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DEVELOPMENT OF A NEW SUNSHINE-BASED GLOBAL SOLAR RADIATION ESTIMATION MODEL FOR IBADAN, NIGERIA

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ABSTRACT

This research focus mainly on five sunshine based models for the estimation of monthly mean daily global solar radiation using 36 years solar radiation and sunshine hour data for Ibadan. The Data used for this study was obtained from the archive of the International Institute of Tropical Agriculture (IITA) meteorological station located in Ibadan, Nigeria. The model evaluated includes Akinoglu-Eceit, Blacket al, Glover Mc-Culloch, Rietveld and Stone models. A new sunshine based regression model was developed using two-third (⅔) of the data collected from the station and were tested with the remaining one-third (⅓) of the data. The results showed that all the models provided estimates that were significantly different from the measured values. The decreasing order of predictive accuracy was as follows order: Stone, Black et al., Rietveld, Akinoglu-Eceit and Glover-McCulloch respectively. The results also showed that model for estimates R values of 0.5 with P<0.0001 for Ibadan when compared with observed values. For the quadratic function Ibadan has 51.3% level of performance at P<0.0001. The model equations $\bar{H}/\bar{H}_o = 0.274 + 0.322(\bar{n}/\bar{N})$.

The model was then validated with the statistical parameters. The model is recommended for use in Ibadan.

KEYWORDS: Solar Radiation, Sunshine Hour, Regression Model, and statistical parameters.

1.0 INTRODUCTION

The primary driver for many physical, chemical and biological processes on the earth's surface is solar radiation. Complete and accurate solar radiation data at a specific region are of considerable significance for such research and application fields as architecture, industry, environment, hydrology, agrology, meteorology, limnology and ecology (Bulut and Büyükalaca, 2007). Besides solar radiation data are a fundamental input for solar energy applications such as photovoltaic systems for electricity generation, solar collector for heating, solar air conditioning climate control in buildings and passive solar devices (Sfetsos et al., 2000).

Global study of the world distribution of global solar radiation requires knowledge of the radiation data in various countries and for the purpose of the worldwide marketing, designer and manufacturers of solar equipment will need to know the average global solar radiation available in different and specific regions (Ibrahim, 1985). Global solar radiation is of economic importance as a renewable energy alternative, recently global solar radiation has been studied due to its importance in providing energy for earth's climate system. The solar radiation reaching the earth's surface depends upon climatic conditions of a location, which is essential to the prediction and modeling of a solar radiation system (Sambo, 1986).

The best way of knowing the amount of global solar radiation of a place is to install pyranometers at many locations in the given region and look after day-to -day maintenance and recording, which is a very costly exercise. The alternative approach is to correlate solar radiation with meteorological parameters at a place where the data is collected. The resultant correlation may then be used for locations of similar meteorological and geographical characteristics at which solar data are not available.

An accurate knowledge of solar radiation distribution at a particular geographical location is very important for the development of many solar energy devices and for estimates of their performances. Unfortunately, for many developing countries solar radiation data are expensive with relatively high technology which is involved. Therefore, it is better to elaborate the methods in which modeling using meteorological data are can easily be done and the objectives of this study are to evaluate trends and variability in solar radiation, evaluate some selective global radiation models for Ibadan and develop a new sunshine based global radiation models for the study area.

1.2. Empirical Models for Estimating Solar Radiation

Over the last two decades, increased interest in modeling radiation-mediated processes has resulted in a greater demand for solar radiation data. This demand has been reflected in the numerous methods, developed for suitable radiation data that have already been reported. These method ranges from simple empirical formulas to complex numerical models that depend on the availability of input data. Simple relationships for estimating sunshine duration and solar radiation, involving such factors as cloud cover, percentage of specific cloud types, evaporation, humidity, number of days with dust or smoke, air temperature, precipitation, latitude and elevation, have been widely reported (Linacre, 1992).

1.2.1. Angstrom Model

Efforts have been made to estimate solar radiation as a function of solar radiation and the state of the atmosphere since the beginning of the century. Sunshine hour has being the parameters commonly used and usually, the ratio of global solar radiation to extra-terrestrial is correlated to the ratio of the effective sunshine hours to total possible sunshine hours.

The effective sunshine hour (n) is measured with a heliograph (Martinez-Lozano et al., 1984). Though the instrument has a threshold, under which sunshine is not recorded, this error is termed not significant when estimating the daily solar radiation. Angstrom Model (1924) suggested a simple linear relationship for estimating the global solar radiation (R_G, $MJm^{-2}day^{-1}$) as a function of extra-terrestrial radiation, actual sunshine hours (n) and potential or theoretical sunshine (N).

$$\frac{RG}{RA} = a + b\, n/N \tag{1}$$

He suggested values of 0.2 and 0.5 for empirical coefficients a and b respectively. Bennet (1962), Davies (1995), Penman (1948), Monteit (1966) have calibrated this expression for different places. The coefficient can vary significantly shows by Doorenbos and Pruit (1975).

1.2.2 Bristow – Campbell Model

In this model, incoming solar radiation is determined by the atmosphere. However, the dynamics of the atmosphere is very difficult to predict. Considering transformations experienced by solar radiation, one can expect to find a relationship to express solar radiation as a function of meteorological variables commonly recorded at the meteorological stations. Chang (1968) reported that there is a good relationship between net radiation and global solar radiation and global solar radiation, since the latter one is the principal source of energy. Bristow and Campbell (1984), suggested the following relationship for daily global radiation, as a function of daily extra –terrestrial solar radiation and difference between maximum and minimum temperatures (ΔT, ^{o}C).

$$\frac{RG}{RA} = A\{1 - exp\,(-B\Delta TC)\} \quad (2)$$

Coefficients, A, B and C are empirical, they have some physical meaning. A represents the maximum radiation that can be expected on a clear day. Coefficients B and C control the rate at which A is approached as the temperature difference increases. Values most frequently used for this coefficients are 0.7 for A, range from 0.004 to 0.010 for B and 2.4 for C.

1.2.3 Allen Model

Allen (1997) suggested the use of self calibrating model for estimating mean global radiation following the work of Hargreaves and Samani (1982). In his work, he suggested that the mean daily global radiation R_G can be estimated as a function of extra –terrestrial solar radiation RA, mean maximum (T_M, ^{O}C) and minimum temperatures (T_m, ^{O}C).

$$\frac{RG}{RA} = Kr(T_M - T_m)^{0.5} \quad (3)$$

1.2.4 Glover-McCulloch Model

Glover and McCulloch (1958) utilized data from seven stations of latitude 0^0 to 60^0 and included the effect of latitude of the location. They proposed the following Angstrom-type relationship:

$$\bar{H} / \bar{H}_0 = 0.29 \text{ Cos } \phi\, 0.52\, (\bar{n} / \bar{N}) \quad (4)$$

1.2.5 Black et al Model

This model is based on the modified Angstrom-type linear equation which is expressed as:

$$\bar{H} / \bar{H}_0 = a + b\, (\bar{n} / \bar{N}) \quad (5)$$

Where,

$\bar{H}$ = the monthly mean daily global radiation, MJm^{-2}

$\bar{H}_0$ = monthly mean daily extraterrestrial radiation, MJm^{-2}

$\bar{N}$ = monthly mean daily bright sunshine duration, h

a, b = empirical coefficients which vary with geographical and climatic conditions.

Black et al (1954) analyzed data from 32 stations of latitude 6^0 to 65^0 and found that a can take values ranging from 0.15 to 0.40 and b from 0.27 to 0.61. They proposed the following Angstrom-type relationship:

$$\bar{H} / \bar{H}_0 = 0.23 + 0.48\,(\bar{n} / \bar{N}) \qquad (6)$$

2.4.6. Rietveld Model

Rietveld (1978), examined several published values of a and b and reported that a and b is themselves functions of the parameter ($\bar{n}$ / $\bar{N}$) and are given by:

$$a = 0.10 + 0.24\,(\bar{n} / \bar{N}) \qquad (7a)$$

$$b = 0.38 + 0.08\,(\bar{n} / \bar{N}) \qquad (7b)$$

Using the above representations of a and b, he proposed the following modified Angstrom-type equation:

$$\bar{H} / \bar{H}_0 = 0.18 + 0.62\,(\bar{n} / \bar{N}) \qquad (8)$$

1.3. Correlation between Global Solar Radiations with Meteorological Data

Global solar radiation (Rs) has wide applications in several disciplines. The data of measured or predicted Rs are widely applied by agriculturists, solar engineers, architects and hydrologists. Due to the importance of Rs, several empirical models have been developed to predict its values all over the world. In several studies, Angstrom model was being used for calibration based on the ratio of actual and possible sunshine hour's n/N by using measured daily data of solar radiation Rs and meteorological data for a year or two. The model is modified by using air temperature for considering the effect of cloudy conditions as well as n/N ratios. The results showed that using both the air temperatures and the ratios of n/N always lead to a higher accuracy.

1.4 Assessment of Solar Radiation and Sunshine Hours Models in Nigeria

Many people have worked on the correlations involving global solar radiation and sunshine hours for different locations in Nigeria. For example, in 1985 Sambo, developed a correlation with solar radiation using sunshine hours for Kano with the regression coefficients a = 0.413 and b = 0.241 for all the months between 1980-1984, (Arinze and Obi, 1983) also developed a correlation with solar radiation using sunshine hours in Northern Nigeria with regression coefficients a = 0.2 and b = 0.74, (Burari et al., 2001) developed a model for estimation of global solar radiation in Bauchi with regression coefficients a =0.24 and b = 0.46. Other workers (Ojosu, 1984; Fagbenle, 1990; Folayan, 1983; Adebiyi, 1988; Turton, 1987; Bamiro, 1983) developed theoretical and empirical correlations of broad applicability to provide solar data for systems design in most Nigeria cities. It was observed that the regression coefficients are not universal but depends on the climatic conditions.

2.0 METHODOLOGY

2.1 Study area

Ibadan **(7°23′47″N 3°55′0″E)** has a sub-humid climate which is characterized by rain forests and slightly heavy rainfall. Its rainfall pattern is Bimodal with mean annual rainfall of 1250mm. The region’s soil in majorly Ferric Luvisols, its season are wet which from March through October and dry running through November to February having annual maximum temperature ranging between 27-34^{o}C and annual minimum temperature ranging between 20-23^{o}C.

Figure 1: Map of Nigeria Showing the study area.

2.2. Data Sources

The meteorological data; Solar Radiation and Sunshine hour used for the study were obtained from the Archives of the International Institute of Tropical Agriculture (IITA), Ibadan. The data collected covered a period of 36 years Ibadan with latitude 7^{0}26’N and longitude 3^{0} 5’E.

2.3 Trend Analysis

MAKESENS (Mann-Kendall test for trend and Sen's slope estimates) an Excel template which was developed for detecting and estimating trends in the time series was used to evaluate the trend and variability of solar radiation and sunshine duration in the area under study. The Mann-Kendall test statistic S is given by Salmi et al. (2002) as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \qquad (9)$$

where n is the length of the time series $x_i \dots x_n$, and sgn(.) is a sign function, x_j and x_k are values in years j and k, respectively. The expected value of S equals zero for series without trend and the variance is computed as:

$$\sigma^2(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5) \right] \qquad (10)$$

Here q is the number of tied groups and t_p is the number of data values in p^{th} group. The test statistic Z is then given as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\sigma^2(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{\sigma^2(S)}} & if \quad S < 0 \end{cases} \qquad (11)$$

As a non-parametric test, no assumptions as to the underlying distribution of the data are necessary. The Z statistic is then used to test the null hypothesis, H_o that the data is randomly ordered in time, against the alternative hypothesis, H_1, where there is an increasing or decreasing monotonic trend. A positive (negative) value of Z indicates an upward (downward) monotone trend. H_o is rejected at a particular level of significance if the absolute value of Z is greater than $Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is obtained from the standard normal cumulative distribution tables. Hobbins et al. (2001) noted that the Mann-Kendall test is non-dimensional and does not quantify the scale or the magnitude of the trend but the direction of trend. To estimate the true slope of an existing trend the Sen's non-parametric method will be used (Salmi et al., 2002).

2.4 New Regression Model Calibration and Validation

The new global solar radiation model was calibrated using two-third (⅔) of data collected from Ibadan (24 years), were divided into two parts at each station. This was done by sorting them into one part containing data and the remaining third forming the one-third part. It was repeated successively until the sorting was completed. The two-third parts from each station were brought together to form the data representing all stations which was used for the model calibration. The remaining one-third (⅓) were used to validate the model generated for the stations. The new regression models were subject to statistical test to ensure that the assumptions inherent in the regression analysis were not violated.

3.0 RESULTS AND DISCUSSION

3.1 Descriptive Statistics

The summary of descriptive statistics of the long term series of solar radiation SR and sunshine hour SH for Ibadan is given in Table 1. SR varied significantly with Z test value of -3.84% in November at 0.001 significant levels to -2.87% in March at 0.01 significant levels. Sunshine hour varied with Z test value of 3.22% in October at 0.01 significant levels to 0.02 %in July at no significant level. The significant decrease in SR in Ibadan was found in all months (January – December). The annual time series of solar radiation at Ibadan is shown in figure 4.1. There was an increase trend in sunshine hour at Ibadan in 11 months in Figure 2. of the year, with only 4 months (June, October, November and December) having trends with significant slopes ($P<0.05$).

This agrees with the wild spread decrease termed “global dimming” which has been reported by (Stanhill and Cohen, 2001). A decrease of 6.5% per decade is only slightly higher than 6.0 % per decade reported for Cairo in Egypt (Omran, 2000). Stanhill and Kalma (1995) have also reported a decrease of 10% per decade in a similar analysis of local series in Hong Kong. This can be linked with the term described as global dimming, a radiative change which is caused by (i) increase cloudiness (ii) solar activity which is a function of the changes in Earth orbital parameters and (iii) changes in aerosols concentrations either naturally due to volcanic eruption or anthropogenic due to population and industrialization.

3.2 Calibration of the New Sunshine based Solar Radiation Model

Having evaluated the solar radiation and sunshine based models, an attempt were also made to develop models suitable for Nigeria environment using two-third (⅔) of the data collected to calibrate or parameterize the model while the remaining one- third (⅓) was used to validate (test) the model. This shows that sunshine is not a good predictor of Solar radiation i. e. it cannot be used as a surrogate to solar radiation.

It is very clear that there is variation in one variable to another variable for correlation coefficient R, MBE, S^2D and RMSE.

3.3. Solar Radiation Model Performance at Ibadan

The five models selected for the study were evaluated using statistical parameters to know their transferability or applicability to Ibadan, Nigeria condition. Out of the models evaluated, Stone model has the best performance with average rank of 1, followed by Black et al., Rietveld, Akinoglu-Ecevit and Glover-McCullock with 5^{th} rank with least performance for the study area. This shows that stone model can be used in Ibadan for the evaluation of solar radiation.

3.4 Model Development for Ibadan

Table 3. Shows the standard parametric results for both linear and quadratic trends summary for the stations. Ibadan has correlation coefficient R of 47% with P value of <0.0001 after the data collected from Ibadan was being calibrated. For the quadratic function Ibadan has 51.3% level of performance at $P<0.0001$.This indicated that the quadratic model equation when used for Ibadan will give average performance.

Appendix

Table 1: Non-parametric Mann-Kendall and Sen's slope test summary statistics.

Time Series	Solar radiation (MJ/m^2) %			Sunshine Hour (hr) %		
	Slope / yr	Test Z	Sig.	Slope / yr	Test Z	Sig.
January	-0.09806	-3.45	***	0.034	1.82	+
February	-0.12531	-4.05	***	0.020	1.84	+
March	-0.09135	-2.87	**	0.034	2.80	**
April	-0.12222	-4.05	***	0.034	2.53	*
May	-0.09495	-3.69	***	0.033	3.00	**
June	-0.10703	-3.80	***	0.035	2.26	*
July	-0.11452	-3.61	***	0.024	0.02	
August	-0.11528	-3.28	**	0.024	2.07	*
September	-0.11953	-3.75	***	0.019	2.24	*
October	-0.11782	-3.42	***	0.033	3.22	**
November	-0.12255	-3.84	***	0.038	2.46	*
December	-0.09113	-3.56	***	0.024	2.12	*
Annual	-0.10353	-4.862	***	0.022	2.89	**

*** Significant at 0.001, **significant at 0.01, * significant at 0.05, $^+$ significant at 0.1

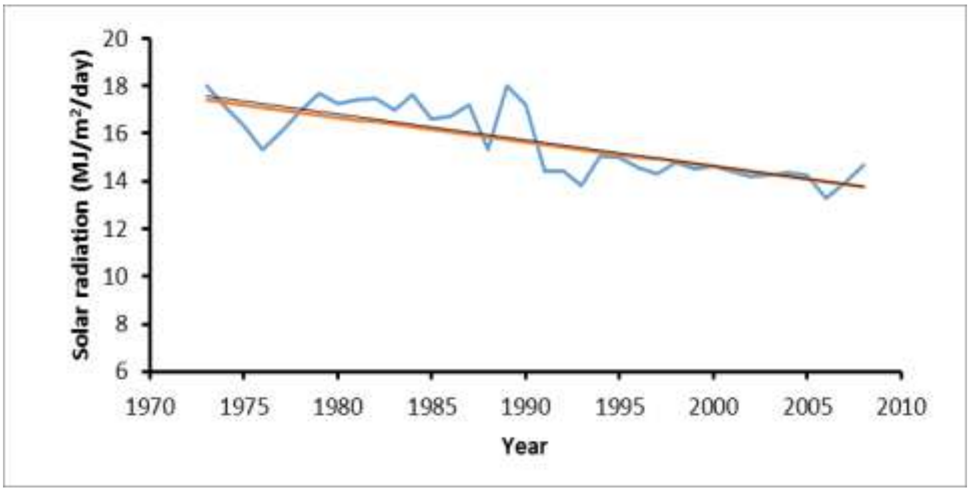

Figure 2: Annual Mean Solar Radiation Trend in Ibadan.

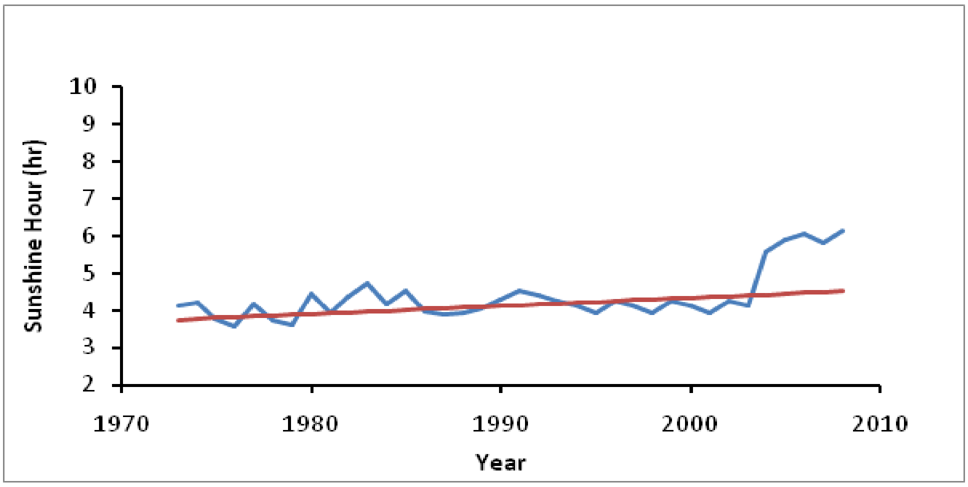

Figure 3: Annual Mean Sunshine Hour (hr) Trend at Ibadan.

Table 2: Summary of Statistical Parameters for Evaluation of Five Solar Radiation Models at Ibadan.

Statistical Parameters	Models				
	Rietveld	**Black et al**	**Stone**	**Akinoglu-Ecevit**	**Glover-McCullock**
MBE	2.275 (3)	1.457 (2)	1.016 (1)	5.207 (4)	96.632 (5)
S^2D	6.677 (3)	5.645 (2)	5.240 (1)	9.385 (4)	22.538 (5)
MAE	2.776 (3)	2.245 (2)	2.033 (1)	5.286 (4)	96.632 (5)
RMSE	3.440 (3)	2.785 (2)	2.502 (1)	6.040 (4)	96.748 (5)
R	0.396 (3)	0.415 (2)	0.436 (1)	0.384 (4)	0.242 (5)
Average Rank	(3)	(2)	(1)	(4)	(5)

Rank Value is given in parenthesis with 1 as the best and 5 as the least performed model.

MBE - Mean Bias Error; S^2D- Measurement of the variability of the difference between the predicted and observed values; MAE - Mean Absolute Error; RMSE - Root Mean square error and r- Correlation Coefficient.

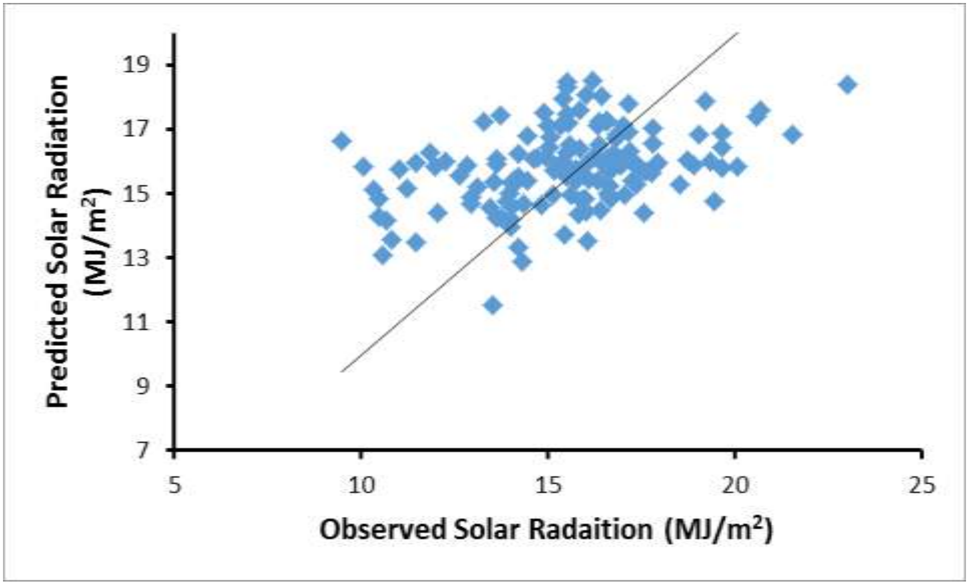

Fig. 4: Comparison between observed and Predicted Solar radiation in Ibadan.

Table 3: Standard Parametric Linear and Quadratic Trends Summary for the Stations.

Stations	Linear trend ($Y = a + bX$)				Quadratic trend($Y = a + bX + cX^2$)				
	a	b	R	P	a	b	c	R	P
Ibadan	0.274	0.322	0.477	<0.0001	0.154	0.790	-15.305	0.513	<0.0001

R is Correlation Coefficient, P is Probability Level.

4.0 CONCLUSION

Five sunshine based regression models for the estimation of monthly mean daily solar radiation were evaluated and ranked according to their degree of accuracies using data collected at IITA Stations located in Ibadan, Nigeria. The models evaluated shows that were significant different in the measured values. A new sunshine based regression model was developed using two-third (⅔) of the data collected from the Ibadan, tested and validated with the statistical parameters.

However, solar radiation is applied in the design of agricultural projects and systems and is also frequently required in the orientation and design of greenhouses, livestock buildings, heating, cooling and crop drying systems. Planning of agricultural operations such as growing, irrigating and crop drying cannot be accomplished without the prior knowledge of solar radiation data.

RECOMMENDATIONS

The recommendations for the studies are as follows;

- There is need for the development of process-based dynamic crop growth model to help in sensitivity analysis of different climate elements in the study area.
- Further work can also be done by using other meteorological data for the evaluation and prediction of solar radiation models in the study area.
- The study can also be carried out in other ecological regions in the country.
- It is recommended for use in the study area.

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