Journal of Natural Sciences Research
ISSN 2224-3186 (Paper) ISSN 2225-0921 (Online)
Vol.3, No.5, 2013

Testing the Performance of Some Empirical Models for Estimating Global Solar Radiation Over Makurdi, Nigeria.

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Abstract

The performance of both temperature and sunshine dependant models were evaluated for the estimation of global solar radiation for Abuja, Nigeria. The variations of the mean monthly, annual temperatures and extraterrestrial solar radiation were estimated and the monthly global solar radiation (R_s) was estimated over eleven years (1990 - 1991, 1995-2003), using three different models: Angstrom (1924), Hargreaves and Sammani (1982) and Garcia (1994) models. Using a performance indicator (standard deviation), the regression constants were obtained for the Angstrom and Garcia models as a = 0.461 and b = 0.605respectively. The estimated solar radiation (R_s) was tested statistically by calculating the standard deviation (SD) to determine which model is more suitable for the simulation of global solar radiation in Abuja. The lowest SD of 1.25, 2.19 and 2.56 were obtained for Hargreaves - Sammani (1982) ; Angstrom (1924) and Garcia (1994) respectively indicating that Hargreaves and Sammani temperature dependent model is more suitable for the simulation of global solar radiation in Abuja and other locations with similar latitudinal variations.

Keywords: Temperature, sunshine hour, sunshine duration, global solar radiation, clearness index

1. Introduction

Knowledge of global solar radiation is essential in the study, prediction and design of the economic viability of systems which use solar energy. The solar radiation reaching the Earth's surface depends upon climatic conditions of a location, which is essential to the prediction and design of a solar energy system (Burari and Sambo, 2001).

Accurate modeling depends on the quality and quantity of the measured data used. Obviously, measured data is the best form of this knowledge. Unfortunately, there are very few meteorological stations that measure global solar radiation, especially in developing countries. For such stations where no measured data are available, a common practice is to estimate global solar radiation from other measured meteorological parameters like relative sunshine durations.

This work hopes to provide empirical models for the estimation of global solar radiation in Abuja, Nigeria. Abuja is the capital city of Nigeria, within the Federal Capital Territory (FCT). Abuja, having an area of about 713 Km^2 is located at latitude $9^o12'$ N, longitude $7^o11'$ E and 1180 feet (360 meters) above sea level.

This work, apart from developing predictive techniques for global solar radiation especially, for regions that encounter difficulties in harnessing solar radiation data due to lack of good equipments, it will help the energy strategists and planners to utilize the solar energy potentials to solve the energy crises of this area of abundant sunshine.

Over the years, many models have been proposed to predict the amount of solar radiation using various parameters. Some works used the sunshine duration, others used mean day time, cloud cover or relative humidity and maximum and minimum temperature, while others used the number of rainy days, sunshine hours and a factor that depends on latitude and altitude (Chegaar and Guechi, 2009 ; Isikwue *et al*, 2012a and b).

However, air temperature is considered as an important climatological variable for solar radiation prediction because it is a reflection of both the duration and the intensity of the solar radiation incident on a given location (Chegaar and Guachi, 2009). Sunshine duration which is one of the most widely measured and applied parameter plays a very major role in the determination of global solar radiation.

In this study, three major formulations whose basic requirement is to utilize temperatures and sunshine duration will be used to develop the models.

Angstrom (1924) and Prescott (1940) developed a correlation model for estimating monthly mean daily global solar radiation on a horizontal surface given as:

$$\frac{R_S}{R_O} = a + b\left(\frac{n}{N}\right) \qquad (1)$$

R_s is the monthly mean daily global solar radiation in MJm^{-2}day^{-1} on a horizontal surface, while R_o is the monthly mean daily extraterrestrial solar radiation (MJm^{-2}day^{-1}), expressed as:

$$R_O = \frac{24(60)}{\pi} G_{sc}\, dr[W_s \sin\emptyset \sin\delta + \cos\emptyset \cos\delta \sin W_s] \qquad (2)$$

G_{sc} is solar constant = 0.0820 MJm^{-2}min^{-1}. The inverse relative Earth – Sun distance, dr [rad] is given by;

$$dr = 1 + 0.033 \cos\left[\frac{2\pi}{365} - J\right] \qquad (3)$$

where J is the number of the day in the year between 1 (1 January) and 365 (December).

N is the daylight hour given as;

$$N = \frac{24W_S}{\pi} \qquad (4)$$

where w_s, which is thee hour angle, is expressed as:

$$W_s = arc \cos[-\tan\emptyset\, tan\delta] \qquad (5)$$

$\emptyset$ and δ are the latitude and declination angles respectively. The declination measured in degree is given as:

$$\delta = 23.45 \sin\left(\frac{360}{365}\right)(284 + d) \qquad (6)$$

where d is the day of the year. R_s are the monthly mean daily global solar radiation (MJm^{-2}day^{-1}). 'a' and 'b' are climatologically determined regression constants.

The regression coefficient 'a' and 'b' were obtained from the relationships given by Tiwari and Sangeeta, (1997) as:

$$a = 0.110 + 0.235 \cos\emptyset + 0.323\left(\frac{n}{N}\right) \qquad (7)$$

$$b = 1.449 - 0.553 \cos\emptyset - 0.694\left(\frac{n}{N}\right) \qquad (8)$$

The physical significance of the regression constants is that 'a' represents the case of overall atmospheric transmission for an overcast sky condition (i.e. $\frac{n}{N}$; while 'b' is the rate of increase of R_s/R_o with $\frac{n}{N}$. The sum of 'a' and 'b' (i.e. a + b) significantly represents the overall transmission under clear sky condition or clear sky index n is the monthly average daily number of hours of bright sunshine, d is the day of year (known as the Julian day).Usually, the solar declination is calculated on the 15th day of each month.

Hargreaves and Sammani (1982) proposed an empirical equation expressed in the form of a linear regression between the clearness index and the square root of ΔT given as:

$$\frac{R_S}{R_O} = a + b\Delta T^{0.5} \qquad (9)$$

ΔT is the difference between maximum and minimum temperature value.

The Hargreaves radiation formula, adjusted and validated at several weather stations in a variety of climate conditions, becomes:

$$R_S = (K_{RS})(R_O)\sqrt{T_{max} - T_{min}} \qquad (10)$$

T_{max} is the maximum air temperature (^{o}C), T_{min} is the minimum air temperature (^{o}C) and K_{RS} is the adjustment coefficient (0.16 to 0.19).

The adjustment coefficient K_{RS} is empirical and differs for "interior" or "coastal" regions. $K_{RS} =$ 0.162 for "interior" and $K_{RS} =$ 0.19 for "coastal" regions. Garcia (1994) model is an adaptation of Angstrom – Prescott with a slight modification described as follows:

$$\frac{R_S}{R_O} = a + b\frac{\Delta T}{N} \qquad (11)$$

Where all the terms assume their usual meanings as already been explained above.

2. Source of Data and Method of analysis

The values of the sunshine hours and the monthly mean (minimum and maximum) air temperature data for twenty years were obtained from the Archives of Nigeria Meteorological Agency, Oshodi, Lagos State.

The monthly mean air temperature, T_{mean} was calculated by taken the average of the difference of T_{min} from T_{max}. The inverse relative Earth – Sun distance (dr), the solar declination (δ) and the sunset hour angle (W_s) were computed from equations (3), (5) and (6) respectively. Subsequently, the extraterrestrial solar radiation was estimated by substituting equations (3), (5) and (6) into equation (2). The regression constants 'a' and 'b' were computed using equation (7) and (8) respectively.

By substituting the regression constants, the extraterrestrial radiationR_o, the sunshine duration hours n, the relative sunshine duration, N into equation (1), the monthly mean global solar radiation, R_s was estimated using Angstrom model. Similarly, substituting these parameters including the difference in Mean air temperature equation (11), the R_s due to Garcia's model was estimated. Finally, the R_s using the Hargreave's model was estimated by substituting $K_{RS} = 0.162$ for "interior" and the values of T_{max} and T_{min} into equation (10).

3. Results

The input parameters for the estimation of monthly mean global solar radiation using Angstrom, Hargreaves and Sammani's and Garcia's models are presented in Tables 1 – 3 respectively, while Table 4 shows the mean monthly variations of clearness index (K_T), given by the ratio $\frac{R_s}{R_o}$ for the three models.

Employing these parameters, the regression constants 'a' and 'b' were evaluated for both the Angstrom model and Garcia model to be a = 0.461 and b = 0.605 respectively.

Figures 1 and 2 show the comparisons in the mean monthly variations of the estimated global solar radiation and mean monthly variations of the clearness index (K_T) respectively, over Abuja, using the three models.

4. Discussions

Figure 1 shows that the Angstrom and the Hargreaves - Sammani models had their peak value of $R_{s,}$ (24.44 MJm^{-2}) and January (24.42 MJm^{-2}) respectively in November, but the least value of 15.14 $MJm^{-2}$was observed in July for both models. On the other hand, the Garcia model showed a peak value of 26.98ast in MJm^{-2} in January and a least value of 19.89 MJm^{-2} in June. Although, the Angstrom model has the same least R_s variation with Garcia model but both Hargreaves and Sammain, and Garcia models have the same variation. This could be due to the fact that the Angstrom model is a sunshine dependent model but both Hargreaves -Sammani, and Garcia models are temperature dependent models.

Figure 2 shows the Mean monthly variations of the clearness index (K_T) using the three models. For the Angstrom model, the K_T was very low for the period July to September, with the lowest value of 0.44 in July. This coincided with the rainy period with possibly highest cloud cover and least sunshine hours. However, the K_T increased to a maximum value of 0.72 in November, when the sunshine hours had increased. Subsequently, the K_T decreased steadily from December to February. Although, there was little or no rain during this period, but the Harmattan laden dust could have obscured the Sun shine, causing a decrease in the sunshine duration n. In addition, the onset of rain in April could have contributed to further reduction in n, thereby causing further decrease in $K_{T.}$ However, because the initial rain in April could have washed out the dust from the air and due to the unsteadiness of the rain from April to June, there was enhancement in n with a corresponding rise in K_T in the months of May and June, after which it decreased sharply due to too much rain.

Considering the behavior of Hargreaves - Sammani models in Figure 2 it could be observed that because the model is the temperature dependent, it followed the increase and decrease trend in temperature. Hence in July, which was marked by lowest temperature due to intense rain, the K_T had the lowest value of approximately 0.44, after which it increased to the highest value of 0.67 in December. And from January, it started decreasing till the lowest value in July. Garcia's model, being temperature dependent, exhibited the same trend as Hargreaves - Sammani models. The highest value of 0.72 was obtained in January.

Using the evaluated regression constants, three new developed models were:

The Angstrom model: $\frac{R_s}{R_o} = 0.461 + 0.605 \left(\frac{n}{N}\right)$ (12)

The Garcia model: $\frac{R_s}{R_o} = 0.461 + 0.605\,\Delta T\ 0.5$ (13)

and the Hargreaves and Sammain model: $R_s = (0.16)(R_o)\sqrt{T_{max} - T_{min}}$ (14)

For each of the models, a performance indicator (standard deviation, SD) was determined. For better performance, the lowest (SD) values are desired. And the lowest value of (SD) of 1.248 were found for the Hargreaves and Sammani (1982) and 2.187 and 2.562 for Angstrom (1924) and Garcia (1994) respectively.

5. Conclusions

Each of the three tested models exhibited some degree of efficiency in the estimation of the global solar radiation in Abuja, Nigeria, although the choice of the desired model would depend on the available parameters. However, due to the small SD obtained in the Hargreaves and Sammani (1982) model, it is hereby recommended for simulating global solar radiation for Abuja, Nigeria.

6. Acknowledgement

We are thankful to the Nigeria Meteorological Agency, Oshodi – Lagos, Nigeria for providing the data used in this work.

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Table 1: Input Parameters for the Estimation of Mean Monthly Global Solar Radiation for Abuja, Nigeria, Using Angstrom Model

Months	n	N	$\frac{n}{N}$	R_o (MJ/m^2/day)	R_s (MJ/m^2/day)
Jan.	7.155	12.451	0.575	37.323	22.078
Feb.	6.764	12.076	0.560	37.514	21.732
March	7.009	11,715	0.598	37.074	22.390
April	6.791	12.485	0.544	36.853	20.829
May	7.755	11.999	0.646	36.952	23.989
June	6.945	11.617	0.598	33.478	20.420
July	4.736	11.770	0.402	35.041	15.430
Aug.	4.727	12.138	0.389	37.070	15.826
Sept.	5.064	12.458	0.406	36.858	16.368
Oct	6.855	12.062	0.569	37.316	21.860
Nov.	8.645	11.680	0.740	34.102	24.440
Dec.	8.109	11.770	0.679	34.885	23.687

Table 2: Input Parameters for the Estimation of Mean Monthly Global Solar Radiation for Abuja, Nigeria, Using Hargreaves and Sammani's Model

Months	T_{max} (^{o}C)	T_{min} (^{o}C)	R_o (MJ/m^2/day)	R_s (MJ/m^2/day)
Jan.	35.267	26.833	37.323	24.423
Feb.	37.010	23.924	37.501	23.831
March	36.724	23.924	36.971	21.373
April	35.461	24.419	36.989	19.679
May	33.219	22.900	36.992	19.067
June	30.767	22.210	33.739	15.847
July	29.271	21.852	34.793	15.140
Aug.	29.076	21.567	36.939	16.108
Sept.	29.976	21.543	36.887	17.067
Oct	31.357	21.357	37.300	18.784
Nov.	34.171	19.448	34.422	21.126
Dec.	34.810	.17.624	34.652	23.026

Table 3: Input Parameters for the Estimation of Mean Monthly Global Solar Radiation for Abuja, Nigeria, Using Garcia's Model

Months	T_{max} (^{o}C)	T_{min} (^{o}C)	R_o (MJ/m^2/day)	R_s (MJ/m^2/day)
Jan.	35.481	18.255	37.323	26.984
Feb.	37.009	20.873	37.514	26.428
March	37.100	23.982	37.074	20.979
April	35.482	24.891	36.853	17.304
May	33.027	23.236	36.954	14.311
June	30.964	22.182	33.478	12.886
July	29.264	21.864	35.041	14.294
Aug.	28.945	21.664	37.070	14.637
Sept.	29.864	21.527	36.858	15.613
Oct	31.273	21.355	37.316	16.230
Nov.	34.273	19.455	34.102	17.823
Dec.	34.884	17.836	34.885	22.083

Table 4: Mean monthly Variations of Clearness Index (KT) for Abuja, Nigeria, Using Angstrom, Hargreaves and Sammani and Garcia's Model

Months	clearness index (K_T)		
Models	Angstrom	Hargreaves Sammani	Garcia's
Jan.	0.592	0.654	0.723
Feb.	0.579	0.635	0.704
March	0.604	0.578	0.565
April	0.565	0.533	0.470
May	0.649	0.515	0.387
June	0.610	0.469	0.385
July	0.440	0.435	0.409
Aug.	0.427	0.436	0.395
Sept.	0.444	0.463	0.424
Oct	0.586	0.504	0.435
Nov.	0.718	0.613	0.530
Dec.	0.680	0.665	0.633

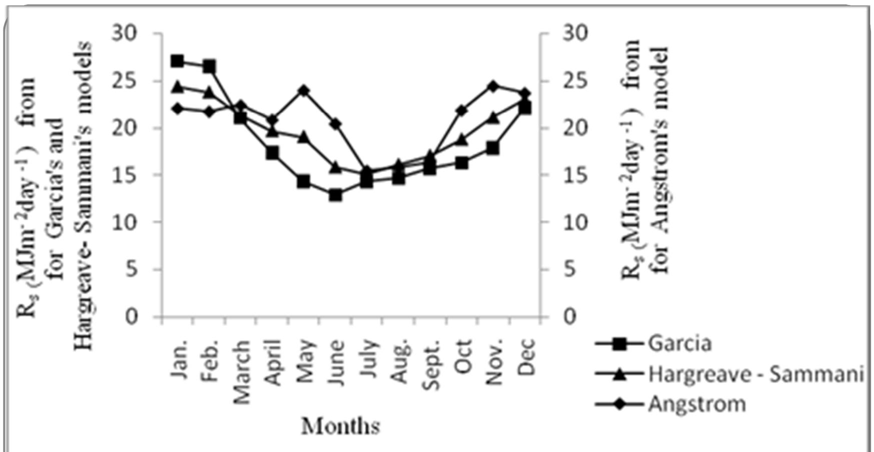

Fig.1: Mean Monthly Variations of the Estimated Global Solar Radiation Using the Three Models.

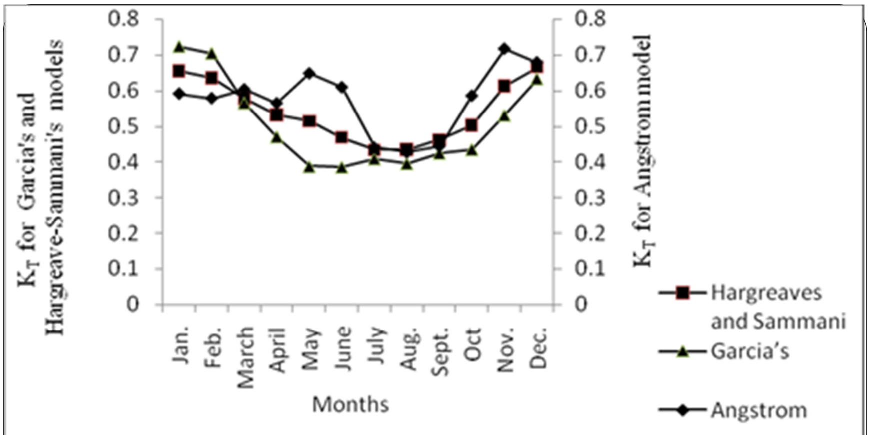

Fig. 2: Mean Monthly Variations of the Clearness Index (K_T) Using the Three Models.

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