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Full Length Research Paper

Performance assessment of Hargreaves model in estimating solar radiation in Abuja using minimum climatological data

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Lack of incident solar radiation is a significant impediment for most related research applications. Mathematical models have been handy in reducing challenges being posed by inability of having solar radiation instrumental sites at every point on the Earth. Hargreaves-Samani's model is one of the several empirical methods so far formulated in estimating global solar radiation (GSR) from maximum and minimum temperature data. Most of these models are often been applied in mid-latitudes. The paper attempts to assess the performance of Hargreaves-Samani's model in the Savanna region using Abuja as the case study. Estimated values of GSR from one month data adapted from Nigeria meteorological Agency (NIMET); using Hargreaves' model shows 90% index of agreement (IA) with the observed values; which suggests a good model performance that has significant correction of about 29%. Concepts are suggested on improving the model performance in the savannah region.

Key words: Global Solar radiation, air temperature, model validation, inversion-layer.

INTRODUCTION

Solar radiation is the largest energy source and is capable of affecting large quantities of events on the Earth's surface including climate, existence and so on. Research outcomes on studies of global solar radiation have facilitated improvement in Agronomy, power generation, environmental temperature controls, etc. Thus, the urgent requirement for daily weather data such as minimum (T_{min}) and maximum (T_{max}) air temperatures, rainfall, and global solar radiation (GSR) become necessary in order to effectively model the tools or mechanisms involved in management of phenomena employing these weather data, such as those mentioned previously (Jagtap and Jones, 2002). The potential amount of radiation that can reach the Earth's surface is determined by its location and time of the year. Due to differences in the position of the sun, the potential radiation differs at various latitudes and in different seasons.

A number of formulae and methods have been developed to estimate GSR at instrumental sites where it is not measured based on other commonly measured meteorological variables or at non-instrumented sites; and most importantly based on cost implications in acquiring, maintaining and mounting solar measuring instruments at every desired point on the Globe. Latha et al. (2011) maintained that these equations range from the most complex energy balance equations requiring detailed climatological data to simpler equations requiring limited data such as Hargreaves-Samani model (1985). The Penman-Monteith (1989) equation is widely recommended because of its detailed theoretical base and its accommodation of small time periods. However, the detailed climatological data required by the Penman-Monteith, are not often available especially in developing nations. For example, in the continent of Africa, there is one such weather station for every three million hectares (Jagtap, 1991). Therefore, models will continue to enjoy wider patronage due to cost implications. Among these

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models, Hargreaves-Samani's (1985) is widely used because it requires only input variable of minimum and maximum air temperatures and many researchers accepted that its GSR estimates correlate well with observed values in many locations (Kra, 2010; Mavromatis and Jagtap, 2003; Liu and Scott, 2001; Hayhoe, 2000; Jegede, 1997).

Many of these models have been used in estimating global solar radiation in the mid-latitudes, where there is appreciable advection condition. Even though most of the models do not account for advection, Salazar (1987) has demonstrated that Hargreaves-Samani (1985) model can successfully be used in advective conditions when calibrated against wind data. However, he opined that any implicit assumption in models could result in significant errors in some conditions. Hargreaves-Samani (1985) model assumes that the difference in maximum and minimum temperature is directly related to the fraction of extraterrestrial radiation (R_a) received at the ground level. However, there are factors other than solar radiation, cloudiness, and humidity that can influence the difference in maximum and minimum temperature in a given location. Other factors include: Latitude, elevation, topography, storm pattern, advection, and proximity to a large body of water (Jagtap, 1991), though some of these factors are taken care of through the extraterrestrial (R_a) term found in the Hargreaves-Samani (1985) model. Therefore, it becomes imperative to equally asses the performances of Hargreaves-Samani model within the Savanna Region due to models are meteorology dependent-which in itself is space dependent.

This research adopted a one month minimum and maximum air temperature data (including its corresponding observed GSR values) from Nigerian Meteorological Agency as an input parameter in order to assess the performance of Hargreaves-Samani (1985) model in estimating GSR within the savanna region.

Hargreaves-Samani equation

Based on the knowledge that the difference between the maximum (T_{max}) and minimum (T_{min}) air temperature is influenced by the degree of cloud cover, humidity and solar radiation; Hargreaves and Samani (1985) used the phenomenon as an indicator of the fraction of extraterrestrial radiation (R_a) that reaches the earth's surface namely global solar radiation (R_s). They formulated a model that is empirical in nature with the form:

$$R_s = K_{Rs}(\sqrt{T_{max} - T_{\min}})R_a \qquad (1)$$

k_{Rs} is adjustment coefficient, which is empirical in nature and has different values for 'interior' and 'coastal' regions. For 'interior' locations, where land mass dominates and air masses are not strongly influenced by a large water body, k_{Rs} is approximately 0.16; for 'coastal' locations, situated on or adjacent to the coast of a large land mass and where air masses are influenced by a nearby water body, k_{Rs} is about 0.19. The extraterrestrial radiation, Ra is given in Hargreaves and Samani (1985) as:

$$R_a = (24(60)/\pi)G_{sc}d_r[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \qquad (2)$$

The terms in Equation (2) are defined as footnote to Table 2. Each of these terms are equations which is fully given in Appendix I.

Hargreaves-Samani (1985) model explicitly accounts for solar radiation and temperature. Although relative humidity is not explicitly contained in the equation, it is implicitly present in the difference in maximum and minimum air temperature. The temperature difference $(T_{max} - T_{\min})$ is linearly related to relative humidity (Hargreaves and Samani, 1985).

MATERIALS AND METHODS

The study area, Abuja is a dry large mass land that is not influenced by any large water body. Abuja lies within the savanna region, in between the extreme climate of high humidity and rainfall of the south; and mass of dry air of the north. The wind speed within this region is averagely 2 ms^{-1} and possibly exhibits inversion properties unlike what is obtainable in the mid-latitudes. Abuja is located between latitude 8.25 and 9.20 north of the Equator and longitude 6.45 and 7.39 east of the Greenwich Meridian. The samples for this study shown in Table 1 were adopted from Nigerian Meteorology Agency carried out between January 1st and 31st, 2009. The samples include minimum (T_{min}) and maximum (T_{max}) air temperatures with their corresponding global solar radiation observed values (O_i). The minimum-maximum thermometer was placed in a Stevenson screen at a height of 10 m from the ground. Table 2 shows the results of Equations (1) and (2) done in Microsoft Excel environment. It includes the extraterrestrial radiation (R_a) and the calculated global solar radiation (R_s) or the predicted values (P_i). Figure 1 is the correlation between the observed and the estimated values.

It is cited in Nath and Patil (2006) that Index of Agreement (IA) was proposed by Willmott (1981) as an alternative to r (correlation coefficient) and r^2 (coefficient of determination). IA is a relative and bounded measure, while r and r^2 are not consistently related to the accuracy of prediction. Willmott and Wicks (1980) observed that the "high" or the statistically significant values of r or r^2 may be misleading as they often are unrelated to the size of difference between observed (O_i) and predicted (P_i) values. IA determines the extent to which mean magnitudes of $\bar{O_i}$ are related to the predicted deviations about O_i, and allows for sensitivity toward differences in O_i and P_i as well as the proportionality changes (Rao et al., 1985). IA is given by

$$IA = 1 - \sum_{n=1}^{n}(P_i - O_i)^2/(|P_i - O_i| + |P_i + O_i|)^2, \quad 0 \le IA \le 1 \qquad (3)$$

Also, Luhar and Patil (1989) had earlier stated that index of agreement IA is a statistical measure of the correlation of the predicted and measured concentrations. The index of agreement calculated for the predicted and observed value in this study is 90%. This shows that there is very good agreement between the observed and predicted values of GSR, indicating a good model performance.

Table 1. Diurnal predicted and observed values in Abuja, January, 2009.

S/N	Predicted Rs (KWH)*	Observed Rs (KWH)#
1	24.78	25.55
2	23.80	26.38
3	25.21	26.20
4	24.87	25.71
5	24.84	25.81
6	26.16	25.09
7	25.59	25.56
8	26.49	25.18
9	23.44	25.16
10	22.97	24.95
11	22.65	24.75
12	20.93	24.85
13	23.46	25.18
14	25.63	24.52
15	25.23	25.15
16	24.75	26.21
17	22.02	25.66
18	21.16	25.16
19	20.11	25.41
20	21.59	25.96
21	20.56	25.70
22	23.01	25.50
23	19.62	25.68
24	22.62	24.84
25	21.34	25.29
26	21.56	25.63
27	19.05	25.73
28	19.45	25.69
29	18.06	25.72
30	18.72	25.52
31	21.00	25.24

* Values calculated using Equation (1) and shown in Table 1; # Values posted by NIMET for the month of January, 2009.

RESULTS AND DISCUSSION

Equation (2) estimates the extraterrestrial radiation (R_a) values for each day in the month of January, 2009. The values are shown in Table 2, which is calculated using equation (2) with the aid of Microsoft Excel software. The mean global solar radiation at the entrance into the earth's atmosphere known as extraterrestrial solar radiation (R_a) obtained for the period at Abuja is 37.23 ± 0.21 $MJm^{-2}day^{-1}$. The predicted mean global solar radiation (GSR), R_s for the month under study is 18.59± 0.41 $MJm^{-2}day^{-1}$ and the observed is 21.35± 2.11 $MJm^{-2}day^{-1}$ for Abuja. The correlation between the predicted and the observed global solar radiation Rs is 79%. The Index of Agreement (a measure of efficiency of a model) between the predicted and the observed monthly GSR values for Abuja is about 90%.

This study has evaluated Hargreaves-Samani model for estimating daily radiation in urban site Abuja using minimum-maximum air temperatures adopted from NIMET. From the correlation and index of agreement results, the model has shown itself to be a robust and reasonably accurate method for estimating GSR also in the savanna region. The quality of these estimates varies with environment (urban-rural) and latitude, yet the errors expressed as RMSE between observed and estimated daily solar radiation were in the range of 0.41 to 2.11 $MJm^{-2}day^{-1}$ and are not sufficiently significant. The model has the tendency to overestimate and under predict the lower and higher range of the observed distribution.

Table 2. Temperature measurement and solar radiation (MJ/m^{-2}/day) Abuja.

S/N	J	Dr (Rad)	δ (Rad)	φ (Rad)	ω_s (Rad)	R_a (Rad)	T_{max} (°C)	T_{min} (°C)	Rs (KWH)
1	1	1.033	0.404	0.156	1.638	39.089	35.2	19.5	24.781
2	2	1.032	0.405	0.156	1.638	39.065	33.4	18.9	23.801
3	3	1.032	0.406	0.156	1.638	39.031	33.1	16.8	25.213
4	4	1.031	0.406	0.156	1.639	38.987	32.9	17.0	24.874
5	5	1.029	0.407	0.156	1.639	38.932	33.5	17.6	24.838
6	6	1.028	0.408	0.156	1.639	38.866	35.4	17.7	26.162
7	7	1.026	0.408	0.156	1.639	38.790	35.3	18.3	25.590
8	8	1.023	0.409	0.156	1.639	38.703	34.8	16.5	26.491
9	9	1.021	0.409	0.156	1.639	38.606	34.4	20.0	23.440
10	10	1.018	0.409	0.156	1.639	38.498	34.9	21.0	22.965
11	11	1.015	0.409	0.156	1.639	38.380	35.3	21.7	22.646
12	12	1.012	0.409	0.156	1.639	38.252	34.6	22.9	20.935
13	13	1.008	0.409	0.156	1.639	38.113	36.2	21.4	23.460
14	14	1.004	0.408	0.156	1.639	37.964	36.4	18.6	25.627
15	15	1.000	0.408	0.156	1.639	37.805	36.1	18.7	25.231
16	16	0.995	0.407	0.156	1.639	37.635	35.3	18.4	24.755
17	17	0.990	0.407	0.156	1.639	37.455	35.0	21.5	22.019
18	18	0.985	0.406	0.156	1.638	37.265	35.1	22.5	21.165
19	19	0.980	0.405	0.156	1.638	37.065	33.6	22.1	20.111
20	20	0.974	0.404	0.156	1.638	36.855	33.4	20.0	21.586
21	21	0.968	0.403	0.156	1.638	36.634	32.5	20.2	20.557
22	22	0.962	0.401	0.156	1.638	36.404	34.4	18.8	23.005
23	23	0.955	0.400	0.156	1.637	36.163	34.7	23.2	19.622
24	24	0.948	0.398	0.156	1.637	35.912	33.9	18.4	22.622
25	25	0.941	0.397	0.156	1.637	35.652	33.0	19.0	21.344
26	26	0.934	0.395	0.156	1.636	35.381	34.6	20.1	21.556
27	27	0.926	0.393	0.156	1.636	35.101	35.2	23.7	19.045
28	28	0.918	0.391	0.156	1.636	34.811	34.0	21.8	19.454
29	29	0.910	0.389	0.156	1.635	34.510	34.1	23.4	18.062
30	30	0.902	0.387	0.156	1.635	34.200	33.7	22.0	18.717
31	31	0.893	0.385	0.156	1.635	33.881	36.7	21.7	20.995

J, number of the day in the year between (1 January) and 365 or 366 (31 December); dr, inverse relative distance Earth-Sun; δ, solar declination; φ, latitude; ωs, solar time angle; Ra, extraterrestrial radiation; T_{max}, maximum air temperature; T_{min}, minimum air temperature; Rs, solar radiation.

Mavromatis and Jagtap (2003) opined that systematic biases at the extremes of the distribution could probably reflect climatic influences on the model other than those associated with daily radiation forcing, such as large-scale advection or persistent cloud cover. In addition, forcing factors that were not included may have a role in the type of models used in this study. For example, dust storms, seasonal burning, grassland fires, and pollution from fires may significantly influence recorded radiation (e.g., Thornton and Running, 1999 cited in Mavromatis and Jagtap, 2003). Biggs et al. (2007) also noted that underlying surface conditions can potentially introduce errors in the estimates. This result need to be re-evaluated with long term data of about five years or more to give it wider acceptance.

The clustering of the scattergram plot of Figure 1 suggests the trend of fairly constant minimum-maximum air temperature witnessed during the month of January within this region. The wind speed is generally low (< 2 m/s) also within this period, advection may not have played any significant role in this result, but other environmental forcing and climatological seasonal uniqueness suggest further validation of the model using five years range of data.

SUMMARY AND CONCLUSIONS

Considering the importance of global solar radiation and other climatological phenomena on the events on the Earth's surface including climate changes, agriculture (in the area of crop modelling), existence and so on, there is

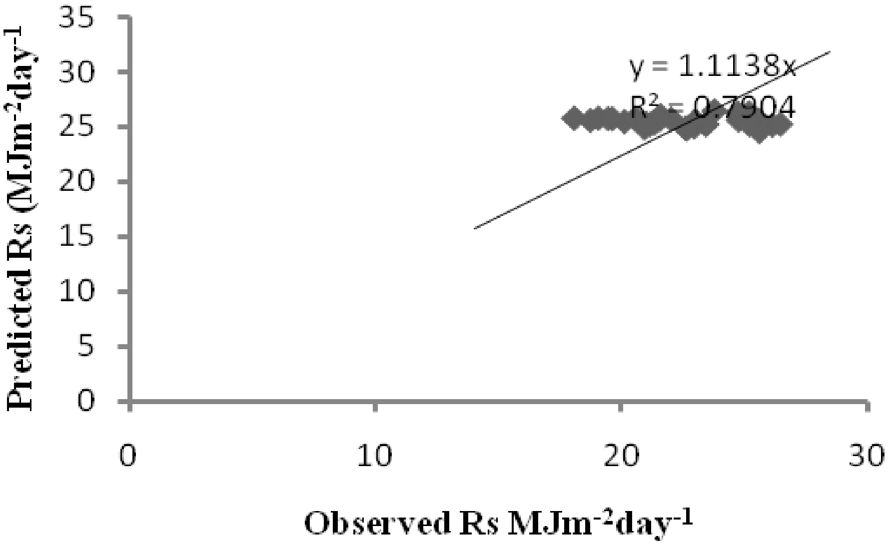

Figure 1. Scattergram plot of predicted and observed global solar radiation Rs.

a need for methods which can estimate these variables with limited data. This paper evaluates one of such methods-Hargreaves-Samani model that estimates solar radiation from latitude and maximum and minimum air temperatures. An adopted minimum-maximum air temperature data from Nigerian Meteorological Agency (NIMET) and used in Hargreaves-Samani model, resulted in predicted values that produced an index of agreement of over 90%. This is an excellent indication that the model performs equally well in the savanna region; a place that the environmental conditions are quite different from that of the mid-latitudes. However, considering the uniqueness of climatological data in each month of a year and other environmental forcings, the model should be subjected to further validation involving several months data running over five years.

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APPENDIX I

Extraterrestrial radiation (R_a) calculation procedure

The extraterrestrial radiation, R_a, for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination and the time of the year by:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)] \quad (1)$$

where R_a is extraterrestrial radiation [MJ m^{-2} day^{-1}];

G_{sc} is solar constant = 0.0820 MJ m^{-2} min^{-1}; d_r, inverse relative distance Earth-Sun (Equation 2), ω_s, sunset hour angle (Equation 4) [rad], φ, latitude [rad], δ, solar declination (Equation 3) [rad].
R_a is expressed in the aforementioned equation in MJ m^{-2} day^{-1}

The inverse relative distance Earth-Sun, d_r, and the solar declination, δ, are given by:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \quad (2)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (3)$$

where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). The sunset hour angle, ω_s, is given by:

$$\omega_s = \arccos\left[-\tan(\varphi) \tan(\delta)\right] \quad (4)$$