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Regional Estimation of Solar Radiation using Routinal Meteorological Variables

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Abstract
In this paper, the monthly surface data of solar radiation, minimum and maximum temperatures, wind speed and evaporation of 1970-1995 for four climatic regions in Nigeria were obtained from the archives of Nigerian Meteorological Agency (NIMET), Oshodi, Lagos. The distributions of solar radiation with each of the four meteorological variables were observed. It was found that solar radiation was well monitored by each of the variables indicating that the linear combination of the variables can be used to develop model from where solar radiation data can be evaluated. Consequently, the multivariate linear regression model was developed using 1970-1990 data of the five meteorological parameters for each of the four regions taking solar radiation as dependent variables and the four other meteorological variables as independent variables. The models were validated using 1991-1995 data of minimum and maximum temperatures, wind speed and evaporation to obtain the predicted solar radiation. Analyses have shown that over seventy percent correlations exist between the measured and estimated values of solar radiation. The efficiency of the developed models was further verified by calculating the values of R^2, MBE, RMSE and t-test at confidence level of $p < 0.05$. The results obtained showed that the models were statistically significant and could be used to estimate solar radiation at the regions in Nigeria.
Keywords: Distribution, Meteorological, Multivariate, Radiation and Statistically.

1. Introduction

Solar radiation is the energy transferred from the sun in the form of radiant energy to the earth's surface. It is a crucial component of the global energy balance which drives different systems, such as the climate and hydrologic systems. Solar radiation passing through the atmosphere to the ground surface is known to be depleted through scattering, reflection and absorption by the atmospheric constituents like air molecules, aerosols, water vap our, ozone and the clouds (Augustine and Nnabuchi, 2009). The reflection of solar radiation is mainly by clouds and this plays an overriding part in reducing the energy density of solar radiation reaching the surface of the earth (Exell, 2000). The radiation arriving on the ground directly in line with the solar disks is called direct or beam radiation. A portion of the scattered and reflected radiation goes back to space and a portion reaches the ground from the sky hemisphere as diffuse radiation. Practically, solar radiation data are easily obtained using the relevant equipment. Pyrheliometer and pyranometer can be readily used to obtain the direct and diffuse component of the radiation and the diffused solar radiation respectively. Weather stations have been used mostly for this purpose.

In an effort to generate solar 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 from various locations of the world. These meteorological variables are easy to measure and have been readily employed for the estimation of solar radiation by means of simple and multiple regression analyses. The development of the solar radiation database for various Nigeria locations has been an on-going task for researchers in the field of atmospheric science for many years now. With the few meteorological stations, the option of using estimation models has been widely adopted in Nigeria for predicting solar radiation at specific location and at a regional scale. This in effect helps one to have a fair knowledge of the insolation power potential over the location. In developing countries such as Ghana, India, Nigeria etc, the facility for global radiation measurement is available at a few places. Some cannot even afford to pro cure the equipment and the techniques involved are highly sophisticated. For such countries it is essential that empirical models be developed so as to predict global solar radiation from readily measured data.

Several models have been proposed to estimate global solar radiation. Page (1964) presents a linear regression model used in correlating the global solar radiation data with relative sunshine duration, which is a modified Angstrom type model Angstrom (1924). 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 Trabea and Shaltout (2000) studied the correlation between the measurements of global solar radiation and the meteorological parameters using solar radiation, mean daily maximum temperature, mean daily relative humidity, mean daily sea level pressure, mean daily vapour pressure, and hours of bright sunshine data obtained from different parts of Egypt; while Sfetsos and Coono ck (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.

In this study, a solar resource parameters (minimum and maximum temperatures, wind speed and evaporation) have been used to develop a four-parameter multivariate linear model for estimating the solar radiation on horizontal surfaces at different climatic regions in Nigeria using monthly mean minimum and maximum temperatures, wind speed and evaporation for Sahel, Guinea Savannah, Derived Savannah and Rainforest Regions.

2. Materials and Methods

The monthly mean solar radiation, minimum and maximum temperatures, wind speed and evaporation data were obtained from the Archives of Nigerian Meteorological Agency, Oshodi, Lagos. The data obtained covered a period of twenty-six years (1970-1995) for four regions which include: Sahel, Guinea Savannah, Derived Savanna and Rain Forest regions according to their respective weather condition as shown in Figure 1.

2.1 Model Development

Stochastic analysis was employed on the monthly surface data of solar radiation, minimum and maximum temperatures, wind speed and evaporation to deduce a set of multivariate linear regression models at confidence level of 0.05 and a model of the form of a four parameter multivariate linear model as shown in equation (1) was developed for each of the four regions using a twenty-one-year period (1970-1990) monthly mean data of above meteorological variables.

$$H = \alpha + \beta_1 Tmin + \beta_2 Tmax + \beta_3 Ws + \beta_4 Ep + \varepsilon \quad (1)$$

where α is the regression constant, ε is the error term, $\beta 1$, $\beta 2$, $\beta 3$, and $\beta 4$ are parameter estimates of minimum temperature (*Tmin*), maximum temperature (*Tmax*), evaporation (*Ep*) and wind speed (*Ws*) respectively for each of the regions.

2.2 Multivariate Linear Regression Analysis Theory

Multivariate Regression Analysis is a technique for modeling and analyzing several variables when the focus is on the relationship between a dependent variable and one or more independent variables. For instance, let $z1$, $z2$ zr be a set of r predictors believed to be related to a response variable Y. The multivariate linear regression model for the jth sample unit has the form:

$$Y = \alpha + \beta_1 z_{j1} + \beta_2 z_{j2} + \ldots + \beta_r z_{jr} + \varepsilon_j \quad (2)$$

where εj is a random error, the βi where i = 1, 2, r are unknown (and fixed) regression coefficients and α is the intercept. With n independent observations, we can write one model for each sample unit or we can organize everything into vectors and matrices so that the model is now

$$Y = Z\beta + \varepsilon \quad (3)$$

where

$$Y = \begin{pmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_n \end{pmatrix} Z = \begin{pmatrix} z_{j1} \\ z_{j2} \\ . \\ . \\ . \\ z_{jn} \end{pmatrix} = \begin{pmatrix} z_{11} & . & . & . & z_{j1} \\ z_{21} & . & . & . & z_{j2} \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ z_{n1} & . & . & . & z_{nr} \end{pmatrix} \beta = \begin{pmatrix} \beta_1 \\ \beta_2 \\ . \\ . \\ . \\ \beta_n \end{pmatrix} \varepsilon = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ . \\ . \\ . \\ \varepsilon_n \end{pmatrix} \quad (4)$$

Ordinary Least Squares (OLS) estimates are commonly used to analyze both experimental and observational data. The OLS method minimizes the sum of squared residual, and leads to a closed-form expression for the estimated value of the unknown parameter β:

$$\hat{\beta} = (Z'Z)^{-1} Z'Y = \left(\frac{1}{n} \sum z_j z' \right)^{-1} \left(\frac{1}{n} \sum z_j y_j \right) \quad (5)$$

where $\hat{\beta}$ to denote the least squares estimate of β and sign ′ denotes the transpose.

3. Results and Discussions

3.1 Distribution of Solar Radiation with Meteorological Variables

Figure 2 shows the distribution of solar radiation with meteorological variables, which are the air temperature, wind speed and evaporation for the four climatic regions in Nigeria.

In the Sahelian station, (see Figure 2 (a) and (b)) it was observed that air temperature and evaporation were increasing with solar radiation between January and April and also between September and October. A downward trend was discernible between JulyAugust. The increasing trends between January and April may be due to the fact that during these months, dry season condition is predominant in that region. The decreasing trend in July-September may be due to the presence of disturbances like cumulous cloud and cloud cluster which are significant enough to cause variation in weather (Adeyemi, 2004a). During this period, all regions in Nigeria will be experiencing intense rainfall because the Inter-tropical Discontinuity

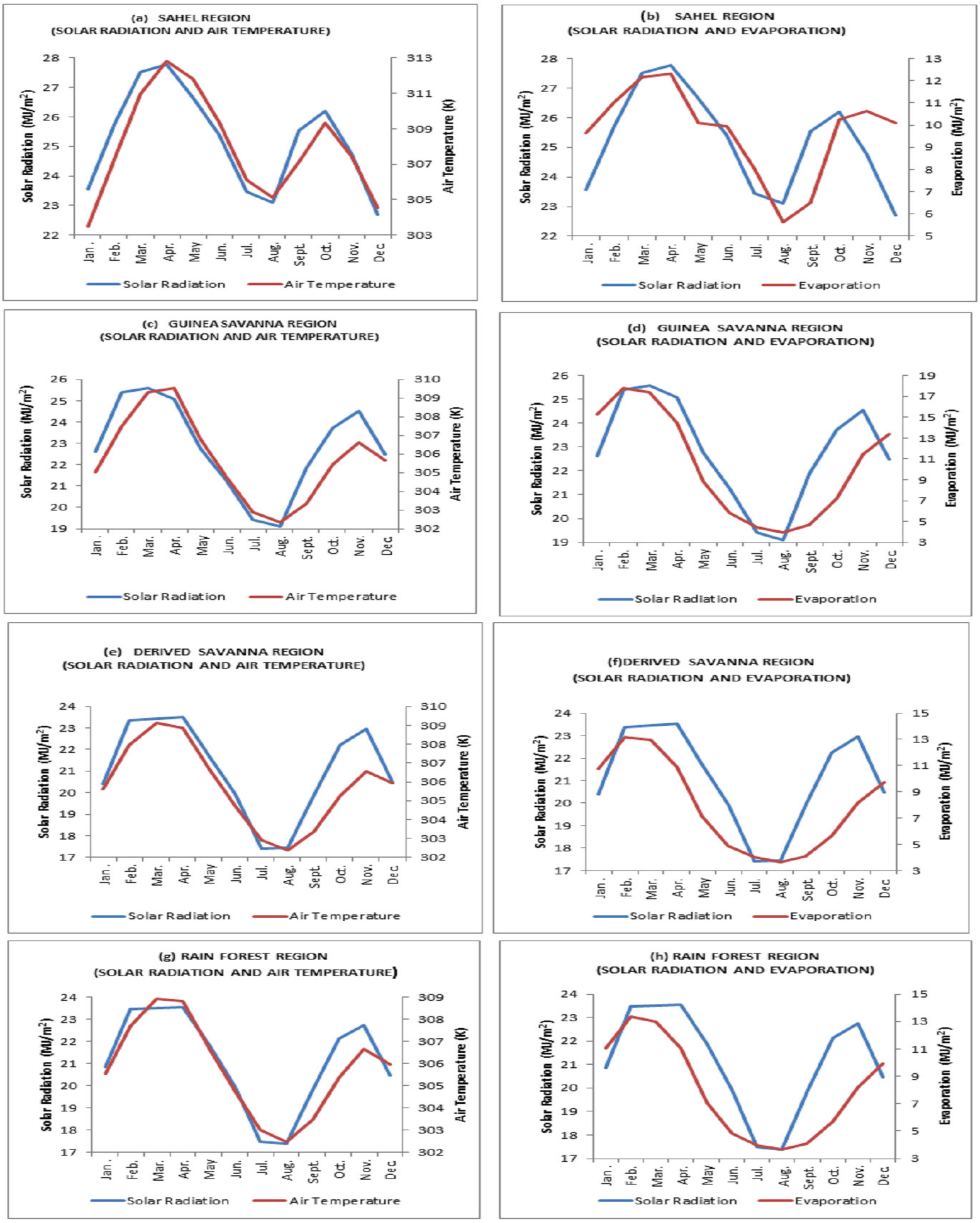

Figure 2: Distributions of Solar Radiation with Air temp erature and Evap oration for four climatic regions in Nigeria

(ITD) would have reached its maximum northern position. Solar radiation and evaporation show the same increasing and downward trends (see Figure 2(b)). The increasing trends are discernible between January-April and September-November, the dry season's period and downward trends between June and August, the rainy season period. This is in agreement with Graham et al. (2004) argument that the physics of evaporation shows that the evaporative demand of the atmosphere is directly dependent on the net radiation which in turn is dependent on solar radiation.

In the Guinea savanna regin (see Figure 2 (c) and (d)), there are increasing trends in variations of solar radiation with air temperature and evaporation between January-April and September-November, the dry season period. This may due to the topography of the zone that is characterized by short grasses and scattered drought-resistant tree which aids incessant surface heating that caused water vapour to be transported to the higher layers of the atmosphere through buoyancy (Adeyemi, 2004b) and (Aro, 1975) . Also, solar radiation shows downward trends with the two meteorological variables between July and August, the rainy season period in the zone. This is as a result of the localized convection due to the usual long period of humid condition in the zone.

In the Derived savannah region, the dry and the wet season's occurrence are greatly influenced by its latitudinal location and solar radiation has considerable seasonal variations." There are downward trends between April and August in the distribution of solar radiation with temperatures and evaporation (see Figure 2 (e) and (f)), that is, during the rainy season period. This may due to the fact that those months were the core rainy months which were characterized with incessant cloud formation and thereby causing depletion in the amount of solar radiation reaching the earth's surface, air temperature and evaporation rate line (Ogolo and Adeyemi, 2009). The increasing trends are observed between September and November, January and February due to the facts that these months are characterized with low humidity and high rate of evaporation aided by the increase in solar radiation and in air temperature in the zone.

In the Rain forest region (see Figure 2 (g) and (h)); solar radiation has two peak values in February and November. This is expected because of a very high sunshine hour which is obtainable in these months due to high clearness index. Least solar radiation is observed in the month of July and August respectively. This is expected because a heavy rainfall characterizes the months in the station. Therefore, the total solar radiation recorded is quite low because of the wet atmosphere and the presence of heavy clouds. If the weather is cloudy, the global solar radiation value would be largely affected.

3.2 Models Development

The multivariate regression analysis was performed at a confidence level of ($p < 0.05$)by taken solar radiation as dependent variable and other four meteorological variables as independent variables. The values p-value for each of the models is zero (*i.e.* $p = 0.0000$) showing that the developed models are highly significant for evaluating solar radiation data in all the investigated region. Four different models were developed: one per region as shown in equations 5–8.

Sahel Model, $R^2 = 0.7386$, p = 0.0000

$$H = -144.223 - 0.142Tmin + 0.689Tmax - 0.089Ws - 0.1368Ep \quad (5)$$

Guinea Model, $R^2 = 0.7052$, p = 0.0000

$$H = -239.905 - 0.402Tmin + 1.249Tmax + 0.056Ws - 0.166Ep \quad (6)$$

Derived savanna Model, $R^2 = 0.7080$, p = 0.0000

$$H = -222.724 - 0.441Tmin + 1.221Tmax + 0.239Ws - 0.087Ep \quad (7)$$

Rainforest Model, $R^2 = 0.7446$, p = 0.0000

$$H = -227.795 - 0.488Tmin + 1.281Tmax + 0.293Ws - 0.100Ep \quad (8)$$

3.3 Model Efficiency

A five-year period (1991-1995) monthly mean data set of minimum and maximum temperatures, wind speed and evaporation was then used to validate the developed models to obtained the predicted value of solar radiation.The accuracy of the predicted values was further tested with the mean bias error (MBE) and root mean square error (RMSE). 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). The 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. On the other hand, the 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 values of the accuracy tests are shown in Table 1.

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-test calculated values must be smaller than the value for that confidence level given in standard statistical tables (Stone, 1993). The t-test calculated values are presented in Tables 1. The critical t-test from the standard statistical table is 1.9847. The t-test shows that the critical t-test from the table is greater than the t-test values as shown in tables above for each of the four regions and hence null hypothesis is rejected. The results of the accuracy tests further affirmed that multivariate linear modelling technique is the best modelling method for solar radiation data evaluation.

The agreement between the predicted and the measured values for each of the four climatic regions considering the values of both the scale factors and coefficients of determination (R^2) as shown in the Figure 2 are remarkable. Considering the scatter gram in Figure 3, the slopes are positive and range from 0.652 - 0.8022.

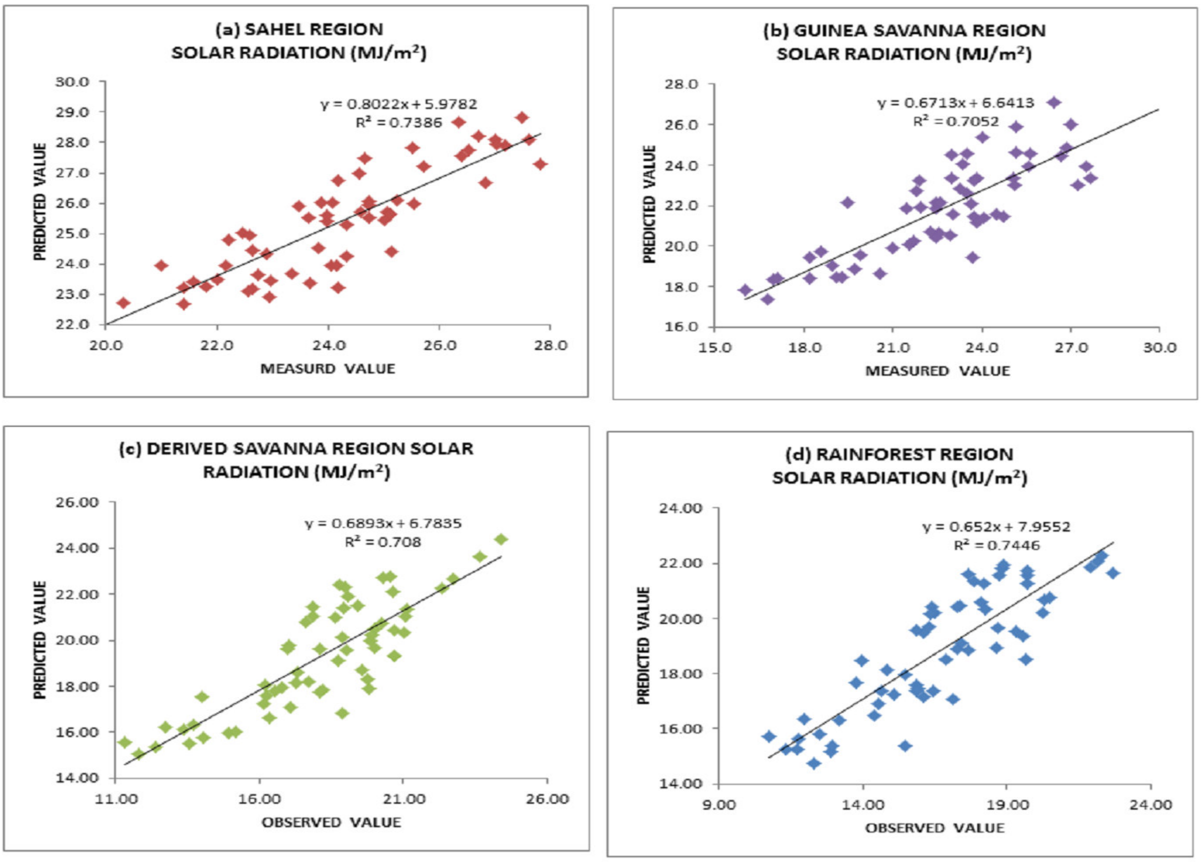

Figure 3: The correlation b etween the predicted and measured values of the monthly solar radiation for the four climatic regions in Nigeria

Also, Tables 1 shows the values of the co efficient of determination (R^2) obtained from the scatter gram and they range from 0.7052 - 0.7446. Therefore, both the slopes and coefficients of the correlation relations are significant for each of the four climatic regions. These values show that using multivariate linear modelling technique, solar radiation data is could be modelled at
regional level.

Table 1: Application of the multivariate proposed model for regional stations using 1991-1995 data.

	Solar Radiation		Models' Testing Parameters			
Stations	Observed	Predicted	R^2	MBE	RMSE	t-test
Sahel	24.16	25.36	0.7386	1.1979	1.5350	-3.6206
Guinea	22.74	21.91	0.7052	-0.8096	1.8159	1.6492
Derived	18.08	19.25	0.7080	1.1660	1.9374	-2.3032
Rainforest	16.73	18.86	0.7446	1.9374	2.1349	-4.3772

The graph of variation was plotted for the measured solar radiation for each of the four climatic regions along with their predicted values (see Figure 4).

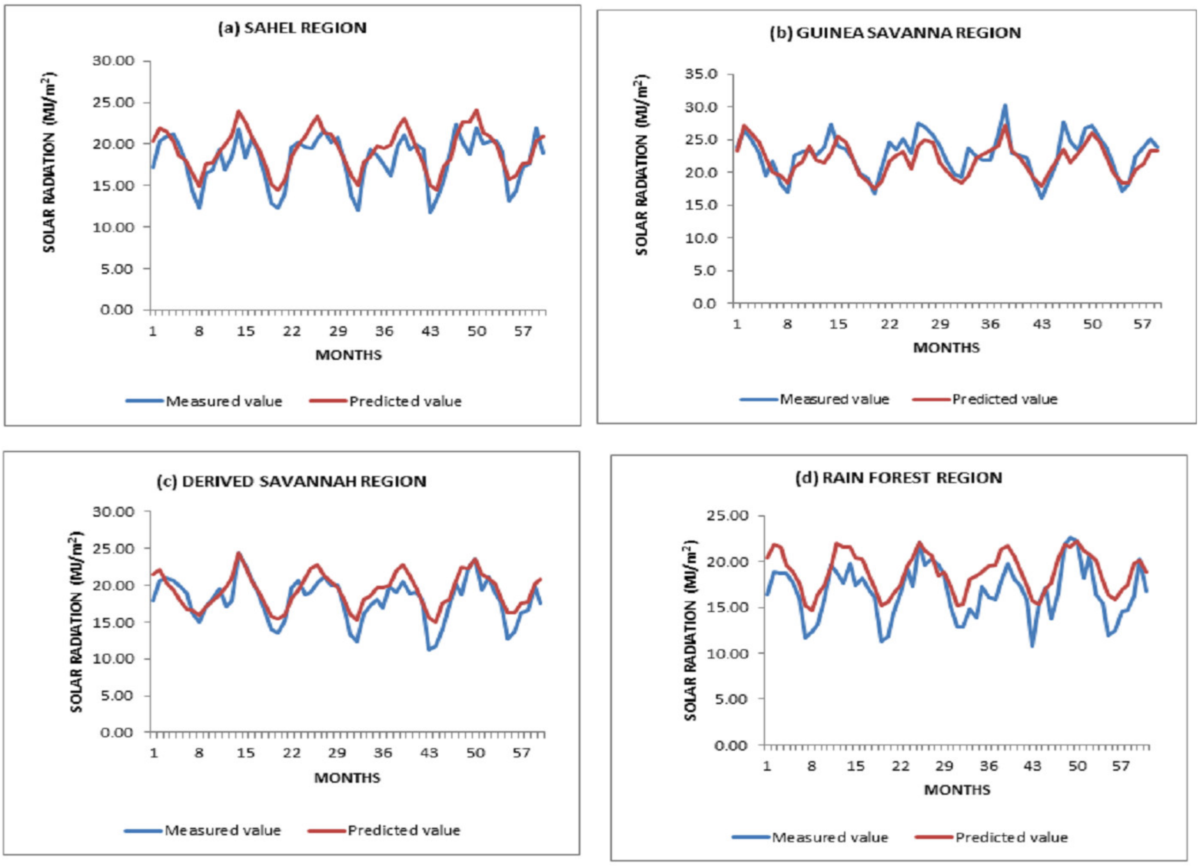

Figure 4: Variations of measured value and predicted value of solar radiation for each of four climatic regions in Nigeria.

It can be observed that solar radiation was well monitored at all the regions by the models. However, some deviations featured which may due to the fact that correlation based measures are limited. This is because the deviations standardize for differences between the measured and predicted means and variances making them to be insensitive to additive and proportional differences between the model simulation and observation according to Willmott (1984) and David (1999). Also, the deviations may due to the fact that they are more sensitive to outliers than to observations near the mean agreeing with Moore (1991) leading to a bias toward extreme events.

4. Conclusion

The monthly model of the solar radiation in the four climatic regions in Nigeria has been developed using the multivariate linear regression technique. Linear combination of solar radiation with air temperature, wind speed and evaporation were used to developed the equations from where solar radiation values for the Sahel, Guinea savannah, Derived savannah and Rainforest regions in Nigeria can be estimated. Analyzes have shown that the predicts values are highly significant and they are strongly correlated with the measured values. The efficiency of the developed models were also verified using standardized statistical tools. The results obtained showed that the models gave good estimation of solar radiation values in the regions and they could be also be used in the stations within their jurisdiction.

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