniran and Sumner, 1989). The coastal zone is dominated by tropical maritime (mT) air round the year. The vegetation is characterized by tropical forest. The zone is found along the coast up to 100 to 150 km inland.

The annual temperature ranges between 27^0C and 30^0C. The relative humidity in the region is as high as 80 percent and characterized by over 300 cm of annual rainfall. They also have a long wet season typically 7 to10 months.

The coastal zone is followed by Derived Savannah zone which experiences the dominance of mT air for about seven months and tropical continental (cT) air for the remaining five months annually. The stations within this zone are found further inland after the coastal zone. The zone experiences longer temperature range, lower annual rainfall and shorter wet season of about 6 to 8 months than the coastal region and well-marked dry season of 4 to 6 months. The region has a widespread of vegetation belt characterized by tall grasses and tall trees and has an annual rainfall of 100 to 200 cm having an annual relative humidity of 60 percent (Ogolo, 2011).

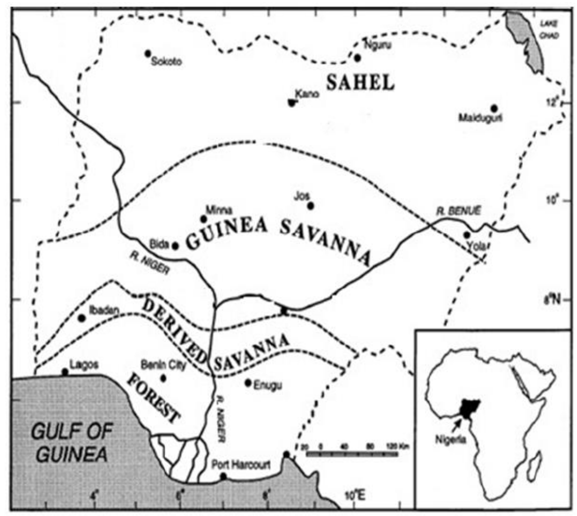


Figure 1: A Map of Nigeria showing four Climatic Regions and the Studied Stations.

The Guinea Savanna zone is dominated by a tropical continental air mass and is predominantly highlands and having a vegetation characterized by short grasses and scattered drought-resistant tree. Effectively, the topography is usually responsible for the usual long period of humid condition due to localized convection (Adeyemi and Aro, 2004).

Sahelian zone is a region where cT air mass predominates and the mT air mass invades for between 2 and 3 months at most because of its distance from the coastal environment. This zone embraces all stations in the North-Eastern extremity of Nigeria. This type of climatic environment has a highly accentuated continentality with a wide annual and diurnal range of about 15^0C to 20^0C. Dry season is excessively long, up to 8 to 10 months and desert-like conditions prevail (Ogolo, 2011; Olaniran and Sumner, 1989).

MATERIALS AND METHODS

The monthly mean daily solar radiation and air temperature were obtained from the archives of Nigerian Meteorological Agency (NIMET), Oshodi, Lagos. The data obtained covered a period of twenty-six years (1970-1995) for fourteen stations selected across all climatic regions of Nigeria. The measured surface data of solar radiation and air temperature for 1970-1990 and geographical coordinates (latitude and longitude) of the stations were used to develop the models.

According to the world Meteorological Organization (WMO, 1967), to ensure the optimal climate modelling, data series should extend to at least thirty years long. However, such longtime series are often unavailable. Good results have also been obtained using short time series (Wotling et al., 2000; Marquinez et al., 2003).

Multiple regression analysis technique was used for the solar radiation modelling. The mean monthly values of solar radiation was considered as dependent variables and the mean monthly values of air temperature (TEM), latitude (LAT) and longitude (LONG) of meteorological stations were considered as independent variables in the regression analysis. The multiple regression equation of the form shown in Equation (1) was developed for the estimation of solar radiation over Nigeria.

$$H = \alpha + \beta_1 TEM + \beta_2 LAT + \beta_3 LONG \qquad \textbf{(1)}$$

where α is the regression constant, β_1, β_2 and β_3, are parameter estimates of air temperature (TEM), latitude (LAT) and longitude (LONG) respectively of the selected locations. The models were then validated using surface data of air temperature for 1991-1995.

The performance of the developed models was evaluated by calculating coefficient of determination (R^2), the t-statistic (t-test), Root Mean Square Error (RMSE), Mean Bias Error (MBE) and Mean Percentage Error (MPE) using Equations (2-5). The mean bias error (MBE) provides information on the long term performance of the model. A positive MBE value gives the average amount of overestimation in the predicted values and vice- versa. A low MBE is desirable (Ajayi and Adeyemi, 2009). On the other hand, the root mean square error (RMSE) test provides information on the short term performance of the model, as it allows a term by term comparison of the actual deviation between the predicted and measured values. The RMSE is always positive but a zero value is desirable (Igbal and Muhammed, 1993; Okogbue and Adedokun, 2002; Ajayi and Adeyemi, 2009).

The mean percentage error (MPE) is also use to check the error of the models. The lower the value of MPE, the more accurate is the model. The RMSE and MBE values have also been subjected to t-test to further test the applicability of the model as stated by (Ajayi and Adeyemi, 2009; Stone, 1993) using Equation (6). The MPE test gives long term performance of the examined regression equations, a positive MPE values provides the averages amount of overestimation in the predicted values, while the negative gives underestimation. A low value of MPE is desirable (Akpabio et al., 2004). The expressions for evaluating the value of MBE, RMSE, MPE and t-test are given below:

$$MBE = \frac{1}{N}\sum_{n=1}^{n}(H_p - H_m) \qquad \textbf{(2)}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{n}(H_p - H_m)^2} \qquad \textbf{(3)}$$

$$MPE = \frac{1}{N}\sum_{n=1}^{n}\frac{H_m - H_p}{H_m} \times 100 \qquad \textbf{(4)}$$

where H_p and H_m is the predicted and measured values of solar radiation and N is the total number of observations.

$$t - test = \sqrt{\frac{(N-1)(MBE)^2}{(RMSE)^2 - (MBE)^2}} \qquad \textbf{(5)}$$

These indicators are mainly employed for adjustment of solar radiation data (Halouani and Ngguyen, 1993; Igbal and Muhammed, 1993; Al-Salihi et al., 2010; Okogbue and Adedokun, 2002).

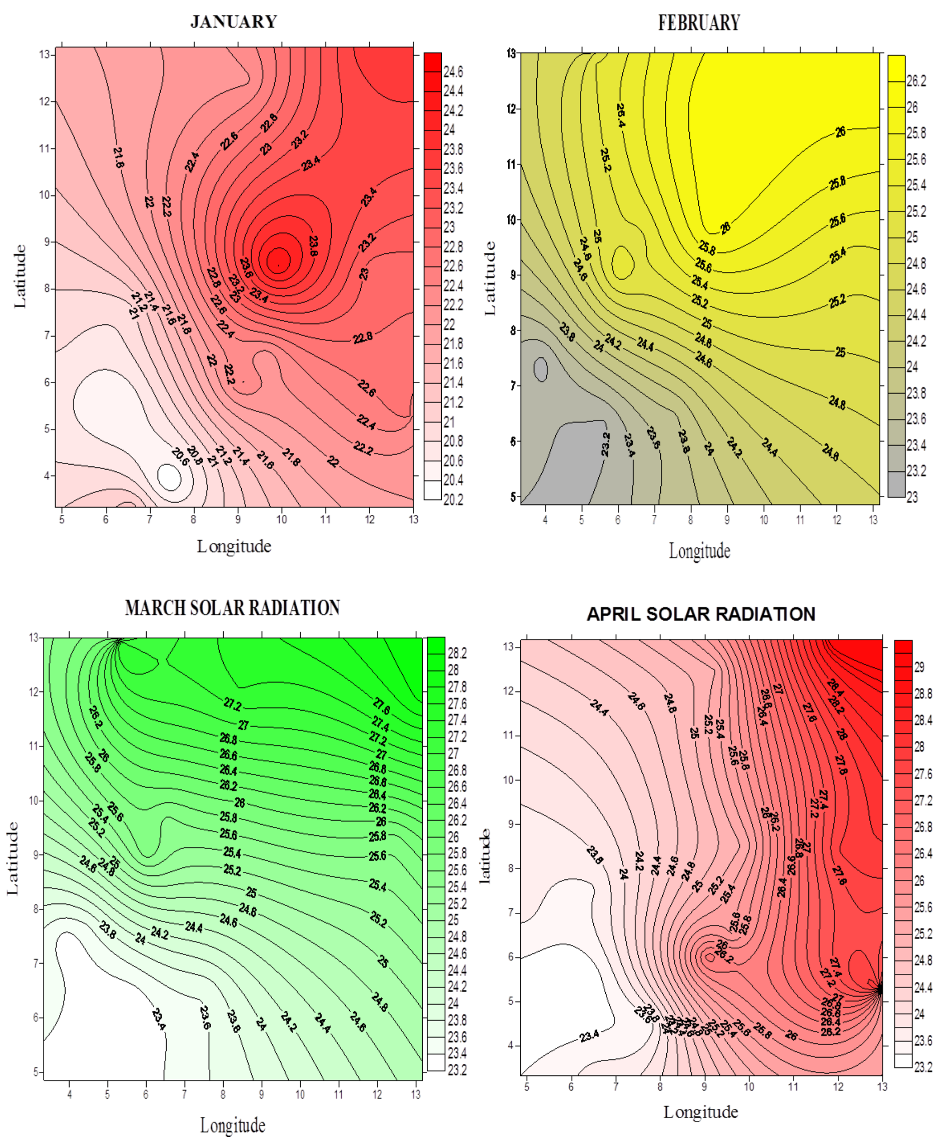
RESULTS AND DISCUSSION

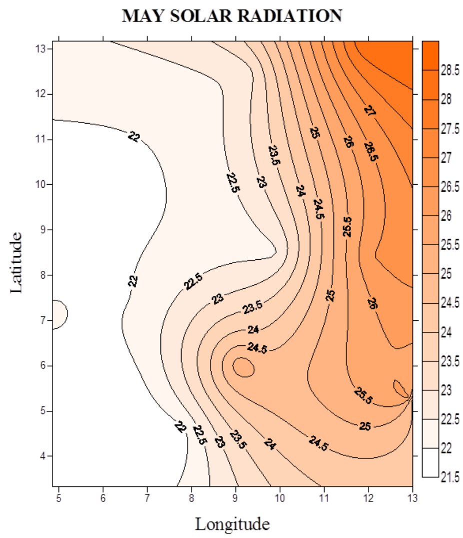
Latitudinal Distribution of Solar Radiation

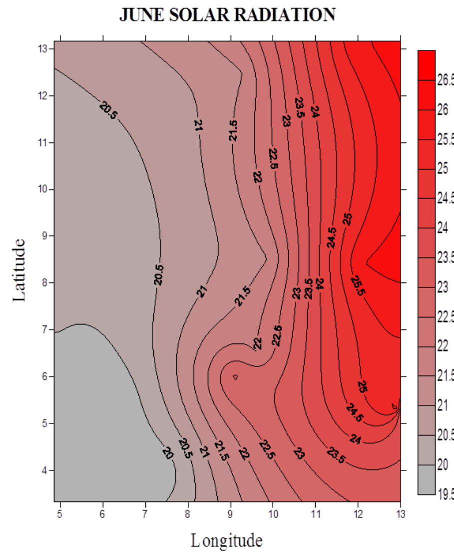
Distributions of solar radiation were obtained between a longitude of 3.33^0E and 13.17^0E, and latitude of 4.85^0N and 13.00^0N. These values were used to plot the contour maps of solar radiation for each month of the year as shown in Figure 2.

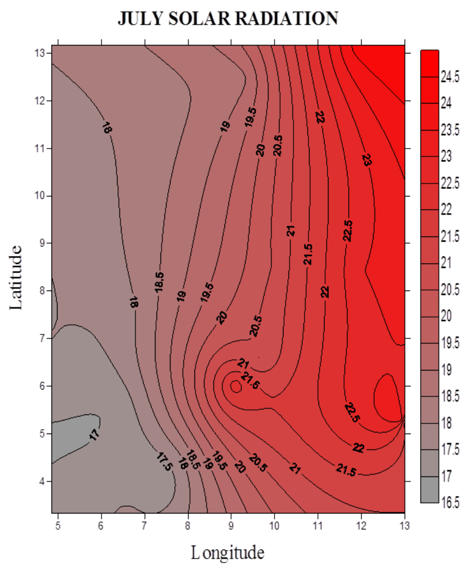
In general, the solar radiation maps of Figure 2 indicate clearly the locations of high and low solar radiation over the years. The seasonal trend, showing lower values of solar radiation in rainy season and higher in dry season is also depicted in this figure.

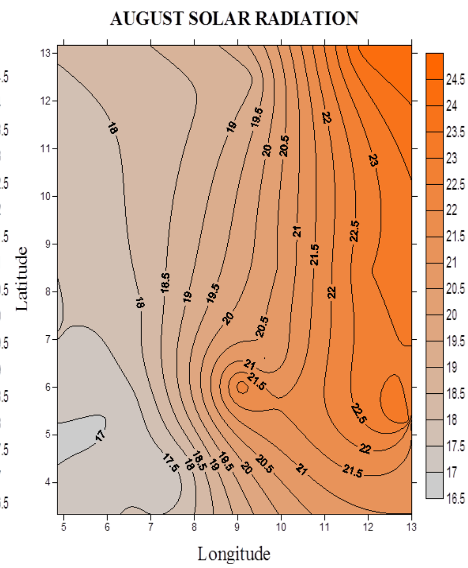
As shown in the maps, the overall maximum value of solar radiation was found at the Sahelian zone, this is expected due to excessively long dry season, up to 8 to 10 months and desert-like conditions which was prevalence in the zone (Ogolo, 2011; Olaniran and Sumner, 1989). On the other hand, the minimum values of solar radiation were found at the coastal zone of Nigeria. The minimum value is expected in the coastal zone because a heavy rainfall characterizes the months in the zone (Ogolo and Adeyemi, 2009). Therefore, the total solar radiation recorded is quite low because of the wet atmosphere and the presence of heavy clouds.

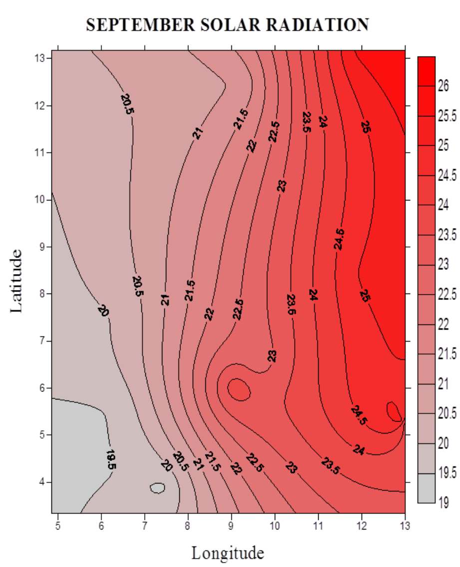


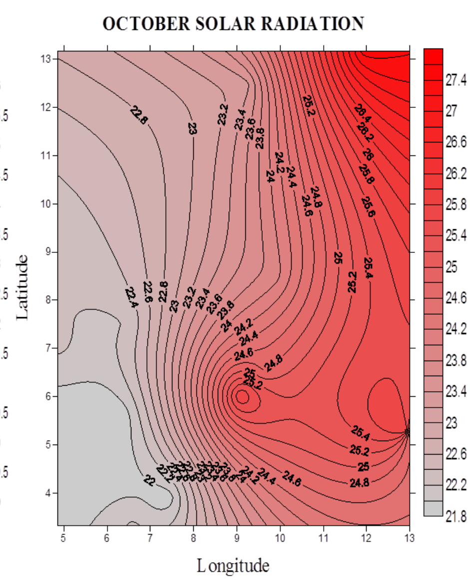

MAY SOLAR RADIATION
Latitude
Longitude


JUNE SOLAR RADIATION
Latitude
Longitude


JULY SOLAR RADIATION
Latitude
Longitude


AUGUST SOLAR RADIATION
Latitude
Longitude


SEPTEMBER SOLAR RADIATION
Latitude
Longitude


OCTOBER SOLAR RADIATION
Latitude
Longitude

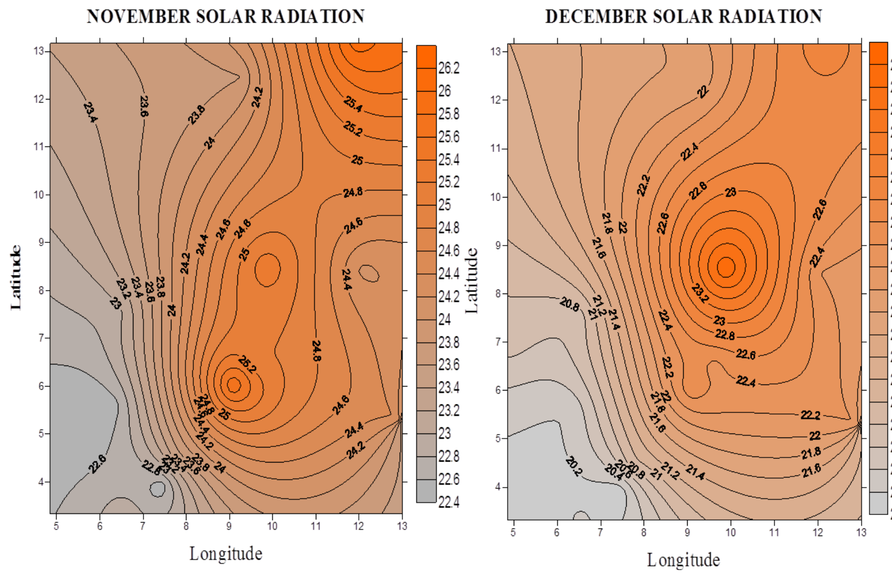


Figure 2: Monthly solar radiation contour maps for the entire Nigeria

If the weather is cloudy, the global solar radiation value would be largely affected (Lam et al., 2002). This shows that solar radiation increases with increasing latitude and it is location dependent.

Model Development

The regression analysis was performed at a confidence of 95 percent (p < 0,05) by taken solar radiation as dependent variable and mean air temperature, latitude and longitude as independent variables. The values of the F- ratio, R square, P-value and standard deviation for each of the models showed that the developed models whose parameter estimates are shown in Table 1 are highly significant for evaluating solar radiation in Nigeria.

Model Assessment

Using the mean monthly air temperature data for each month in the year 1991-1995, the models developed whose parameter estimates are shown in Table (1) were applied to evaluate the solar radiation for each of the months in a year for the entire Nigeria. The results of these, as compared with the actual measured values obtained from the surface as in the scatter gram of the predicted and measured values shown in Figure 3. The agreement between the predicted and the measured values for each of the twelve months and for Nigeria, considering the values of both the scale factors and coefficients of determination (R^2) as shown in the Figure 3 are remarkable.

Considering the scatter gram in Figure 3, the slopes are positive and range from 0.2012 – 0.617 for each month. Also, Table 2 shows the values of the coefficient of determination (R^2) obtained from the scatter gram and they range from 0.6257 – 0.9167 for each month of the year. Therefore, both the slopes and coefficients of the correlation relations are significant for each month in a year for the entire Nigeria.

The values of slopes and coefficients of determination show that the monthly developed models performed better than annual model and they are suitable for estimating solar radiation data in Nigeria.

The accuracy of the predicted values of solar radiation was further tested with the MBE, RMSE and MPE using Equations (2) - (4). The values of the accuracy tests are shown in Table (2).

Table 1: Multivariate Parameter Estimates of the Monthly Models for the Study Stations.

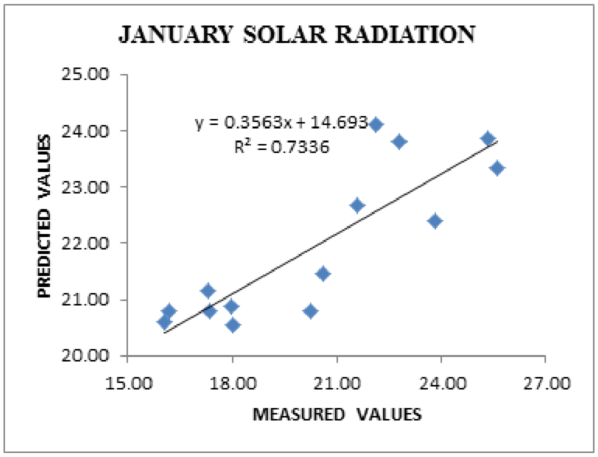
Month	Models' Parameter Estimates and their properties							
	α	β_1	β_2	β_3	F-RATIO	P-VALUE	R^2	SE
January	128.7013	-0.3591	0.1494	0.1854	13.1620	0.0008	0.7979	0.6534
February	74.3615	-0.1731	0.2403	0.1838	17.9203	0.0002	0.8432	0.5109
March	40.0269	-0.0676	0.5133	0.2033	28.7072	0.0000	0.8960	0.6229
April	-34.2680	0.1750	0.4380	0.1802	11.6951	0.0013	0.7782	1.0392
May	-101.1076	0.3915	0.3095	0.1711	10.8091	0.0018	0.7643	1.2196
June	-85.7910	0.3338	0.5183	0.1260	22.6551	0.0001	0.8717	0.9695
July	-31.1364	0.1425	0.7429	0.1422	12.8337	0.0009	0.7938	1.3332
August	-39.9024	0.1737	0.6992	0.0797	12.6440	0.0010	0.7914	1.2311
September	-45.5086	0.1998	0.6555	0.1141	18.5989	0.0002	0.8480	1.0282
October	-75.6792	0.3114	0.3299	0.1496	11.2868	0.0015	0.7720	0.9792
November	52.2319	-0.1027	0.2325	0.1577	3.0860	0.0768	0.4807	1.0072
December	106.8783	-0.2877	0.1240	0.2023	5.8549	0.0142	0.6372	0.8090
Annual	4.3844	0.0408	0.5206	0.1500	14.5074	0.0006	0.8132	0.8739

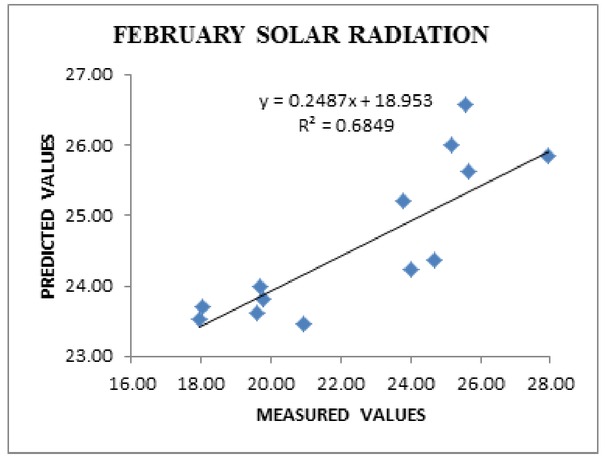
Table 2: Application of the Proposed Model for all of Nigeria using 1991-1995 Data.

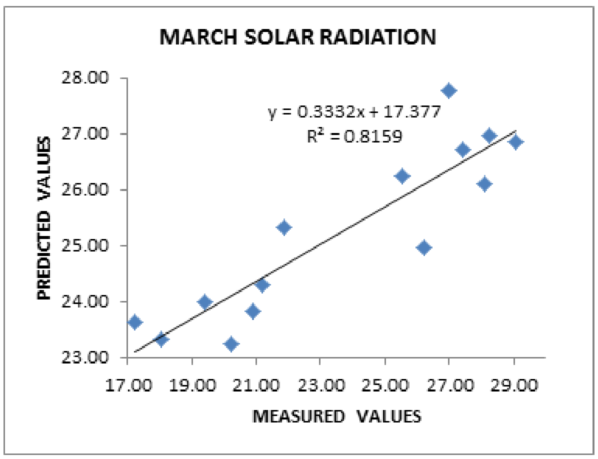
	Solar Radiation		Models' Testing Parameters				
Month	Measured	Predicted	MBE	RMSE	MPE	R^2	t-test
January	20.36	21.95	1.8554	2.8872	-11.169	0.7336	0.1065
February	22.93	24.66	2.0139	3.3805	-10.985	0.6849	0.0905
March	23.59	25.24	1.9192	3.4550	-10.784	0.8159	0.1762
April	22.13	24.98	3.3214	4.0639	-18.219	0.9205	0.0349
May	21.43	23.03	1.8690	2.3759	-10.057	0.8606	0.1573
June	20.11	21.68	1.8326	2.4732	-10.958	0.8462	0.1991
July	16.90	19.73	3.3057	3.9111	-25.060	0.9167	0.0478
August	16.16	19.46	3.8517	4.1895	-28.469	0.8724	0.0109
September	18.93	21.91	3.4732	4.0817	-22.614	0.8581	0.0280
October	20.81	23.45	3.0782	3.6648	-17.252	0.7223	0.0215
November	21.93	24.03	2.4513	3.5552	-13.497	0.6316	0.0262
December	20.57	21.67	1.2889	2.9209	-8.619	0.6257	0.2438
Annual	20.54	20.86	0.3694	3.0333	-4.575	0.4561	0.7717

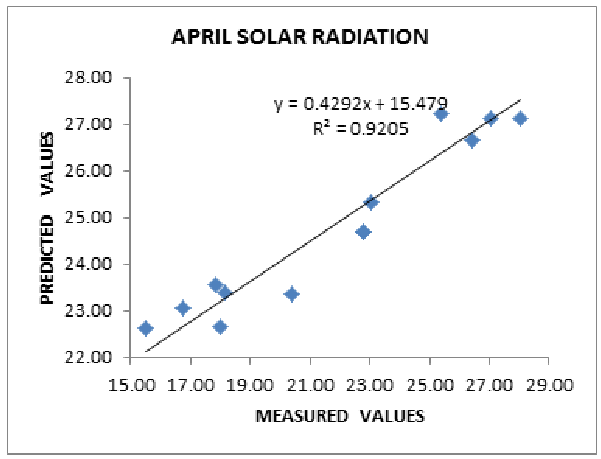
Table 3: Statistical Parameters of the Measured Data.

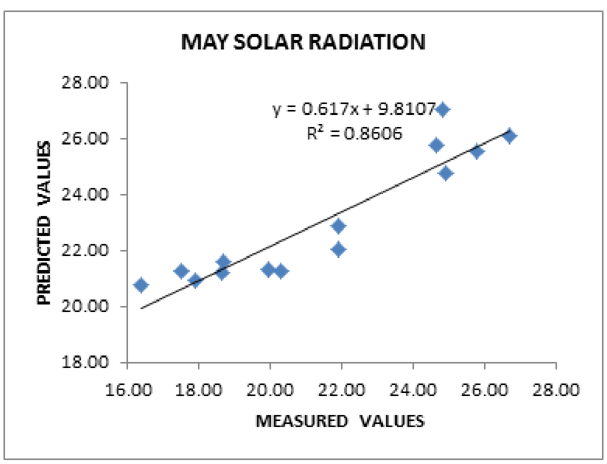
	Models' Statistical Parameters				
Month	Mean	Median	Variance	Standard Deviation	Skewness
January	22.18	22.15	0.9065	0.9521	-0.0331
February	24.89	24.96	0.7889	0.8882	-0.3504
March	25.38	25.33	1.7814	1.3347	0.1286
April	25.39	25.09	2.2976	1.5158	0.5026
May	23.57	22.93	3.0261	1.7396	0.7601
June	22.07	21.47	3.7158	1.9276	0.5872
July	19.93	19.68	4.1059	2.0263	0.2869
August	19.66	21.32	3.731	1.9316	0.2723
September	22.14	21.96	3.4308	1.8523	0.2239
October	23.87	23.73	1.8649	1.3656	0.3110
November	24.07	24.15	0.6889	0.8300	-0.1453
December	21.84	21.92	0.7253	0.8516	-0.2877
Annual	22.77	22.65	1.3901	1.9326	0.2099

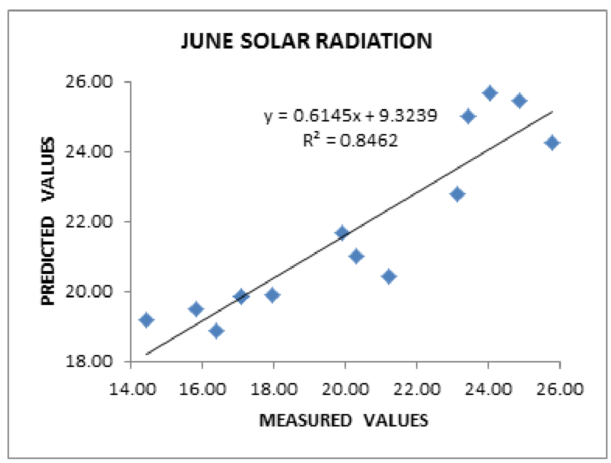

JANUARY SOLAR RADIATION
y = 0.3563x + 14.693
R² = 0.7336
PREDICTED VALUES
MEASURED VALUES
25.00
24.00
23.00
22.00
21.00
20.00
15.00
18.00
21.00
24.00
27.00


FEBRUARY SOLAR RADIATION
y = 0.2487x + 18.953
R² = 0.6849
PREDICTED VALUES
MEASURED VALUES
27.00
26.00
25.00
24.00
23.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00


MARCH SOLAR RADIATION
y = 0.3332x + 17.377
R² = 0.8159
PREDICTED VALUES
MEASURED VALUES
28.00
27.00
26.00
25.00
24.00
23.00
17.00
19.00
21.00
23.00
25.00
27.00
29.00


APRIL SOLAR RADIATION
y = 0.4292x + 15.479
R² = 0.9205
PREDICTED VALUES
MEASURED VALUES
28.00
27.00
26.00
25.00
24.00
23.00
22.00
15.00
17.00
19.00
21.00
23.00
25.00
27.00
29.00


MAY SOLAR RADIATION
y = 0.617x + 9.8107
R² = 0.8606
PREDICTED VALUES
MEASURED VALUES
28.00
26.00
24.00
22.00
20.00
18.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00


JUNE SOLAR RADIATION
y = 0.6145x + 9.3239
R² = 0.8462
PREDICTED VALUES
MEASURED VALUES
26.00
24.00
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18.00
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18.00
20.00
22.00
24.00
26.00

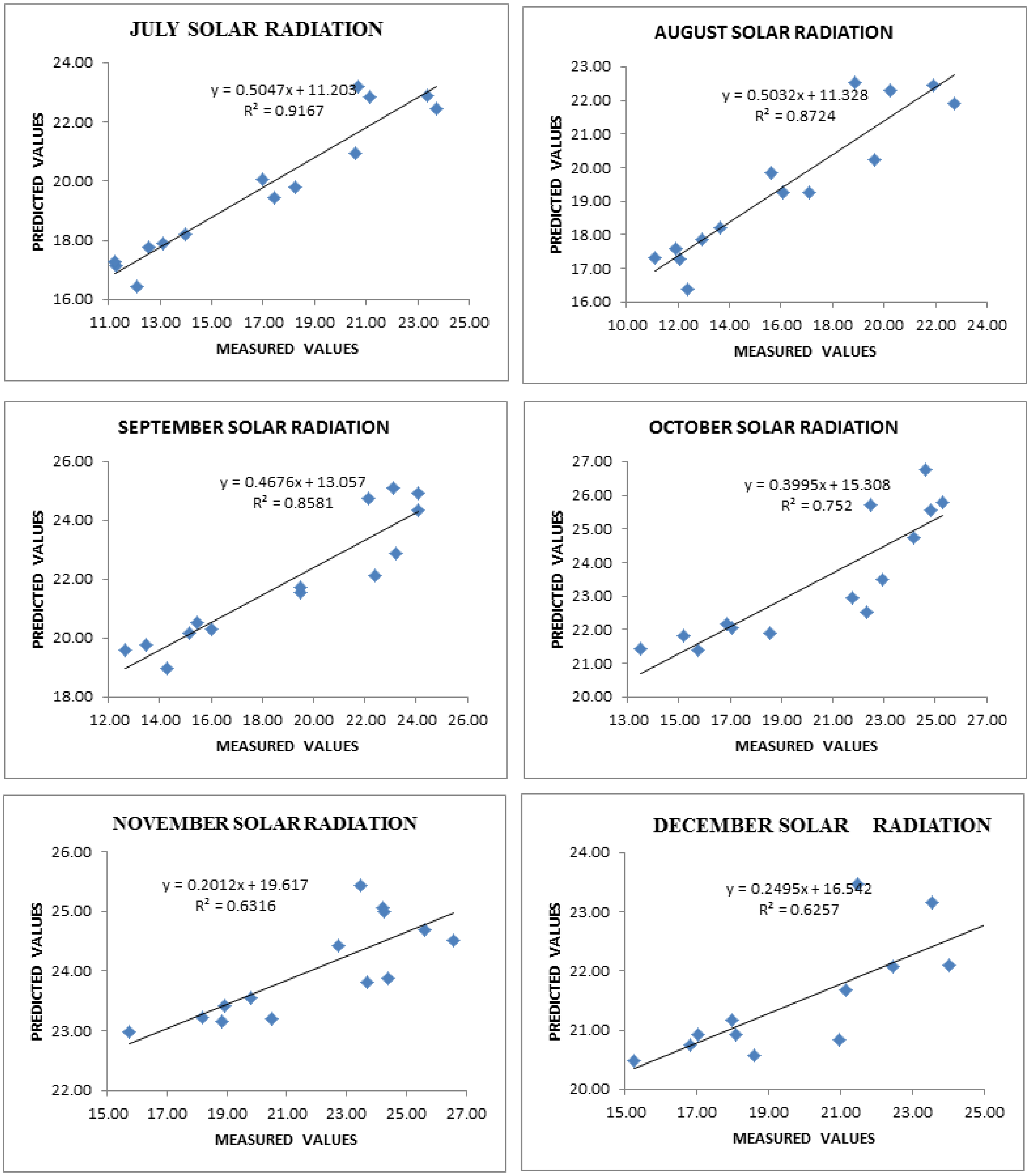

Figure 3: The Correlation between the Predicted and Measured Values of the Monthly Solar Radiation for all of Nigeria.

The MBE and RMSE values separately may not give a reliable assessment of the model's performance and this may lead to false selection of the best model. In order for the models' estimates to be significant, the t-value calculated must be smaller than the value for that confidence level given in standard statistical tables (Trabea and Shaltout, 2000).

The t-test calculated values are presented in Table 3. The critical t-test from the standard statistical table is 2.0555. The t-test shows that the critical t-test from the table is greater than the t-test values as shown in Table 2. The results of the accuracy tests further affirmed that multivariate linear modelling technique is a good modelling method for solar radiation data evaluation in Nigeria. The statistical parameters (mean, median, variance, standard deviation, and skewness) of the measured solar radiation are summarized in Table 3. The mean, median, and mode give information about the center of the distribution. The variance and standard deviation give information about the variability of the data. The coefficients of skewness and variance provide information about the symmetry and length of the tail for certain types of distributions, respectively (Krige, 1951). The distributions for most of the months are almost symmetric, except for January, February, November and December, which are negatively skewed.

CONCLUSION

This paper presented an application of the multivariate regression technique to evaluate the solar radiation data in Nigeria using air temperature and geographical coordinates. It is concluded that multivariate regression technique of this type is very useful to study the spatial variation of the solar radiation in Nigeria and also to evaluate its data. The contour method allows drawing solar radiation maps. The difference between the measured and estimated values using this technique is minimal. The mean deviation between the measured and estimated values varied from a maximum of 3.3 in August to a minimum of 1.1 in December.

Analyses have shown that strong correlation exists between solar radiation and air temperature together with latitude and longitude of the selected stations. Multiple regression models were developed for each of the twelve months and annual model for all of Nigeria. The values of coefficient of determination (R^2), Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE) and t-statistics (t-test) were calculated to estimate efficiency of the developed models. The coefficients of determination ($p < 0.05$) varied in the range of 0.6257 – 0.9167 for monthly models and 0.4561 for annual model, showing that multiple regression analysis is an accurate method for the modelling of solar radiation for Nigeria. These also show that the monthly developed models performed better than annual models at the selected stations in Nigeria.

Finally, the solar radiation intensity produced by the developed model can be utilized in design, analysis, calibration, and performance estimation of solar energy conversion system, which is gaining significant attention in Nigeria today.

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