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Time-space distribution analysis of Direct Solar Radiation in Nigeria

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ABSTRACT

Background: The paper utilizes data obtained from geostationary satellite platform to describe the seasonal and spatial distribution of direct solar radiation over Nigeria.

Objectives: The study aim to examine the geographical nature of direct solar radiation over Nigeria.

Methods: All data was collected from the NASA Goddard Earth Observing System – Version 1 (GEOS-1) Multiyear Assimilation Time series Data on the NOAA 17 satellite.

Results: Results show that direct solar radiation (DSR) increases in value from the Atlantic coast northwards, and is generally lower during the rainy season than the dry season. The northward increase was found to be almost parallel with lines of latitude although the contour lines are slightly skewed to a West-North-West to East-South-East orientation. Bivariate regression models show a direct relationship between direct solar radiation and latitude; clearness index; and average elevation above sea level, whereas an inverse relationship is shown with daily cloud amount; average daily solar angle; and average daily relative humidity.

Conclusions: Spatial distribution of daily direct solar radiation is closely related to latitude. This understanding is useful for solar energy policy development in Nigeria.

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KEY WORDS

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spatial;
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1. INTRODUCTION

There is a considerable demand for accurate data on the downward flux of solar radiation at the earth's surface (Ayoade, 1980; Miller, 1981; Trewartha, 1954) over the entire globe, not only for the purposes of investigating physical processes within the climate system and measuring climate fluctuations, but also for the estimation of spatial variations and more practical uses such as solar energy for electricity production (Onafeso, 2006). Several studies have been carried out on the character of solar radiation over whole countries (Islam et al., 2016; Osinowo et al., 2015; Power, 2003; Sarkar, 2016). The increasing demand for solar energy products especially in most developing regions and in the Sub-Saharan Africa, continues to make solar applications and research into how they are implemented more and more popular. In Nigeria for instance, where electricity generation is almost entirely reliant on hydro, studies on solar energy has been growing.

Satellite data, are recently proving increasingly useful in mapping solar radiation at a regional scale (Gautier et al., 1980; Raschke et al., 1987; Tarpley, 1979). Very little work has been undertaken in tropical environments where the lack of westerly circulation and greater solar heating encourages a more localized cloud regime (Nunez et al., 1984). Furthermore, the evaluation of solar energy potential for wide areas in the low latitudes has been difficult due to the little knowledge of the spatial variability of solar beam irradiance (Broesamle et al., 2001; Gautier, 1982). Rubio et al. (2002) concluded that with an increasing

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number of solar applications all over the world, the need for solar radiation data has become more important. It was observed that using remote sensing data, radiation measurements with high temporal covertures and spatial resolution can be obtained. The use of remote sensing to obtain meteorological data has also improved knowledge significantly, this is because many African countries lack the capacity and resources to procure up to date equipment required for adequate weather forecasting and other climatological enterprise. Therefore, in recent times, climate scientists in Africa have been increasingly relying on the advanced data acquisition platforms provided mostly by western countries. Aside from the challenge of data availability, the very sparse and distant networks of the few available weather stations does not provide for adequate spatial and temporal distribution of most weather and climatic parameters, especially the rare ones like direct solar radiation (DSR).

Solar radiation estimates have been derived for Nigeria from sunshine duration estimates and radiation measurement (Ayoade, 1980; Davies, 1966; Oguntoyinbo, 1974, 1976; Ojo, 1976). The aim of this paper is to provide an accurate geographical appraisal of the spatial distribution of Direct Solar Radiation (DSR) in Nigeria, utilizing satellite technology for data collection. Beyond this intent, it is important to underscore the value of this research in adding to the capacity to acquire solar radiation data across the country.

2. METHODS

2.1 Research design

This section provide a concise and precise description of the methodology employed to arrive at the results, their interpretation as well as the conclusions drawn from this study.

2.2 Setting

The key elements of the study design is the secondary data assimilation from archival sources over static locations across the country.

2.3 Variables

This study assesses the spatial and seasonal distribution of Direct Solar Radiation with respect to latitude as well as clearness index, solar angle relative to the horizon, daylight cloud amount, and relative humidity.

2.4 Data sources

The dataset employed for the study were obtained from the archives of the National Aeronautical and Space Agency of the United States of America (NASA) Langley Research Centre. The data was generated using the NASA Goddard Earth Observing System – Version 1 (GEOS-1) Multiyear Assimilation Time series Data. The solar energy data was generated using the Pinker/Laszlo shortwave algorithm while cloud data was taken from the International Satellite Cloud Climatology Project DX dataset (ISCCP). The data used for analysis consists of continuous and consistent 10 year coverage, from July 1, 1983 to June 30, 1993 with the 10-year average derived for the monthly and annual assessments.

2.5 Sample design

Thirty-seven stations were selected for study, particularly taking the State capital as representative of the entire country. The sample points were selected based on their administrative capacity as headquarter settlements representative of their immediate region.

2.6 Data analysis methods

(a) The Pearson correlation analysis was employed to determine the relevance of the indices and the similar variables were separated through collinearity while the influences were determined from the *r* statistics at 0.05 α-level of significance. All the variables involved in this analysis were pulled together in the correlation analysis of the form:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$$

(b) The spatial-seasonal autocorrelation trends were obtained from the generalized least square fit for multi-model mean regressed over three monthly time windows of December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON) to distinguish seasonal differences in DSA with the more negative values indicating greater autocorrelation based on the geographical distances.

(c) Linkage analysis was however computed from the near similarities in DSA from these different location, where the correlation between DSA of locations are used to group them into geographical points of similar values. The centroid values and the major coefficient links derived from the cross-correlation values were employed to analyze the linkages of points for grouping. Linear regression analysis was used to evaluate the extent of influence of confounding variables (e.g. latitude, clearness index, average elevation, cloud cover, solar angle and relative humidity) on DSA and formulate models in the form:

$$y = b0 \pm b1x1 \ldots \pm e$$

(d) The interpolation of the distribution was generated using ArcView 3.2a (GIS software) and the entire country was classified into regions of high and low occurrence using an elementary linkage analysis.

(e) Missing data were addressed on a case-wise basis to ensure that the mean values of the series represented the missing values.

3. RESULTS

3.1 Similarity in monthly occurrence and distribution

The monthly mean of daily Direct Solar Radiation for the selected stations is presented in Table 1. The range statistics for the frequency distributions of the (10-year Average) monthly mean values shows that the highest measure of dispersion of 4.81 kWh/m^2/day occur in June, followed by 4.46 kWh/m^2/day in October, 4.29 kWh/m^2/day in July, 4.23 kWh/m^2/day in May, 4.20 kWh/m^2/day in September, 4.03 kWh/m^2/day in April, 3.93 kWh/m^2/day in March, 3.84 kWh/m^2/day in August, 3.27 kWh/m^2/day in November, 3.08 kWh/m^2/day in February, 2.18 kWh/m^2/day in December and 1.74 kWh/m^2/day in January. The standard deviation statistic shows that the highest deviation of 1.274 kWh/m^2/day occur in June, followed by 1.226 kWh/m^2/day in October, 1.1674 kWh/m^2/day in September, 1.167 kWh/m^2/day in May, 1.166 kWh/m^2/day in July, 1.085 kWh/m^2/day in March, 1.081 kWh/m^2/day in April, 1.065 kWh/m^2/day in August, 0.964 kWh/m^2/day in November, 0.876 kWh/m^2/day in February, 0.556 kWh/m^2/day in December, and the lowest of 0.475 kWh/m^2/day in January.

The highest variance of 1.623 kWh/m^2/day is observed for June, followed by 1.504 kWh/m^2/day in October, 1.363 kWh/m^2/day in September, 1.362 kWh/m^2/day in May, 1.36 kWh/m^2/day in July, 1.176 kWh/m^2/day in March, 1.168 kWh/m^2/day in April, 1.134 kWh/m^2/day in August, 0.929 kWh/m^2/day in November, 0.767 kWh/m^2/day in February, 0.309 kWh/m^2/day in December, and 0.225 kWh/m^2/day in December, being the lowest variance. The month of November with a distribution skewness of -0.631, is observed to be the most negatively skewed, followed by a distribution skewness of -0.38 in January, -0.225 in February, -0.122 in October, -0.092 in December, and -0.015 in March. However, the least positive skewness of 0.256 was noted in the month of April, with a skewness of 0.336, 0.399, 0.549, 0.628 in

September, July, August, and May respectively. The most positive skewness of 0.643 in noted for the month of June. A standard error of 0.388 was observed for all the months alike.

Table 1 Monthly averaged DSR (kWh/m^2/day)

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Port-Harcourt	5.3	4.5	3.5	3.1	2.8	2.3	1.5	1.7	1.6	2.1	3.4	4.7
Yenogoa	5.3	4.5	3.5	3.1	2.8	2.3	1.5	1.7	1.6	2.1	3.4	4.7
Calabar	5.5	5.1	3.7	3.3	2.9	2.4	1.6	1.4	1.6	2.0	3.4	4.9
Uyo	5.8	5.3	4.3	4.0	3.5	3.3	2.4	2.2	2.4	3.1	4.4	5.4
Owerri	5.5	5.0	4.2	3.9	3.4	3.0	1.9	1.9	2.1	3.0	4.2	5.1
Umuahia	5.8	5.3	4.3	4.0	3.5	3.3	2.4	2.2	2.4	3.1	4.4	5.4
Awka	6.1	5.6	4.7	4.3	3.7	3.5	2.8	2.4	2.7	3.5	4.8	5.7
Asaba	5.9	5.5	4.4	4.2	3.7	3.4	2.6	2.2	2.6	3.5	4.8	5.4
Abakaliki	6.2	5.8	4.8	4.4	3.9	3.6	3.0	2.6	2.9	3.8	5.0	5.9
Benin-City	5.7	5.3	4.5	4.1	3.6	3.1	2.1	1.9	2.3	3.5	4.7	5.3
Enugu	6.2	5.7	4.7	4.3	3.7	3.5	2.8	2.4	2.7	3.5	4.8	5.7
Ikeja	5.5	5.4	4.6	4.3	3.7	3.0	2.5	2.3	2.5	3.5	4.4	5.2
Abeokuta	6.1	5.9	5.0	4.5	4.2	3.7	2.7	2.2	2.7	3.8	4.9	5.8
Akure	6.2	6.0	5.0	4.5	3.9	3.6	2.6	2.2	2.6	3.7	5.1	5.8
Ibadan	6.1	5.9	5.0	4.5	4.2	3.7	2.7	2.2	2.7	3.8	4.9	5.8
Ado-Ekiti	6.2	6.0	5.0	4.5	3.9	3.6	2.6	2.2	2.6	3.7	5.1	5.9
Markurdi	7.1	6.9	5.7	4.9	4.4	4.1	3.5	3.4	3.6	4.6	6.3	6.9
Lokoja	6.6	6.1	5.0	4.6	4.0	3.7	3.0	2.6	2.9	3.9	5.3	6.1
Oshogbo	6.1	6.0	5.0	4.5	4.0	3.5	2.5	2.1	2.7	3.7	5.0	5.8
Ilorin	6.5	6.3	5.6	4.9	4.4	3.9	2.9	2.5	3.1	4.1	5.6	6.3
Lafia	6.8	6.6	5.7	5.0	4.2	3.8	3.2	2.9	3.4	4.4	6.2	6.5
Jalingo	6.9	6.7	5.9	5.4	4.8	4.4	3.6	3.3	3.6	4.8	6.3	6.6
Abuja	6.7	6.6	5.8	5.4	4.6	4.0	3.2	2.8	3.6	4.8	6.3	6.4
Yola	6.3	6.6	6.1	5.5	5.0	4.9	4.0	3.8	4.2	5.3	6.2	6.1
Minna	6.6	6.6	5.9	5.5	4.8	4.2	3.5	3.0	3.8	5.1	6.2	6.5
Jos	7.0	6.9	5.9	5.2	4.5	4.1	3.3	2.8	3.4	4.7	6.6	6.8
Gombe	6.5	6.8	6.2	5.7	5.5	5.3	4.6	4.2	4.7	5.6	6.0	6.2
Bauchi	6.6	6.7	6.1	5.5	5.1	5.1	4.3	3.9	4.6	5.5	6.2	6.4
Kaduna	6.7	6.8	6.2	5.7	5.3	4.6	3.8	3.3	4.2	5.4	6.6	6.6
Dutse	6.7	7.4	6.7	6.5	6.1	5.9	4.9	4.5	4.9	5.7	6.0	5.6
Damaturu	6.9	7.6	6.9	6.5	5.9	5.9	5.0	4.5	5.1	5.9	6.3	5.9
Maiduguri	6.8	7.4	7.0	6.3	5.7	5.7	4.6	4.3	5.0	5.9	6.3	6.1
Kano	6.5	7.5	7.0	6.8	6.6	6.4	5.3	4.7	5.1	6.1	6.3	5.5
Gusau	6.3	7.3	7.0	6.7	6.7	6.4	5.1	4.6	5.0	5.9	6.2	5.5
Birmin-Kebbi	6.3	7.3	7.0	6.6	6.7	6.4	5.0	4.6	5.3	6.0	6.2	5.5
Katsina	6.3	7.2	6.8	6.6	6.4	6.2	5.0	4.6	4.9	5.8	6.1	5.5
Sokoto	6.6	7.6	7.4	7.2	7.1	7.1	5.8	5.2	5.8	6.5	6.6	6.0

Source: NASA Goddard Earth Observing System – Version 1 (GEOS-1)

The distribution of DSR for each month of the year show a characteristic pattern peculiar to what is expected in the low latitudes (Bosmans et al., 2015). January with 6.324 kWh/m^2/day has the highest mean occurrence, this is due to the ellipticity of the earth's orbit around the sun which results in the earth's being closer to the sun in January with a distance of 91,300,000 miles, than in July when the distance is 94,500,000 miles (Levin et al., 2017). Since the earth revolves round the sun in an orbit that is not particularly perfectly circular, the possibilities of wobbling therefore goes beyond mere hypothesis thus determining the seasonality of intensities in DSR as a result of alterations in solar flare and proximity to the sun from time to time.

The January mean occurrence is followed by 6.315 kWh/m^2/day in February, 5.855 kWh/m^2/day in December, 5.507 kWh/m^2/day in March, 5.458 kWh/m^2/day in November, and 5.079 kWh/m^2/day in April. This seasonality goes to show that DSR varies significantly from month to month, year in and year out.

The lower mean occurrences of 4.614 kWh/m^2/day in May, 4.408 kWh/m^2/day in October, 4.281 kWh/m^2/day in June, 3.472 kWh/m^2/day in September, 3.392 kWh/m^2/day in July, and the lowest of 3.053 kWh/m^2/day in August, only attest to the fact that the sun is farther away from the earth in these months. This considerably reduces the amount of Solar Radiation reaching the earth surface at this time. Thus, the annual occurrence of Direct Solar Radiation presents a division of the year into two seasons as it were. Between November and April is one season, when relatively high Direct Solar Radiation is generally observed all over the country. This season encourages all human activities that require relatively high amounts of Direct Solar Radiation. The other season is observed between May and September, when relatively lower Direct Solar Radiation is observed.

The similarity in occurrence and distribution of Direct Solar Radiation between the months as derived by Pearson's correlation is shown in Table 2. The months of August and July as well as July and September are the most correlated, with a correlation coefficient of 0.992. These are closely followed by the months of May and June which shows correlation coefficient of 0.991, and the months of March and April showing correlation coefficient of 0.990. The months of March and October as well as June and July both show correlation coefficients of 0.989, whereas, August and September, April and May, and, February and March shows correlation coefficients of 0.987, 0.986, and 0.983 respectively. Furthermore, the months of April and September, April and October, June and August as well as June and September, all have a correlation coefficient of 0.982.

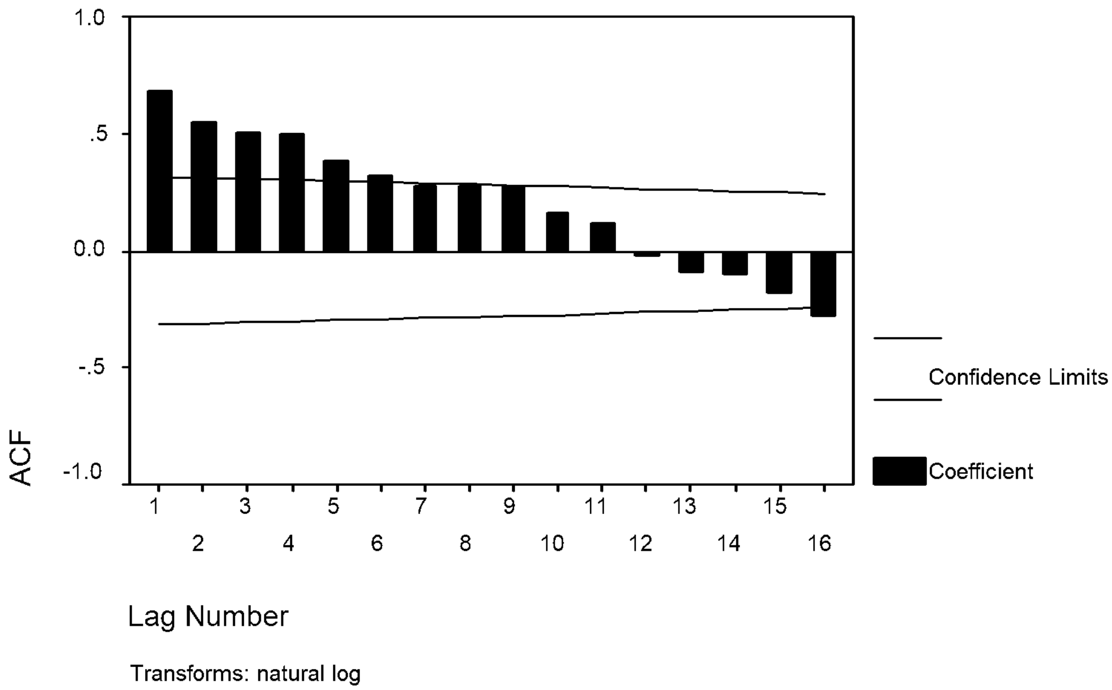
Table 2 Correlation of monthly DSR

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jan	1											
Feb	0.84	1										
Mar	0.76	0.98	1									
Apr	0.70	0.96	0.99	1								
May	0.60	0.92	0.96	0.98	1							
Jun	0.60	0.92	0.96	0.97	0.99	1						
Jul	0.66	0.94	0.96	0.97	0.97	0.98	1					
Aug	0.63	0.91	0.95	0.96	0.96	0.98	0.99	1				
Sep	0.69	0.94	0.97	0.98	0.97	0.98	0.99	0.98	1			
Oct	0.76	0.96	0.98	0.98	0.95	0.95	0.97	0.95	0.98	1		
Nov	0.91	0.94	0.92	0.88	0.81	0.80	0.84	0.81	0.87	0.93	1	
Dec	0.89	0.60	0.52	0.43	0.32	0.31	0.38	0.34	0.43	0.54	0.78	1

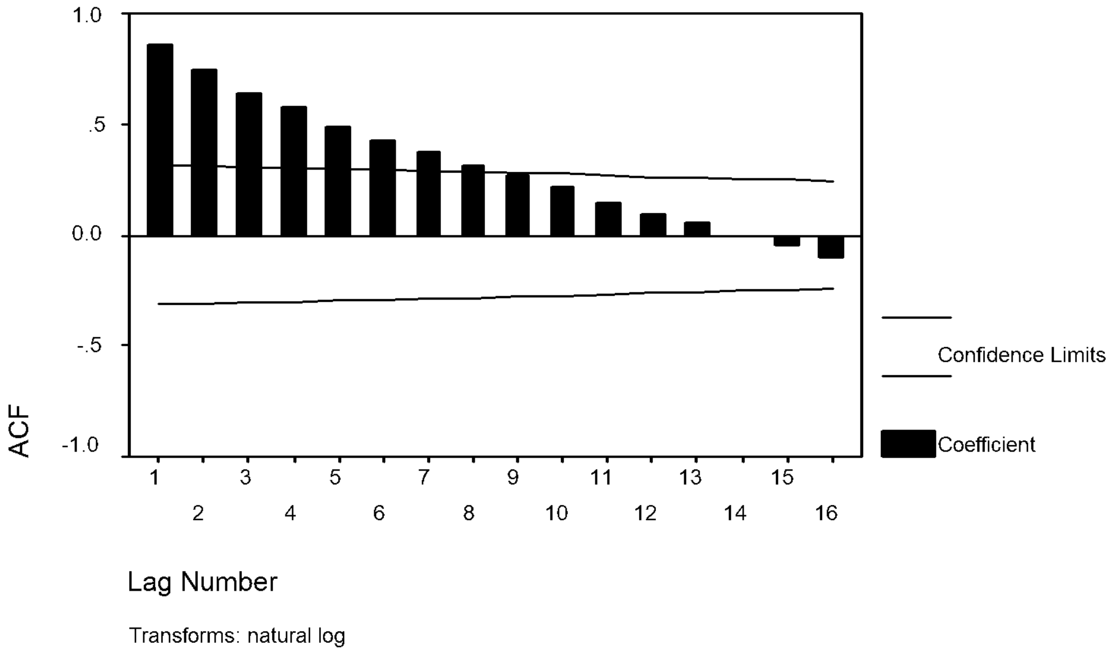
Most months are found to correlate well above 0.5. However, the correlation coefficients of 0.434, 0.431, 0.388, 0.343, and 0.329 exists between the months of April and December, September and December, July and December, August and December, and, May and December respectively. The months of June and December with a correlation coefficient of 0.315 have been found to be the least correlated.

4. DISCUSSION

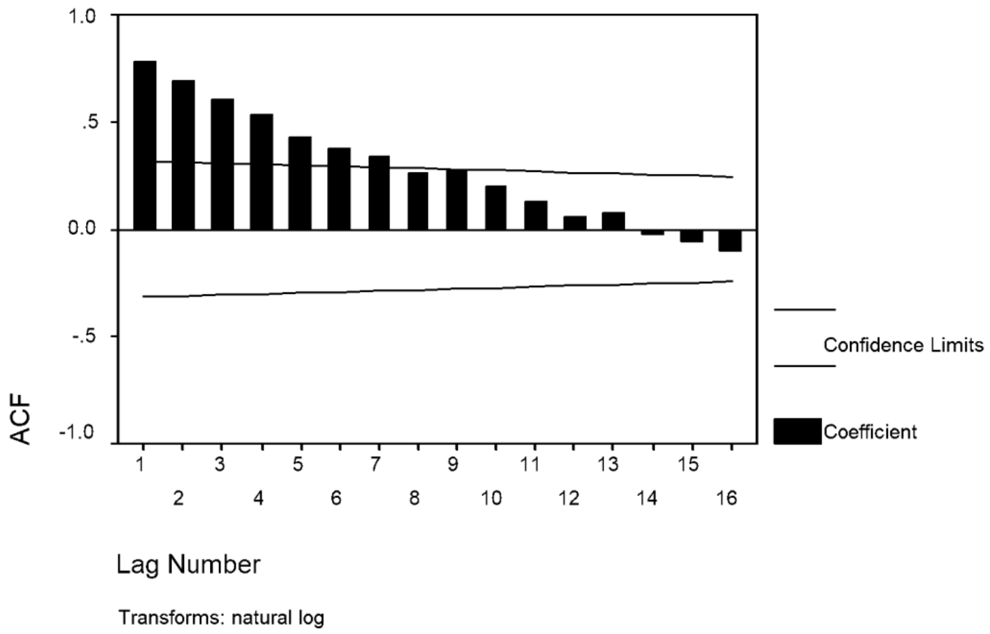
The autocorrelation of direct solar radiation distribution over Nigeria is graphically shown in Fig. 1. The highest lag number for which autocorrelation is computed for all the months is 16 and all the values were transformed into natural log. The confidence limit for the positive coefficients was fairly exceeded in all the months, while it was only slightly exceeded in January and December on the negative coefficients. The autocorrelation however, shows similar trends in all the months alike.



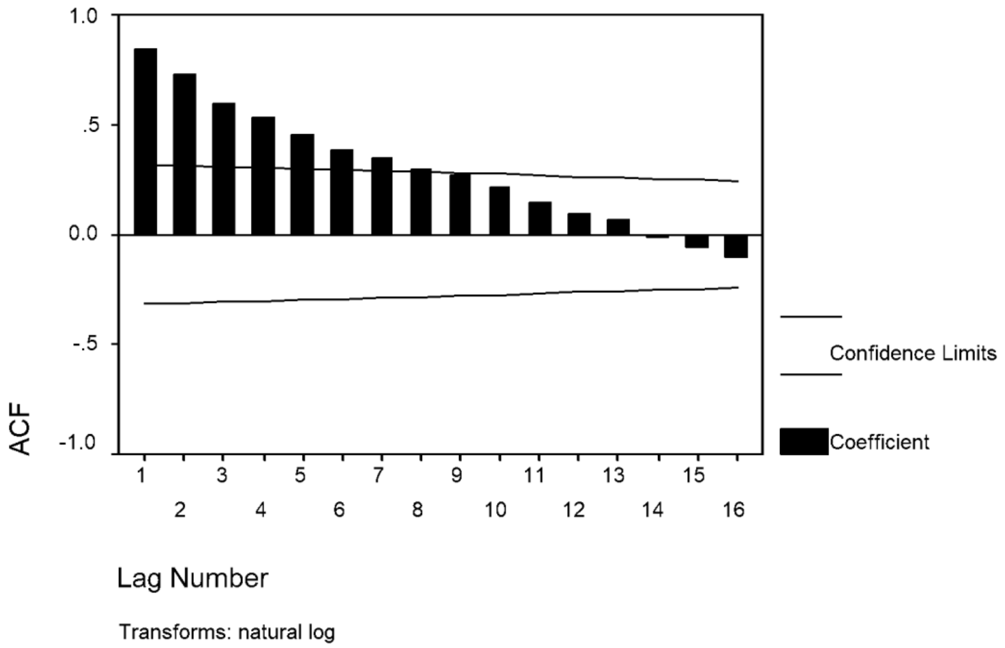
(a) DJF



(b) MAM



(c) JJA



(d) SON

Figure 1(a-d). Spatial-seasonal autocorrelations

The import of these autocorrelations in both the spatial (as indicated by geographical locations) and the seasonal (or temporal) distributions of DSR in Nigeria is evident from the larger portion of the coefficients falling within the positive side of the confidence limits. This goes to show that the regions of the country are suitably endowed with adequate radiation amounts for sustainable application as renewable source of future energy potentials. These findings are in agreement with previous similar studies e.g. (Jiang et al., 2019; Silva et al., 2019; Tang et al., 2018). This is also not far from the established understanding from previous studies especially one by Skartveit and Olseth (1992) which suggested that even for different hours, a typical bimodal pattern of intermittent global and beam radiation normally occurs. The study further observed fluctuations of high and low irradiances indicating low probabilities near hourly means thus averaging over the hour usually require flattening substantial deviations even within the short timeframe of the hour. So even intra-hour variability has been established to be subject to particular time with this distribution lag observed within three hourly averages, that is the particular hour, that preceding and of course the hour after. These differences are found in the lag autocorrelation estimated as a function of time.

4.1 Annual occurrence of direct solar radiation

The annual mean values of Direct Solar Radiation in all the 37 selected stations show that the least amounts of 3.08 kWh/m2/day occur in both Port-Harcourt and Yenogoa. An increase to 3.19 kWh/m2/day occurs in Calabar and the value further rises to 3.89 kWh/m2/day in Uyo. It however declines to 3.64 kWh/m2/day in Owerri and the rises back to 3.9 kWh/m2/day in Umuahia. In Awka, the annual mean direct solar radiation rises to 4.21 kWh/m2/day and then declines to 4.07 kWh/m2/day in Asaba rising again to 4.37 kWh/m2/day in Abakaliki. A decline to 3.89 kWh/m2/day is noted in Benin-City, rising to 4.21 kWh/m2/day in Enugu and declining again to 3.94 kWh/m2/day in Ikeja. It rises to 4.33 kWh/m2/day in Abeokuta, declines slightly to 4.31 kWh/m2/day in Akure, rises back to 4.33 kWh/m2/day in Ibadan and declines again to 4.31 kWh/m2/day in Ado-Ekiti.

The annual mean direct solar radiation attains a sharp rise to 5.16 kWh/m2/day in Markurdi, declines to 4.53 kWh/m2/day and 4.28 kWh/m2/day in Lokoja and Oshogbo, and then rises to 4.73 kWh/m2/day in Ilorin. A steady rise from 4.92 kWh/m2/day to 5.22 kWh/m2/day occurs between Lafia and Jalingo, followed by a decline to 5.07 kWh/m2/day in Abuja and a rise to 5.37 kWh/m2/day in Yola.

However, a slight decline from 5.19 kWh/m2/day to 5.15 kWh/m2/day occurs between Minna and Jos with a rise to 5.65 kWh/m2/day in Gombe followed by another slight decline to 5.54 kWh/m2/day and 5.48 kWh/m2/day in Bauchi and Kaduna. A slight steady rise to 6.08 kWh/m2/day from 5.96 kWh/m2/day occur between Damaturu and Dutse, with a slight decline to 5.95 kWh/m2/day in Maiduguri, a slight rise to 6.18 kWh/m2/day in Kano, and a decline again to 6.12 kWh/m2/day in Gusau and Birmin-Kebbi. The annual mean direct solar radiation increases to 6.02 kWh/m2/day in Katsina and further rises to 6.6 kWh/m2/day in Sokoto.

4.2 Spatial distribution

The spatial distribution of Direct Solar Radiation in Nigeria for the twelve months of the year is shown in map as presented in Figure 2. The spatial differences in the occurrence of direct solar radiation are characteristically deductible from the variations in the contour lines. The increase northwards was found to be almost parallel with lines of latitude although the contours are slightly skewed in a West-North-West to East-South-East orientation. In the north, Sokoto, Jos and Markurdi exhibited high incidence of direct solar radiation as relative to other area shown in the maps, while Port-Harcourt, Yenogoa and Calabar, exhibited relatively low values.

The scatterplot of the relationship between Direct Solar Radiation and Latitude show a close linear pattern (Figure 3). This implies a direct relationship between the spatial distribution of Direct Solar Radiation and Latitude. Hence, it can be deduced that as the latitude increases northwards from the equator, Direct Solar Radiation also increases steadily northwards. The lower latitudes thus experience less direct radiation values than the higher latitudes within Nigeria.

The spatial differences of DSR in Nigeria, has recently been suggested as imposing increasing demands for electricity and because of its location close to the equator, solar energy has been identified as important source of readily accessible alternatives to meet this need.

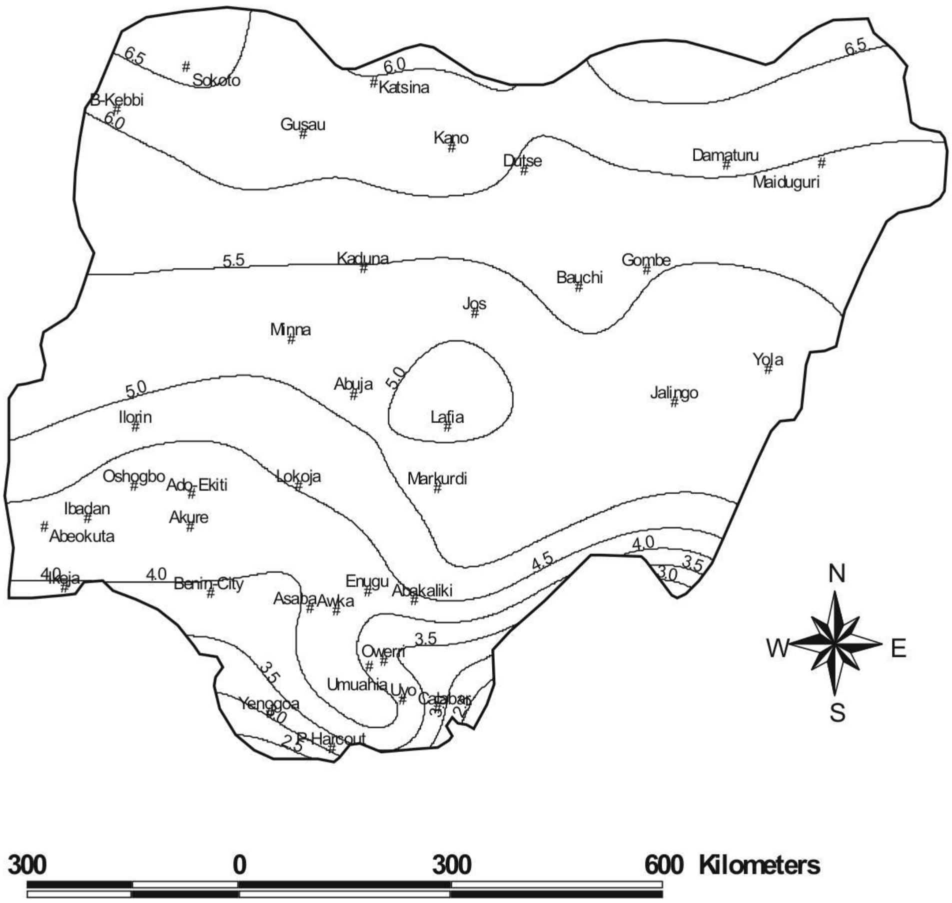


Figure 2 Annual mean DSR in Nigeria (kWh/m²/day)

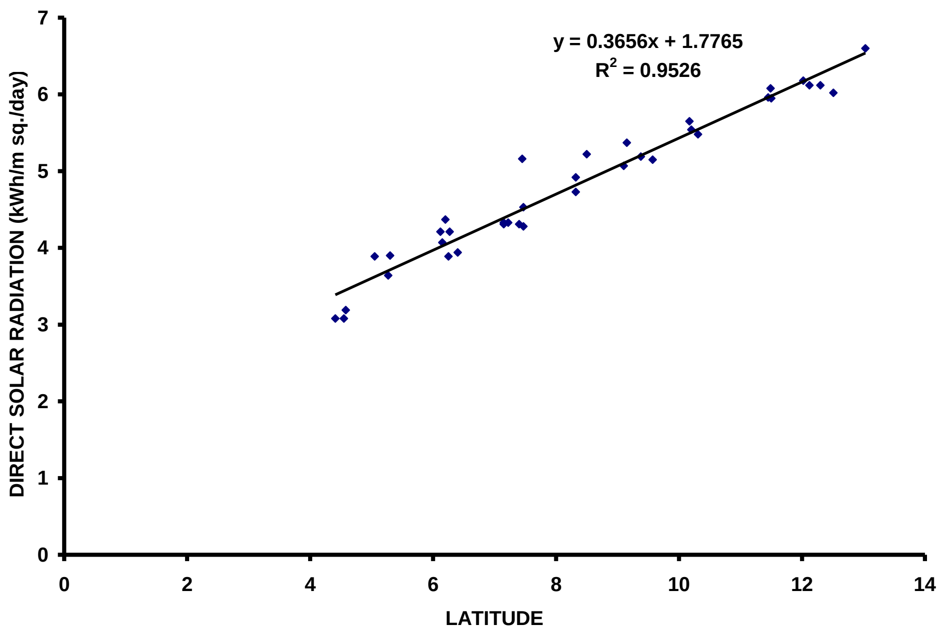


Figure 3 Regression of DSR with latitude

The linear regression with 95% individual prediction interval presents an equation:

$$y = 1.78 + 0.37\,x \qquad (1)$$

Where y and x represents the Direct Solar Radiation and Latitude respectively. This model implies that for every 0.37 increase in latitudinal location, there is a unit rise in Direct Solar Radiation occurrence. The result is in agreement with the 0.976 correlation coefficient between Direct Solar Radiation and Latitude, as reported in Table 2. The relationship between the two parameters is significant at 0.01 level for a one-tailed test.

Beside the influence of latitude on the amount and distribution of direct solar radiation on the surface of the earth, other surface meteorological and atmospheric conditions also affect the spatial distribution of direct solar radiation. The clearness index which is the fraction of insolation at the top of the atmosphere which reaches the surface of the earth shows a direct linear relationship with direct solar radiation (Figure 4). This is mathematically presented in form of the regression equation:

$$y = -3.68 + 15.53\,x \qquad (2)$$

Where y represents direct solar radiation and x represents clearness index. The result is in agreement with the 0.999 correlation coefficient between Direct Solar Radiation and Clearness Index. The relationship between the two parameters is significant at 0.01 level for a one-tailed test. The higher the values of the clearness index, which increases northwards in Nigeria, the more amount of direct solar radiation is experienced at any particular location. The clearness index is the measured global horizontal radiation divided by the extraterrestrial radiation. It basically determines how cloudy that moment is so if the clearness index is known, then one can calculate the extraterrestrial radiation regardless of the weather and thus calculate the solar radiation. In a really cloudy day, all the radiation can be assumed to be diffuse such that input of the clearness index into Erbs correlation to calculate the fraction of diffuse solar radiation and the fraction of direct solar radiation can be provided.

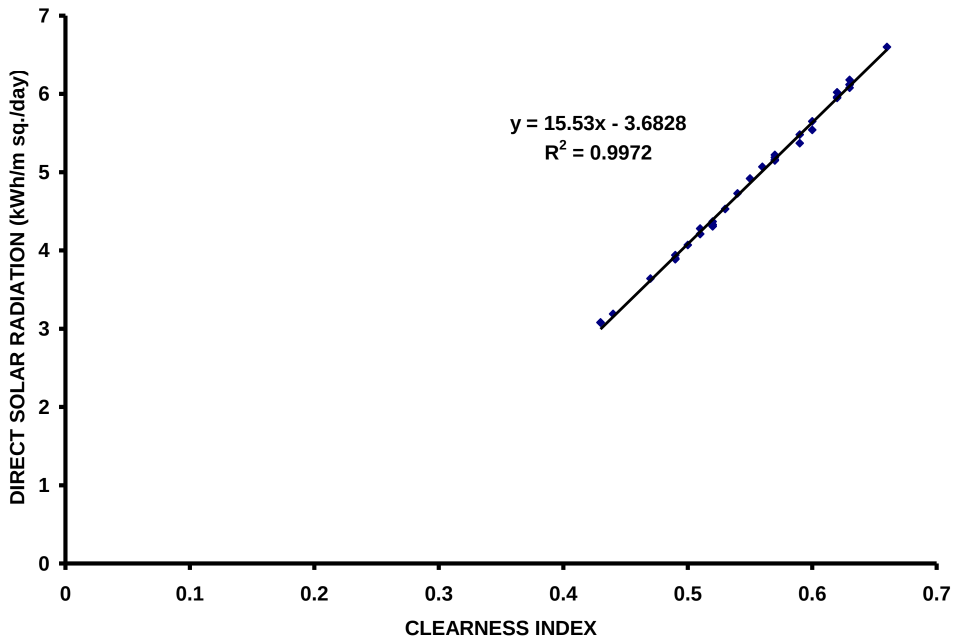


Figure 4 Regression of DSR with Clearness Index

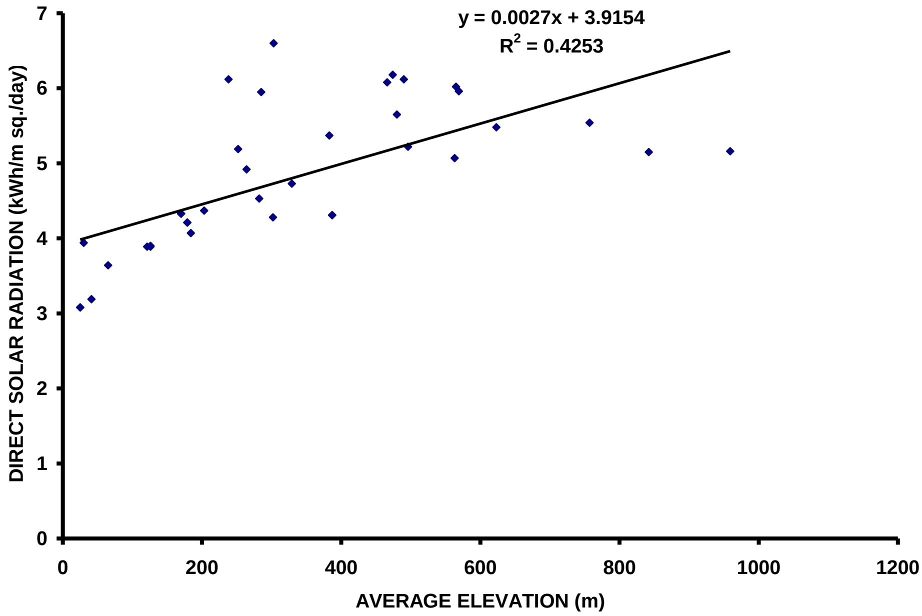


Figure 5 Regression of DSR with Average Elevation

On a local scale, differences in average elevation are found to also control the amount of direct solar radiation received on the earth surface at any location in Nigeria (Figure 5). However, the effect of average elevation may not be explicitly explainable on the basis of altitude without considering aspect, that is, the direction which the surface faces. Some slopes may be more exposed to the sun than others, while really high elevations which have a smaller mass of air above them receive considerably more direct solar radiation under clear skies than locations near sea-level. These are observed in the regression equation:

$$y = 3.92 + 0.00\,x \qquad (3)$$

Where y represents direct solar radiation and x represents average elevation. The 3.92 constant shows there is a positive linear relationship but the 0.00 coefficient of x, the independent variable, suggests that average elevation by itself does not impose the control on direct solar radiation without the influence of aspect, wind speed and cloudiness among others. The result is in agreement with the 0.652 correlation coefficient found between Direct Solar Radiation and average elevation. The relationship between the two parameters is significant at 0.01 level for a one-tailed test.

When cloud cover is thick and complete enough, it forms a significant barrier to the penetration of solar radiation. The cloud cover reflects solar radiation back to space and allows the passage of some as diffuse solar radiation. Hence, direct solar radiation is only observed in areas where the cloud amount is low. This makes for an inverse negative relationship between direct solar radiation and daily cloud amount with a regression equation:

$$y = 11.97 - 0.12\,x \qquad (4)$$

Where y represents direct solar radiation and x represent daily cloud amount. Since daily cloud amount decreases northwards in Nigeria the amount of direct solar radiation increases considerably (Figure 6). The result is in agreement with the -0.977 correlation coefficient between Direct Solar Radiation and average daily cloud amount. The relationship between the two parameters is significant at 0.01 level for a One-tailed test.

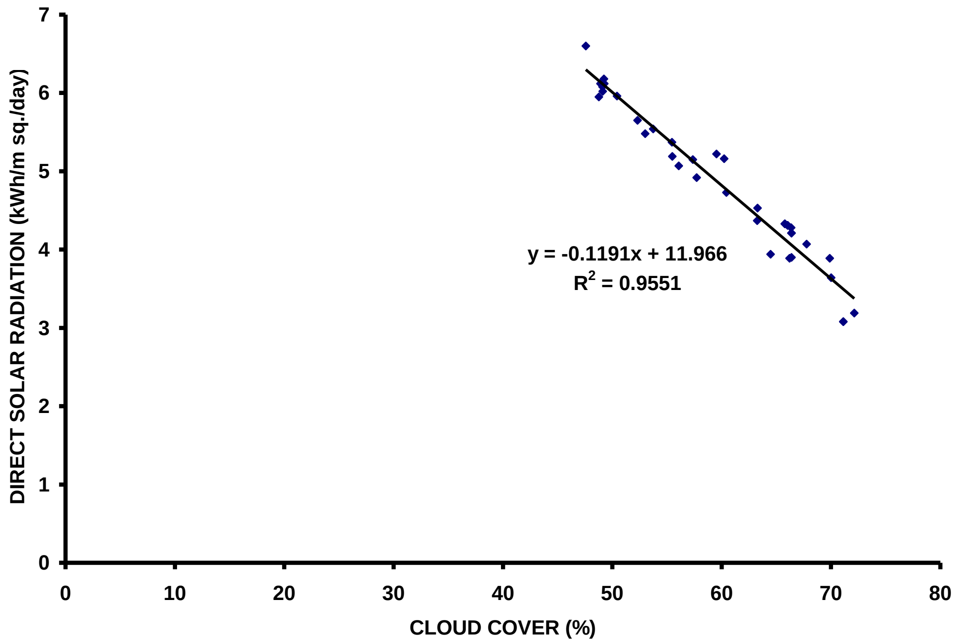


Figure 6 Regression of DSR with Daily Cloud Amount

The effect of average daily solar angle on the amount of direct solar radiation experienced in any particular location in Nigeria also shows an inverse negative linear relationship with a regression equation:

$$y = 175.71 - 2.25\,x \qquad (5)$$

Where y represents direct solar radiation and x represent daily solar angle as shown in Figure 7. The larger the daily solar angle, the less the amount of direct solar radiation experienced. This is in agreement with the -0.928 correlation coefficient between Direct Solar Radiation and Average Daily Solar Angle. The relationship between the two parameters is significant at 0.01 level for a one-tailed test.

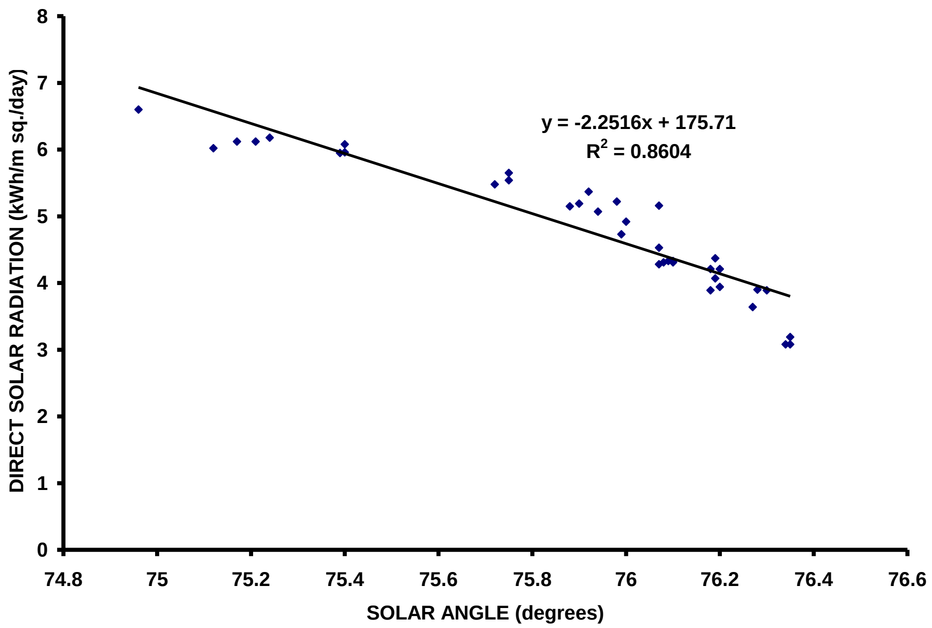


Figure 7 Regression of DSR with Daily Solar Angle

Similarly, the effect of average daily relative humidity on the amount of direct solar radiation experienced in any particular location in Nigeria also shows an inverse negative linear relationship with a regression equation:

$$y = 9.49 - 0.07\,x \qquad (6)$$

Where y represents direct solar radiation and x represent daily relative humidity (Figure 8). The larger the daily relative humidity, the less the amount of direct solar radiation experienced. The result is in agreement with the -0.881 correlation coefficient between Direct Solar Radiation and average daily relative humidity. The relationship between the two parameters is significant at 0.01 level for a one-tailed test. The multiple regression equation for this relationship is mathematically given as:

$$y = 0.08x1 + 13.39x2 + 9.970E\text{-}07x3 - 0.006x4 - 0.035x5 + 0.0006x6 \qquad (7)$$

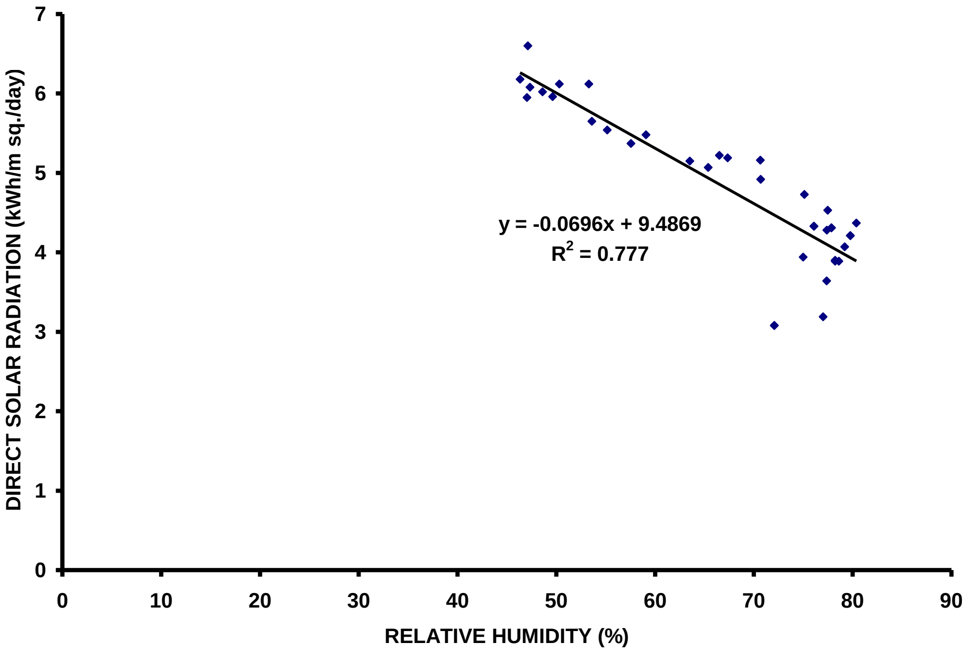


Figure 8 Regression of DSR with Relative Humidity

4.3 Regional grouping

The spatial variability of direct solar radiation due to several factors already discussed was studied using elementary linkage analysis developed by McQuitty (1957) which adopts correlation analysis, as used in Adelekan (1998). The correlation coefficient shows a measure of the tendency two parameters to vary in the same manner. Correlation of monthly mean values of direct solar radiation for the 37 stations used in this analysis is derived. A classification of the stations based on their homogeneity of direct solar radiation occurrence derived from the correlation matrix between stations.

The elementary linkage analysis gives a grouping result which approximates to that of orthogonally rotated factor analysis and factor analysis techniques. It also allows grouping to be done by the inspection of the matrix of correlations among the objects to be classified (Johnston, 1976; Lawley & Maxwell, 1962). Each station is assigned to a group based on its highest index of association with another station, while the lower limit of association used in building the clusters is exclusively determined from the data. Thus, each station in any group is more highly correlated with another station in the same group than it is with any other station in another group. In most cases, the second highest correlation for any station also falls within the same group whereas most stations in the same group are highly interlinked with little or no significant correlations outside such a group.

The classification is shown in Figures 9 and 10. Region I experiences direct solar radiation of 2-3 kWh/m2/day. Port-Harcourt, Yenogoa and Calabar fall within this region. These cities are coastal cities and the low levels of surface albedo and clearness index are the most likely reasons for the low distribution of direct solar radiation in this region. By and large, in virtually all the regions of Nigeria, amounts of dissimilarity of solar radiation remained high with low amounts experienced in in the southern ecological zones as compared with the northern. The grouping map displayed that high and low values of DSR were observed in the Northern to Southern increasing inclination across locations of Nigeria.

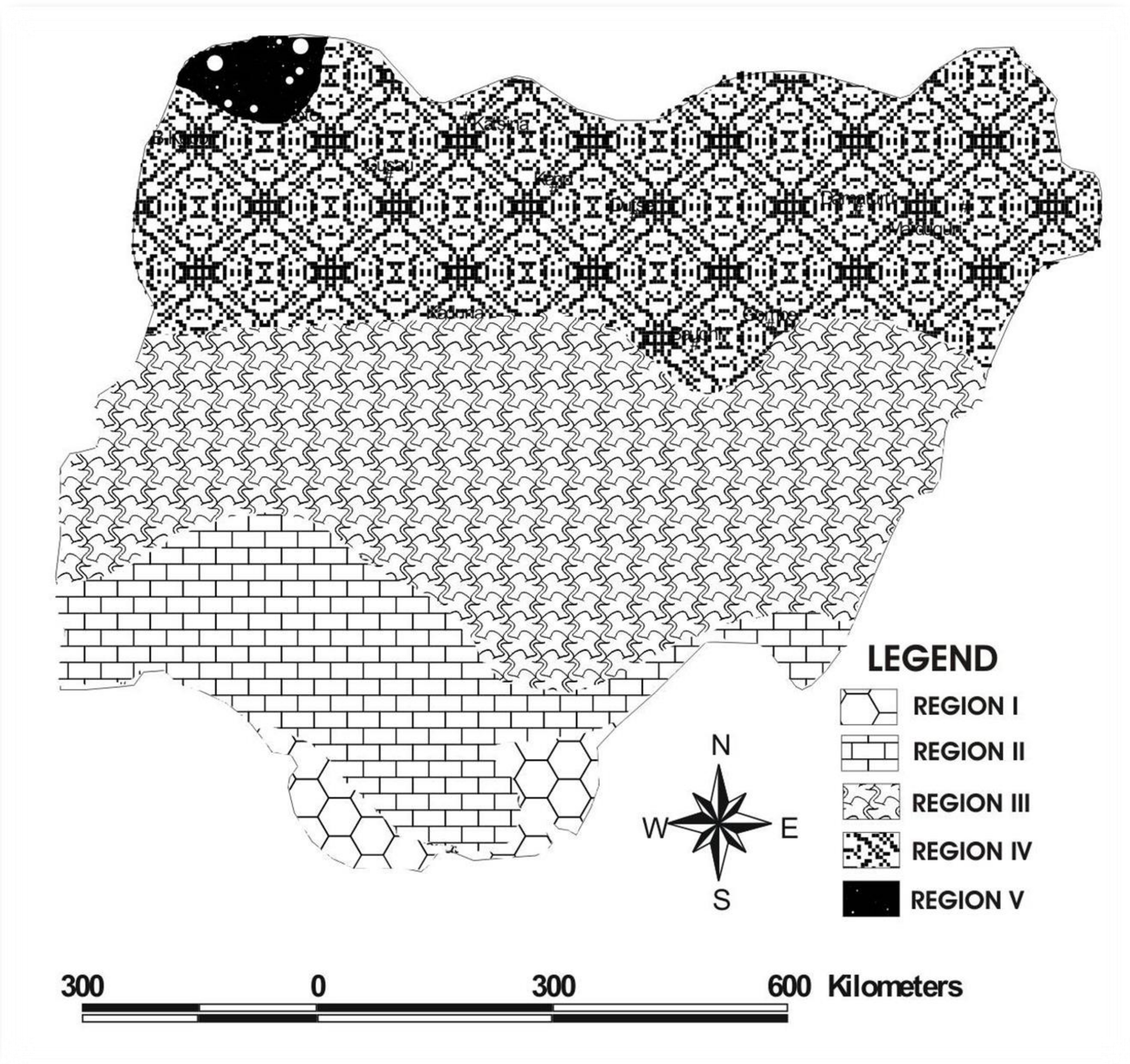


Figure 9 Map of Nigeria showing regions of DSR

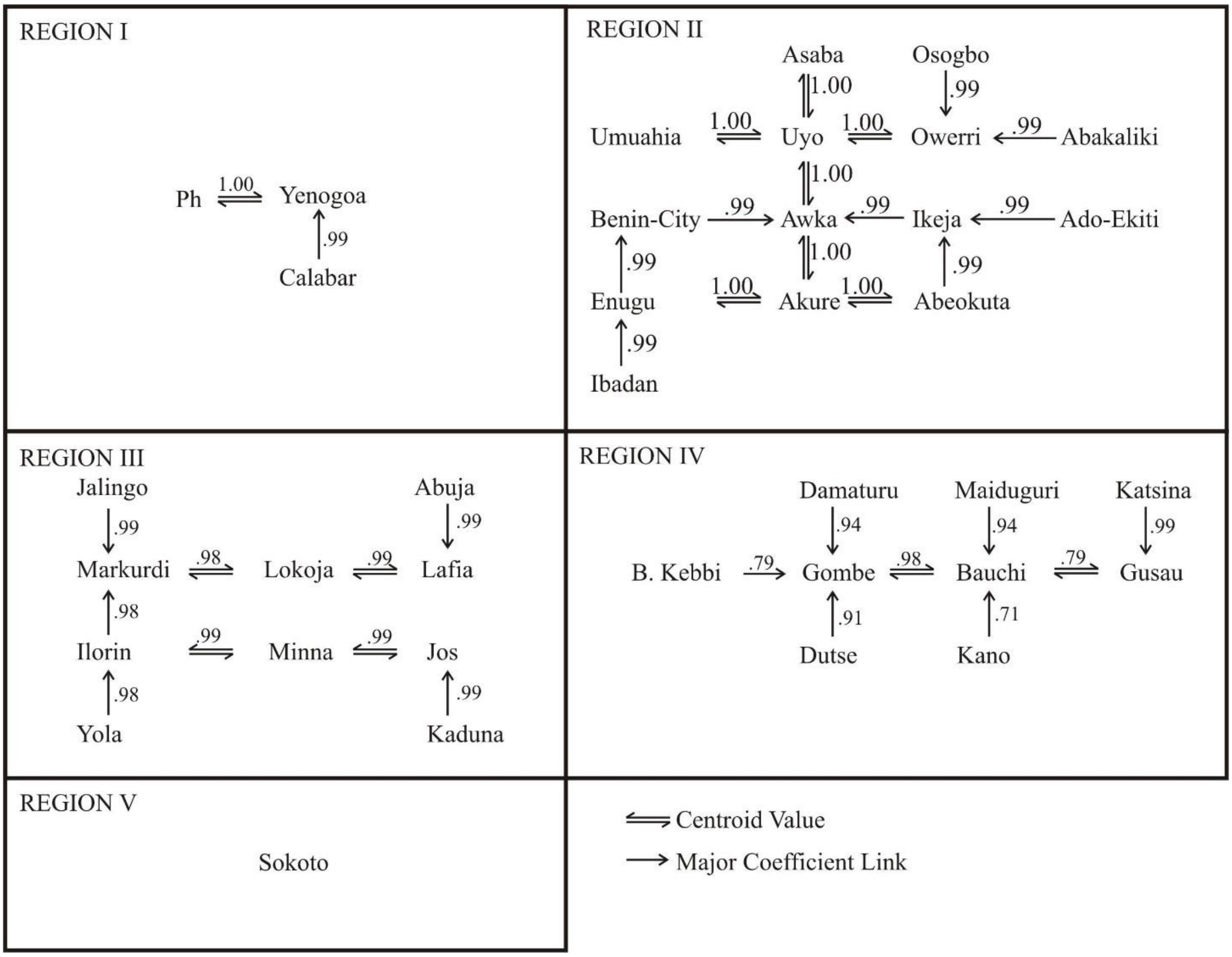


Figure 10 Linkage Analysis diagram

Region II comprises of Uyo, Umuahia, Owerri, Ikeja, Abeokuta, Ibadan, Awka, Asaba, Benin-City, Enugu, Abakaliki, Akure, Ado-Ekiti and Oshogbo with a fair distribution of direct solar radiation of 3-4 kWh/m2/day. Region III with direct solar radiation between 4-5 kWh/m2/day comprises of Lokoja, Ilorin, Markurdi, Lafia, Abuja, Minna, Jalingo, Yola, Jos and Kaduna. The spatial distribution of direct solar radiation is moderate. Region IV comprises of Bauchi, Gombe, Dutse, Damaturu, Maiduguri, Kano, Katsina, Gusau and Birmin-Kebbi. This region has relatively high amounts of direct solar radiation ranging between 5-6 kWh/m2/day. The spatial extent of Region IV mostly lie in the northern parts of Nigeria.

Region V has a very high occurrence of direct solar radiation as high as 6-7 kWh/m2/day. Sokoto falls within this region among the 37 stations selected for this study. The very high values of direct solar radiation in the last two regions can be accounted for by the corresponding high surface albedo, temperature range, average solar insolation and clearness index as well as very low amounts of cloud. They are also closer to the Sahara desert more than stations in the other groups.

5. CONCLUSIONS

Spatial distribution of daily direct solar radiation is closely related to latitude. The10-year average annual and monthly direct solar radiation values obtained from satellite measurements are greatest at the northernmost parts of Nigeria and decreases regularly towards the Atlantic Ocean in the southern parts of the country. As the rays of the sun shift seasonally along the latitude, the zone of maximum possible direct solar radiation moves as well.

The direct solar radiation conditions in Nigeria also shows a generally high occurrence towards the end of the year and at the beginning of the year, both of which periods usually falls within the harmattarn dry season. The direct solar radiation however, generally lowers towards the middle of the year during the rainy season. Essentially, the solar radiation potential is exploitable all over the country because the values of direct solar radiation receipt is adequate and is not lower than the amounts required for solar technology at any location of study at any time of the year. The North-South differential spatial pattern of DSR may well be attributed to seasonality in cloudiness and solar angle

Future study could therefore, utilize satellite data on solar radiation and other surface and atmospheric meteorological conditions upon which its occurrence and distribution depends, to derive models which would show the nature and pattern of solar radiation in the low latitudes using cutting edge methods, particularly, Geostatistical kriging and neural network. This will not only expand the frontiers of knowledge but would also help to promote sustainable development goals in Nigeria, which will definitely rub off to impact the Sub-Saharan Africa region. Improved capacity to also make adequate provision to harness the potentials of solar energy has been known to promote economic development worldwide, the case will not be different in Nigeria.

DECLARATIONS

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