Performance Assessment of Hargreaves Model in Estimating Global Solar Radiation in Sokoto, Nigeria

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ABSTRACT

This paper presents, an estimation of daily global solar radiation in Sokoto (latitude $13^{\circ}02N$ and longitude $05^{\circ}15E$) for the year 2009 using Hargreaves model. This estimation was based on latitude and daily minimum and maximum temperature in Sokoto State. The measured and estimated solar radiation data were compared forand analyzed using coefficient of residual mass (CRM), root mean squared error (RMSE), coefficient of determination (R^2) and percentage error (e). The results showed that the value of CRM is 0.04, which indicates the tendency of the estimation model to under-estimate the measure solar radiation. Meanwhile, the value of RMSE was 1.63% and the value of R^2 is 0.8260 which is very closed to 1, indicating that about 82.60% of the total variation is explained in the data. For the percentage error, the value was -3.16%, which indicates that the model estimation is good. The model has shown itself to be a robust and reasonably accurate method for estimating global solar radiation in Sokoto and its environment. However, considering the uniqueness of climatological data in each month of a year, it is recommended that the model should be subjected to further validation involving months of data running over five years.

Keywords: Solar radiation, Temperature, Model, latitude and Percentage error.

1.0 INTRODUCTION

1.1 BACKGROUND OF THE STUDY

In many applications of solar energy, the most important parameters that are often needed are the average global solar irradiation and its components. Unfortunately, the measurements of these parameters are done only at a few places. For this reason there have been attempts at estimating them from theoretical models. Latha et al., mentioned 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 [1-2]. Hargreaves-Samani's 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 [3].

The extraterrestrial solar radiation is the rate at which solar energy arrives on a horizontal surface at the top of the atmosphere. It varies according to the latitude of the location, the distance of the Earth from the Sun, and the time of the year. On any particular day, it varies from zero at sunrise to a maximum at noon and back zero at sunset [4].

Despite the large range of applications demanding solar radiation data, direct measurements of solar energy are not available. Thus use of numerical techniques becomes essential. With such indirect techniques, other meteorological parameters are mathematically exploited in order to estimate the amount of solar radiation reaching the earth surface.

The estimation of daily global solar radiation has been reviewed in most of the researches based on the duration of sunshine, identifying the best model and determining different coefficients for several locations. There are several types of models (linear,

quadratic, third degree polynomial, exponential and logarithmic) in literature for estimating the global radiation from extra-terrestrial irradiance and measured daily sunshine duration.

Akpabio et al., presented a quadratic form of the Angstrom-Prescott model to estimate global solar radiation at Onne (lat. 4°46′N, long. 7°10′E), a tropical location [5].. Ogelman et al. (1984) model, Akinoglu and Fagbenle's (1990) model were compared with the ones developed for the Nigerian environment [5-7]. The results showed that the relationship between clearness index and relative shine in quadratic form is to some extent locality dependent.

Haydar et al. (2006) presented a third-order equation for the calculation of the monthly-average daily global solar radiation for Erzurum, Turkey (lat. 39°55'N, long.41°16'E, altitude 1869m) [8]. Measured data was taken from Turkish State Meteorological Service for four years. Additionally for computing the monthly-average daily global solar radiation, nine models available in the literature were used. The models were examined by three statistical methods, respectively; mean bias error (*MBE*), root mean square error (*RMSE*), and *t*-statistic. It has been concluded that the lowest *RMSE* and *MBE* values were gathered from the third-order equation model and the lowest *t*-statistic value was taken from the model of Ulgen and Hepbasli (2004). Except Tiris' model, all used models were appropriate for calculating the monthly-average daily global radiation in Erzurum due to t-critic value that is 3.106 [9].

Hargreaves and Samani (1982) proposed a simple model to estimate global solar irradiation (H) using the maximum (T_{max}) and minimum (T_{min}) air temperatures and the extraterrestrial solar irradiation (H_o). The Hargreaves-Samani model is based on the correlation between the global atmospheric transmittance ($\tau = H/H_\circ$) and the daily thermal amplitude ($\Delta T = T_{max} - T_{min}$) (Allen, 1997). The application of the Hargreaves-Samani model requires the specification of an empirical coefficient of proportionality (k_r) between τ and $\Delta T^{0.5}$ that depends on the location and altitude of the station [10].

This paper is therefore aimed at assessing the performance of Hargreaves model in estimating global solar radiation in Sokoto State using a one year minimum and maximum air temperature data including its corresponding observed Global solar radiation (GSR) values from Nigerian Meteorological Agency, Sokoto State as an input parameter in order to assess the performance of Hargreaves model in estimating GSR within Sokoto State.

2.0 MATERIALS AND METHODS

2.1. Description of the study area

The location of Sokoto in Nigeria is at latitude $13°02N$ and longitude $05°15E$. Sokoto is in the dry Sahel, surrounded by sandy savannah and isolated hills. Sokoto is a city located in the extreme northwest of Nigeria. Sokoto as a whole is very hot area. The raining season is from June to October during which showers are a daily occurrence. From late October to February, during the cold season, the climate is dominated by the Harmattan wind blowing Sahara dust over the land. The dust dims the sunlight there by lowering temperatures significantly and also leading to the inconvenience of dust everywhere.

2.2 Data Source

In the present work the values of measured data of minimum (T_{min}) and maximum (T_{max}) air temperatures with their corresponding global solar radiation observed values for the period of one year (2009) were obtained from Nigerian Meteorological Agency, Sokoto. The station is standardized weather station in which climatic data are measured primarily for the purpose of aviation.

2.3. Theoretical considerations

Several empirical models exist to evaluate global solar radiation, using available meteorological and geographical parameters such as sunshine duration, difference between the maximum, T_{max}, and the minimum, T_{min} daily temperatures and latitude. In this study, Hargreaves-samani's model was used to estimate the daily mean global solar radiation from maximum and minimum air temperature differences. Hargreaves and Samani (1982) first suggested that the solar radiation (R_s) can be estimated from the difference between maximum and minimum air temperature using a simple equation [11]. They formulated a model that is empirical in nature with the form:

$$R_s = K_{RS}\left(\sqrt{T_{max} - T_{min}}\right)R_a \tag{1}$$

where R_s is in MJ.m^{-2}.d^{-1}; T_{max} and T_{min} are daily maximum and minimum air temperature, in $°C$, respectively, K_{RS} is an empirical coefficient, the value of K_{RS} is approximately 0.16 for interior regions, where land mass dominates and air masses are not strongly influenced by a large water body and is about 0.19 for coastal regions, situated on or adjacent to the coast of a large

mass and where air masses are influenced by a nearby water body; and R_a is extraterrestrial radiation, in MJ.m^{-2}.d^{-1} which is a function of latitude and day of the year. It is given in Hargreaves and samani (1985) as:

$$R_a = \{24(60/\pi)G_{SC}d_r[w_s\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(w_s)]\} \tag{2}$$

Where G_{SC} is solar constant=0.0820 MJ m^{-2} min^{-1}, d_r is inverse relative distance earth-sun, and is obtained by the expression:

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right) \tag{3}$$

Where φ is latitude of the site, and is obtained by the expression:

$$\varphi = latitude \cdot \pi/180 \tag{4}$$

and δ is solar declination, and is obtained by the expression:

$$\delta = 0.409\sin\left(\frac{2\pi}{365} - 1.39\right) \tag{5}$$

W_s is sunset hour angle, and is obtained by the expression:

$$w_s = arccos[-\tan(\varphi)\tan\delta] \tag{6}$$

J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December).

Daily estimated solar radiation (R_{sest}) values were compared with measured (R_{smea}) values. To assess the predictive accuracy for daily solar radiation estimation, four performance indicator were used, namely, coefficient of residual mass (*CRM*), root mean squared error (*RMSE*), Nash–Sutcliffe equation (*NSE*) and percentage error (*e*) expressed as a percentage of the arithmetic mean of the measured solar radiation [12].

The *CRM* indicates overall under- or over estimation. For perfect estimation, the value of *CRM* would be zero. A positive value of *CRM* indicates the tendency of the estimation model to under – estimate the measured solar radiations, whereas, a negative *CRM* indicates a tendency to over-estimate the measured solar radiations. The calculation of *CRM* is given by

$$CRM = \frac{\sum_{i=1}^{n} R_{smea,i} - \sum_{i=1}^{n} R_{sest,i}}{\sum_{i=1}^{n} R_{smea,i}} \tag{7}$$

Where, $R_{smea,i}$ is the measured daily solar radiation at *i* day, $R_{sest,i}$ is the estimated daily solar radiation at *i* day, $R_{smea,i}$ is the average measured solar radiation and n is the day number of estimated solar radiation.

The *RMSE* is expressed as percentage to make it dimensionless, a lower value of it indicates better performance. The calculation of *RMSE* is given by:

$$RMSE(\%) = \frac{\sum_{i=1}^{n} R_{sest,i} - \sum_{i=1}^{n} R_{smea,i}}{\sum_{i=1}^{n} \bar{R}_{smea,i}} \tag{8}$$

The *NSE* is also known as coefficient of determination (R^2), a model is more efficient when *NSE* is closer to 1 when all the estimated solar radiations match perfectly with the measured ones. A lower value (close to zero) of *NSE* indicates poor performance of the estimation model used and a negative value indicates that the estimated solar radiations are worse than simply using measured mean. The R*NSE* is given by

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(R_{smea,i} - R_{sest,i}\right)^2}{\sum_{i=1}^{n}\left(R_{smea,i} - \bar{R}_{smea,i}\right)^2} \tag{9}$$

A relative percentage error between -10% and +10% is considered acceptable. The mean percentage error can be defined as the percentage deviation of the estimated and measured monthly average daily solar radiation. The calculation of *e* is given by

$$e(\%) = \frac{R_{smea,i} - R_{sest,i}}{R_{smea,i}} \tag{10}$$

3.0 RESULTS AND DISCUSSION

Figures 1.0 to 12.0 presents the results of Daily measured global solar radiation versus predicted solar radiation for the months of the year 2009 while figure 13.0 presents the results of monthly-averaged daily global solar radiation for 2009.
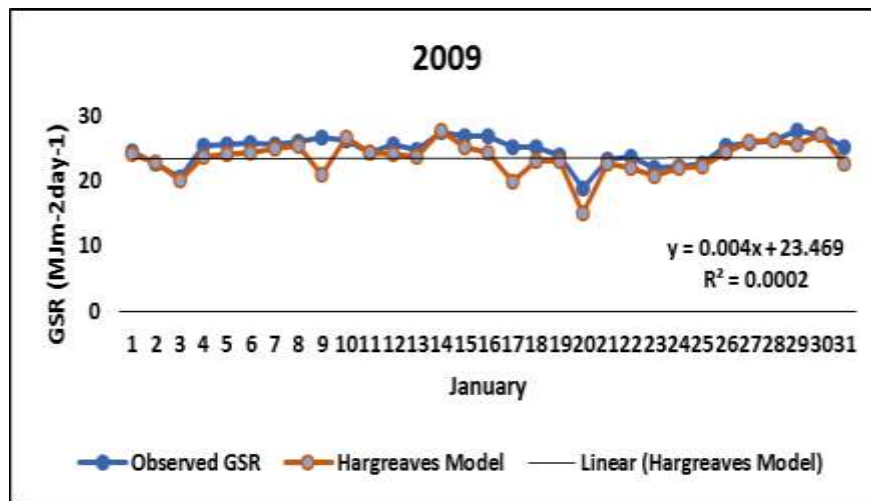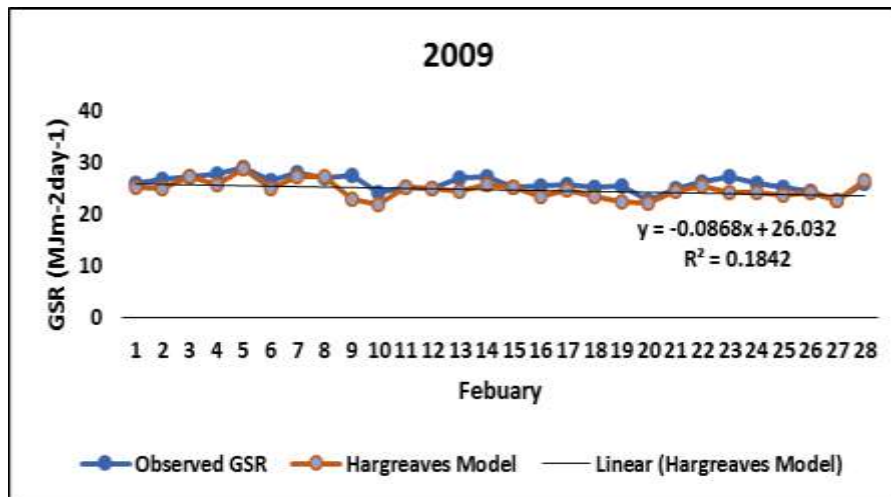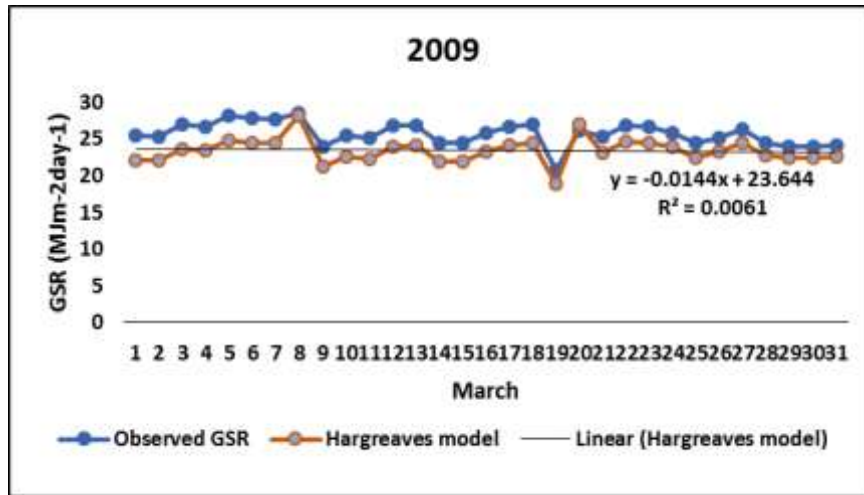

Figure 1.0. Daily measured global solar radiation versus predicted solar radiation for January, 2009.

Statistical analysis results: CRM = - 0.0516, RMSE (%) = 3.17,

R^2 = 0.6616 & e (%) = -5.22

Figure 2.0 . Daily measured global solar radiation versus predicted solar radiation for February, 2009.

Statistical analysis results: CRM = - 0.0459, RMSE (%) = 1.67,

R^2 = 0.5196 & e (%) = - 4.55

Figure 3.0 . Daily measured global solar radiation versus predicted solar radiation for March, 2009.

Statistical analysis results: CRM = - 0.0899, RMSE (%) = 2.48,
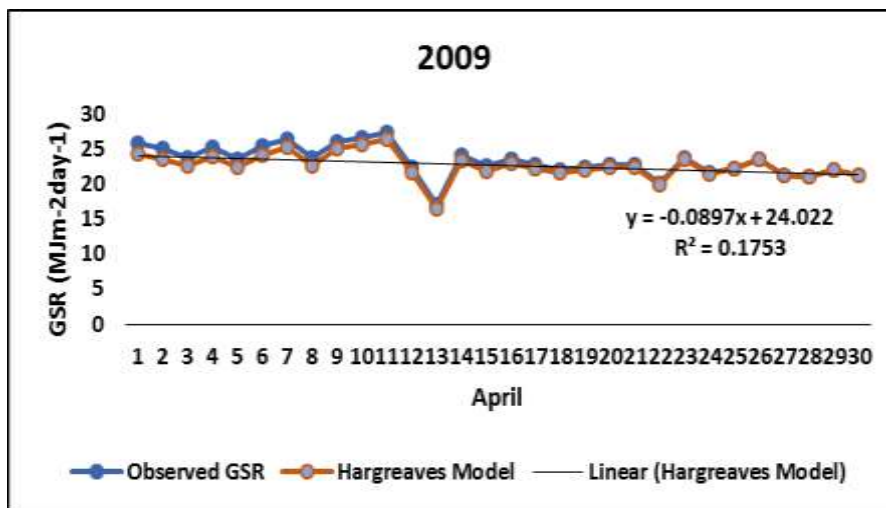
R^2 = 0.7171 & e (%) = - 8.98

Figure 4.0 . Daily measured global solar radiation versus predicted solar radiation for April, 2009.

Statistical analysis results: CRM = 0.0276, RMSE (%) = 0.81,
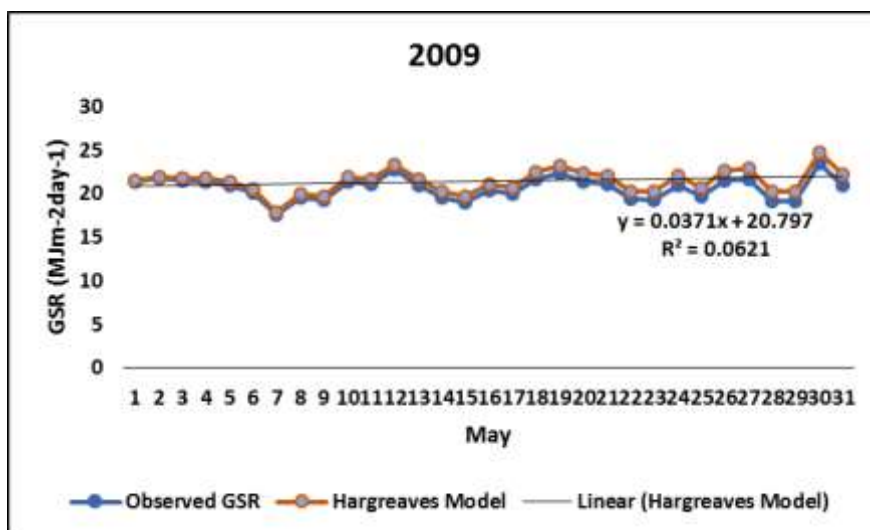
R^2 = 0.9602 & e (%) = - 2.65

Figure 5.0 . Daily measured global solar radiation versus predicted solar radiation for May, 2009.

Statistical analysis results: CRM = 0.0348, RMSE (%) = 0.79,
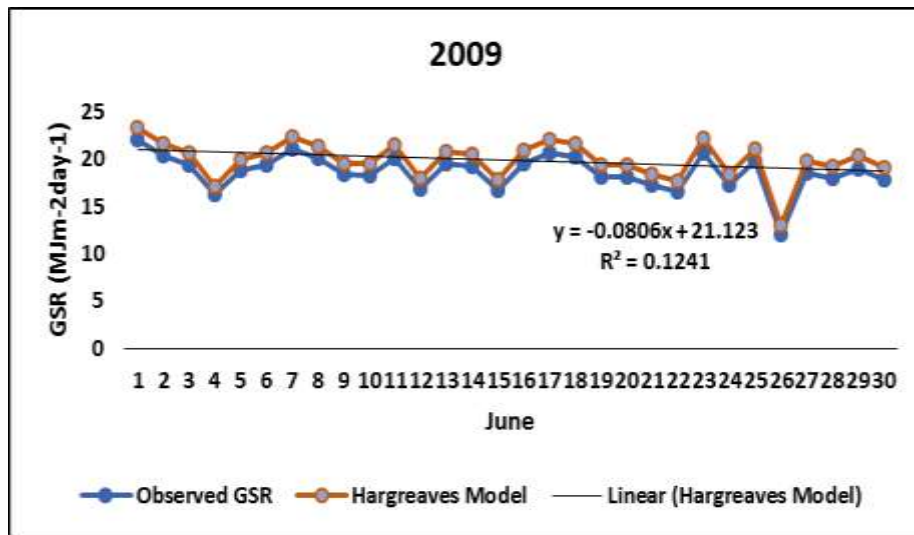
R^2 = 0.9449 & e (%) = 3.48

Figure 6.0 . Daily measured global solar radiation versus predicted solar radiation for June, 2009.

Statistical analysis results: CRM = 0.0653, RMSE (%) = 1.22,
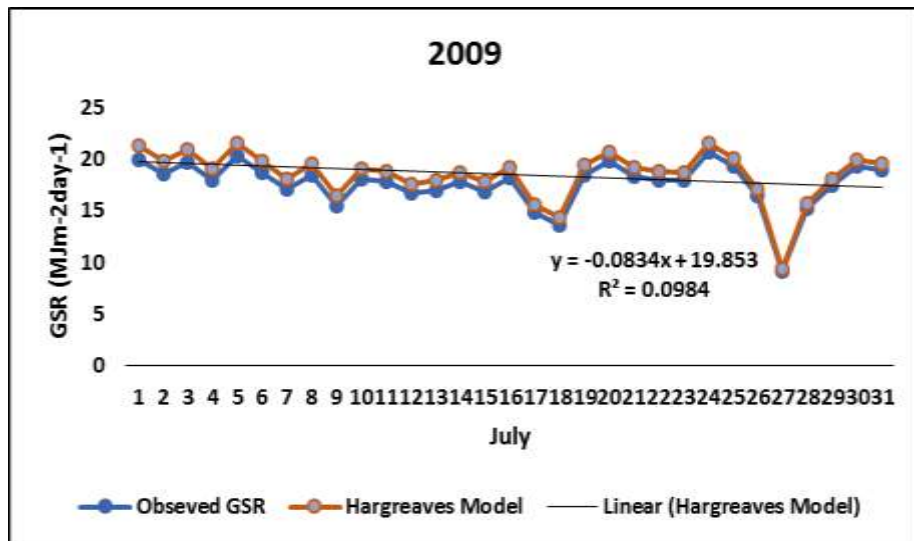
R^2 = 0.9991 & e (%) = 6.54

Figure 7.0 . Daily measured global solar radiation versus predicted solar radiation for July, 2009.

Statistical analysis results: CRM = 0.0506, RMSE (%) = 0.93,
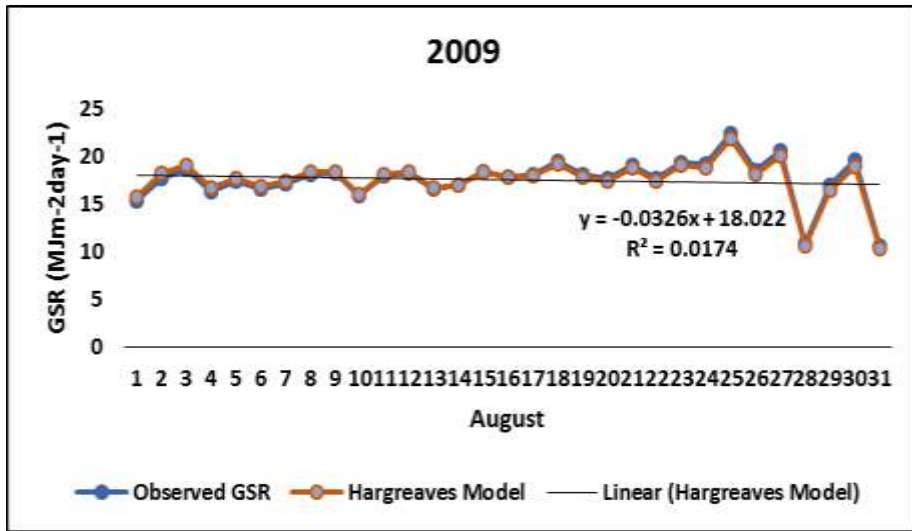
R^2 = 0.9940 & e (%) = 5.05

Figure 8.0 . Daily measured global solar radiation versus predicted solar radiation for August, 2009.

Statistical analysis results: CRM = - 0.0027, RMSE (%) = 0.34,

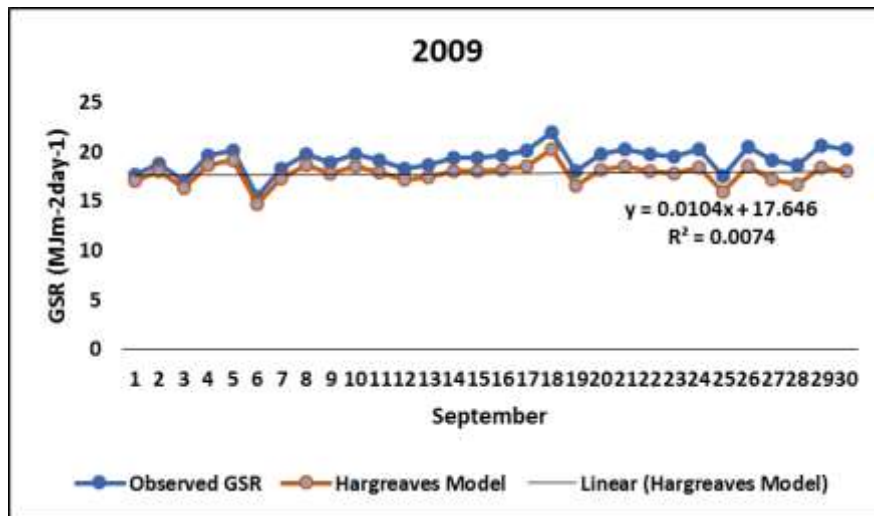R^2 = 0.9773 & e (%) = 0.26

Figure 9.0 . Daily measured global solar radiation versus predicted solar radiation for September, 2009.

Statistical analysis results: CRM = - 0.0727, RMSE (%) = 1.46,

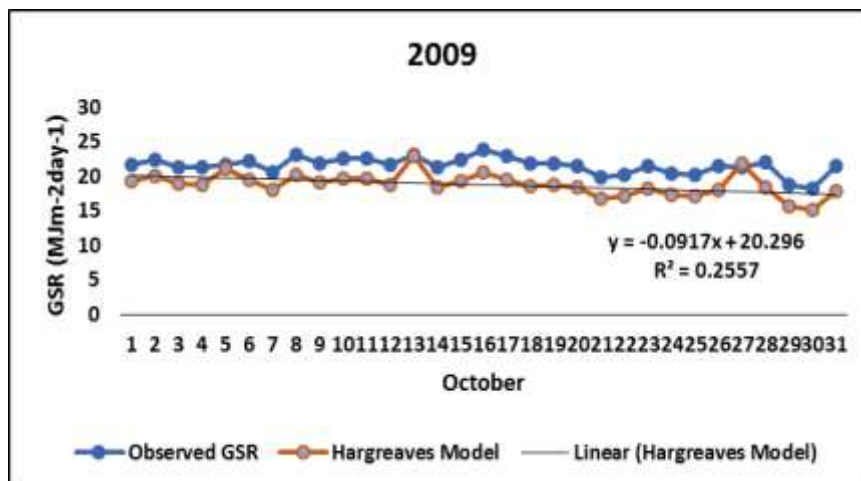R^2 = 0.8814 & e (%) = -7.21

Figure 10.0 Daily measured global solar radiation versus predicted solar radiation for October, 2009.

Statistical analysis results: CRM = - 0.1267, RMSE (%) = 2.89,
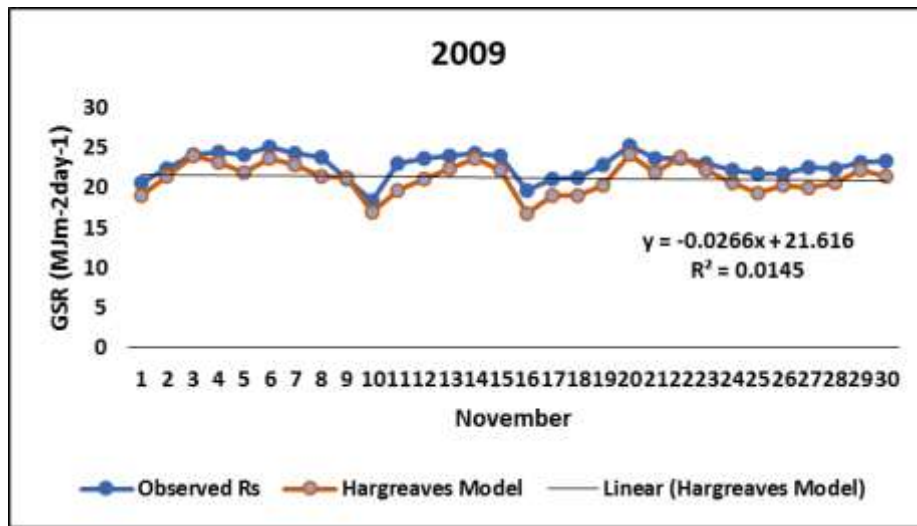
R^2 = 0.6631 & e (%) = 12.75

Figure 11.0   Daily measured global solar radiation versus predicted solar radiation for November, 2009.

Statistical analysis results: CRM = - 0.0716, RMSE (%) = 1.84,
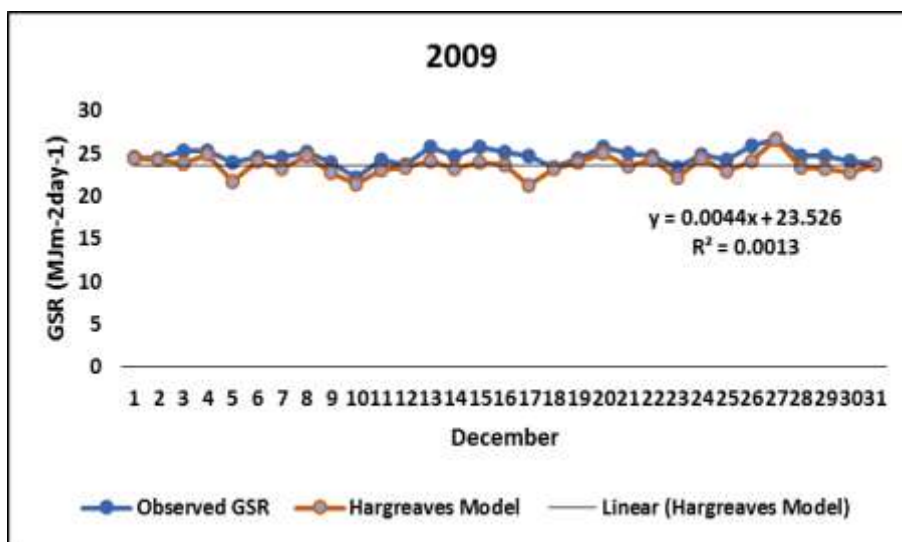
R^2 =0.8132 & e (%) = - 7.24

Figure 12.0 . Daily measured global solar radiation versus predicted solar radiation for December, 2009.

Statistical analysis results: CRM = -0.0416, RMSE (%) = 1.26,

R^2 = 0.5407 & e (%) = -4.15

As can be seen from Statistical analysis results, the accuracy of the model in the estimation of global solar radiation in Sokoto for the year 2009 was tested by calculating the coefficient of residual mass (CRM), root mean square error (RMSE%), coefficient of determination (R^2) and percentage error (e%) from equations (7), (8), (9) and (10) respectively. It is observed that the lower the RMSE, the more accurate the model. Positive CRM shows under estimation and a negative CRM shows over estimation.

Furthermore, the Figures showed the monthly mean daily global solar radiation estimated by Hargreaves model in addition to measured data. Clearly, there exist a good correlation between the measured and predicted global solar radiation. However, the predicted global solar radiation overestimated the measured in the months of January, February, March, August, September, October, November and December and is underestimated in the months of April, May, June and July.
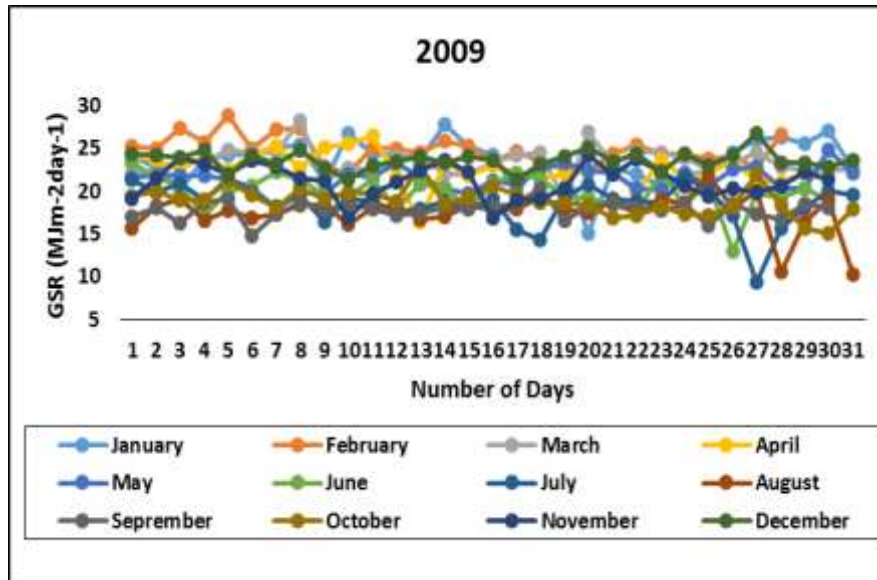
Figure 13.0 . The graph of monthly-averaged daily global solar radiation for 2009.

Also, figure 13 indicates that the model is suitable for calculating daily averaged global solar radiation. In addition, statistical analysis result for the daily averaged predicted solar radiation from January to December for the year 2009 indicates that the value of CRM is 0.04, this indicates the tendency of the model to underestimate the overall daily observed values for the year. Meanwhile, the value of RMSE is 1.63%, shows the percentage error is small. The value of R^2 is 0.8260, closed to 1 indicates that about 82.60% of the total variation is explained in the data and the value of e is small, about -3.16% which is within the acceptance range of -10% to +10%. The model has shown itself to be a robust and reasonably accurate method for estimating global solar radiation in Sokoto.

4.0 CONCLUSION

According the results obtained from the four performance indicators used namely coefficient of residual mass (CRM), root mean squared error (RMSE), Nash-Sutcliffe equation (NSE) and percentage error (e) to compare the daily estimated solar radiation from the daily measured temperature with measured values, the Hargreaves model can be used successfully to estimate daily GSR values in Sokoto State with relative accuracy.

5. RECOMMENDATION

Global solar radiation and other climatological phenomena are important on the events on the earth's surface including climate changes, Agriculture, existence, designing of any solar energy device and so on, there is a need for methods which can estimates these variables with limited data. However, considering the uniqueness of climatological data in each month of a year, the model should be subjected to further validation involving months of data running over five years.

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