ESTIMATING GLOBAL SOLAR RADIATION FROM TEMPERATURE DATA IN MINNA LOCATION

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Abstract

Information on the availability of solar radiation at a location is an important factor in selecting suitable solar energy system and devices for various applications. Maximum and minimum temperature data measured in Minna (09.65°N, 06.47°E), Niger state, for a period of thirteen years (2000 – 2012), were used to establish Angstrom-type regression equations (models) for estimating the global solar radiation received on a horizontal surface in Minna. The results of the correlation were also tested for error using statistical test methods of the mean bias error, MBE, root mean square error, RMSE, and mean percentage error, MPE, to assess the performance of the models. It was observed that temperature data could be used to estimate, (to a very reasonable accuracy), the total solar radiation incident on a location.

Keywords: Estimating, global solar radiation, maximum, minimum, temperature

1. Introduction

The world-wide quest for renewable and sustainable energy has provided the spur for increased research in the assessment and harnessing of available solar energy in any given locality. Solar energy is the renewable radiation energy of the sun and it is fast becoming an alternative to other conventional sources of energy (Nwokoye and Ike, 2003).

Fossil fuel energy resources have now been known to be finite in nature and by the rate of its demand and use, it is feared that the world would soon run out of its energy resources. In addition, the negative impact of fossil fuel energy resources on human and global environment (by way of gaseous emissions that pose serious threat to life and global climate), has invigorated search for clean, abundant and renewable energy to meet the unlimited energy needs of man (Agbo and Oparaku, 2006; Omubo-Pepple, Israel-Cookey and Alaminokuma, 2009; Ohijeagbon, Adekunle and Awolaran, 2009; Bello, Makinde and Sulu, 2010).

Among the various types of clean and renewable sources, solar energy appears to be the most favoured option because of its infinite and non-polluting nature. According to Bolaji (2005), solar energy is an ideal alternative source of energy because it is abundant and inexhaustible.

Solar energy availability is quite abundant in Nigeria because of its tropical location; hence Nigeria is viable for solar energy technology applications (Nwokoye, 2006). Solar energy is received on any surface as solar radiation. But the amount that is received by any horizontal surface in Nigeria depends on the geographical latitude of such surface and therefore varies from place to place. It is greatest in the Northern part with drier weather conditions than the more humid southern part.

Light and heat are the commonest indicators of solar energy radiation on earth's surface. Light is measured with light meters while heat is measured with thermometer which indicates the temperature of an object as a measure of the heat content of that object. Therefore, temperature is a meteorological or climatological indicator which can be used to quantify the size of solar radiation at a given location.

Since solar radiation measurement is not having total coverage for all locations in most developing nations such as Nigeria, it has become a commonplace to extrapolate solar radiation reaching a surface from meteorological indicators like sunshine hours, temperature, relative humidity and rainfall, to name but a few (Togrul, 2009). In this regard, several researchers have employed simple empirical equations of the Angstrom-type to correlate measured global solar radiation reaching a horizontal surface with different meteorological parameters to estimate the total solar radiation at such location.

Angstrom (1924) used the ratio of the measured solar radiation, $\overline{H}_m$ to mean clear sky solar radiation, $\overline{H}_c$ as the dependent variable and the ratio of the bright sunshine hours, $\overline{n}$, to the maximum possible bright sunshine hours or the day length, $\overline{N}$, as the independent variable of the correlation. Prescott (1940), however, modified the Angstrom equation to a more convenient form replacing the mean clear sky radiation with extraterrestrial solar radiation.

Apart from using the fraction of sunshine hours, researchers have used temperature data as independent variables for the correlation technique (Iheonu, 2001; Sanusi, 2004; Chiemeka, 2008; Falayi and Rabiu, 2008; Ekpe and Nnabuchi 2012).

This paper aims at using temperature data measured in Minna for a period of thirteen years (2000 – 2012), as an independent variable for the Angstrom-type correlation, to generate empirical equations for calculating the global solar radiation in Minna. The solar radiation data obtained from these correlations will be tested for error using the popular error test methods of the mean bias error MBE, root mean square error RMSE and mean percentage error, MPE to compare the measured with the calculated values. The best performed model (equation) from this test will be recommended for predicting global solar radiation in Minna.

1. Materials and Methods

Meteorological data comprising of Gunn-Bellani radiation and maximum and minimum temperatures, measured in Minna for thirteen years period (2000 – 2012) were obtained from Nigerian Meteorological Agency of the Federal Aviation Authority, Minna. The Gunn-Bellani radiation data in millimetres, which relate the volume of liquid distilled by solar radiation to the amount of solar radiation reaching a horizontal surface, were first converted to solar radiation intensity unit of $MJm^{-2}day^{-1}$ using the conversion factor of 1.216 ($MJ^{-2}day^{-1}$) proposed by Ododo (1994). This data represents the measured global solar radiation, $\overline{H}_M$, for the experimental period. The monthly mean daily values of the converted Gunn-Bellani and temperature data were also determined. Again, the monthly mean daily extraterrestrial solar radiation (radiation intensity outside the earth's atmosphere), $\overline{H}_O$, values were calculated.

These processed data ($\overline{H}_M$, $\overline{H}_O$, and temperature data), were used to form Angstrom-Prescott type correlation models (equations) for estimating global solar radiation on a horizontal surface in Minna.

The Angstrom-Prescott regression model was given by Igbal (1983) as:

$$\frac{\overline{H}_M}{\overline{H}_O} = a + b\left(\frac{\overline{n}}{\overline{N}}\right) \quad (1)$$

where $\frac{\overline{H}_M}{\overline{H}_O}$ is the clearness index K_T, $\frac{\overline{n}}{\overline{N}}$ is the fraction of sunshine, a and b are regression constants.

The values of the mean extraterrestrial solar radiation $\overline{H}_O$ and day length $\overline{N}$ as in equation (1) were calculated for the fifteenth day of the month as given by Igbal (1983), Duffie and Beckman (1991) and Nwokoye (2006):

$$\overline{H}_O = \frac{24}{\pi} I_{sc} E_o \left(\frac{\pi}{180} w_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s\right) \quad (2)$$

where I_{sc} is the solar constant in (MJm^{-2}-day), expressed as:

$$I_{sc} = \frac{1367 * 3600}{1000000} \text{MJm}^{-2} \text{day}^{-1} \quad (3)$$

E_o is the eccentricity correction factor, expressed as:

$$E_o = 1 + 0.033 \cos\left(\frac{360N}{365}\right) \quad (4)$$

w_s is the hour angle, expressed as:

$$w_s = \cos^{-1}(-\tan\varphi \tan\delta) \quad (5)$$

φ and δ are the latitude and declination angles respectively.

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

where N is the characteristic day number for each month: N = 1 on 1st January to 365 on 31st December.

The mean day length $\overline{N}$ is expressed as:

$$\overline{N} = \frac{2}{15} w_s \quad (7)$$

The expressions for the MBE ($\text{MJm}^{-2}\text{day}^{-1}$), RMSE ($\text{MJm}^{-2}\text{day}^{-1}$), and MPE (%) as stated by El-Sebaii and Trabea (2005) are:

$$MBE = \frac{\left[\sum(\overline{H}_{i,cal} - \overline{H}_{i,meas})\right]}{n} \quad (8)$$

$$RMSE = \left[\frac{\sum(\overline{H}_{i,cal} - \overline{H}_{i,meas})^2}{n}\right]^{½} \quad (9)$$

$$MPE = \frac{\left[\sum\left(\frac{\overline{H}_{i,meas} - \overline{H}_{i,cal}}{\overline{H}_{i,meas}} \times 100\right)\right]}{n} \quad (10)$$

where $\overline{H}_{i,cal}$ and $\overline{H}_{i,meas}$ are the ith calculated and measured values respectively, of solar radiation. n is the total number of observations. MBE provides information on the long-term performance of models. A positive and a negative value of MBE indicate the average amount of over estimation and under estimation in the calculated values, respectively.

RMSE provides information on short-term performance of the models. It is always positive. The demerit of this parameter is that a single value of high error leads to a higher value of RMSE. MPE test provides information on long-term performance of the examined regression equations. A positive and a negative value of MPE indicate the average amount of over estimation and under estimation in the calculated values, respectively.

It is recommended that a zero value for MBE is ideal while a low RMSE and low MPE are desirable (Igbal, 1983; Akpabio and Etuk, 2003).

Table 1 shows the monthly mean daily solar radiation and temperature data for Minna between 2000 and 2012. Table 2 shows the models used for this study.

Table 1 Monthly mean daily solar radiation and temperature data for Minna (2000 - 2012)

Month	$\overline{T}_{max}$ (°C)	$\overline{T}_{min}$ (°C)	$\frac{\overline{T}_{min}}{\overline{T}_{max}}$ (θ)	$\overline{H}_M$ (MJm^{-2}day^{-1})	$\overline{H}_O$ (MJm^{-2}day^{-1})	Clearness index $\overline{K}_T = \frac{\overline{H}_M}{\overline{H}_O}$	$\frac{\overline{n}}{\overline{N}}$
Jan.	34.6	20.6	0.60	16.5	32.1	0.5137	0.5866
Feb.	37.2	23.3	0.63	17.3	34.6	0.5013	0.6456
Mar.	38.7	25.6	0.66	18.3	37.0	0.4953	0.5917
Apr.	36.8	25.3	0.69	18.3	37.9	0.4825	0.6047
May	33.8	24.1	0.71	17.5	37.4	0.4664	0.5893
Jun.	31.3	22.5	0.72	16.2	36.8	0.4409	0.4557
Jul.	29.8	22.1	0.74	15.0	37.0	0.4060	0.3883
Aug.	28.9	22.0	0.76	14.4	37.5	0.3830	0.3483
Sep.	30.0	21.6	0.72	16.7	37.1	0.4496	0.5028
Oct.	31.9	21.9	0.69	18.0	35.1	0.5125	0.6245
Nov.	35.1	20.5	0.58	18.4	32.6	0.5655	0.7732
Dec.	35.7	19.8	0.56	16.6	31.2	0.5325	0.6943

Table 2 Proposed models for this study

1. $\frac{\overline{H}}{\overline{H}o} = a + b\left(\overline{T}_{max}\right)$
2. $\frac{\overline{H}}{\overline{H}o} = a + b\left(\overline{T}_{max}\right) + c\left(\overline{T}_{max}\right)^2$
3. $\frac{\overline{H}}{\overline{H}o} = a + b\left(\overline{T}_{min}\right)$
4. $\frac{\overline{H}}{\overline{H}o} = a + b\left(\overline{T}_{min}\right) + c\left(\overline{T}_{min}\right)^2$
5. $\frac{\overline{H}}{\overline{H}o} = a + b\,(\theta)$
6. $\frac{\overline{H}}{\overline{H}o} = a + b\,(\theta) + c\,(\theta)^2$
7. $\frac{\overline{H}}{\overline{H}o} = a + b\,(\theta) + c\,(\theta)^2 + d(\theta)^3$

Models 1, 3 and 5 are linear single-parameter correlations. Models 2 and 4 and 6 are quadratic correlations while model 7 is cubic correlation. Tmax and Tmin are maximum and minimum temperatures respectively while θ is temperature ratio (Tmin/Tmax).

3. Results and Discussion

Table 3 Models obtained for the study

1. $\frac{\overline{H}}{\overline{H}o} = 0.093 + 0.011\left(\overline{T}_{max}\right)$
2. $\frac{\overline{H}}{\overline{H}o} = -3.386 + 0.220\left(\overline{T}_{max}\right) - 0.003\left(\overline{T}_{max}\right)^2$
3. $\frac{\overline{H}}{\overline{H}o} = 0.625 - 0.007\left(\overline{T}_{min}\right)$
4. $\frac{\overline{H}}{\overline{H}o} = 5.689 - 0.453\left(\overline{T}_{min}\right) + 0.010\left(\overline{T}_{min}\right)^2$
5. $\frac{\overline{H}}{\overline{H}o} = 0.955 - 0.709\,(\theta)$
6. $\frac{\overline{H}}{\overline{H}o} = -0.987 + 5.256(\theta) - 4.536\,(\theta)^2$
7. $\frac{\overline{H}}{\overline{H}o} = 0.147 + 3.537\,(\theta)^2 - 4.110(\theta)^3$

Table 4 Monthly mean daily measured and predicted values of global solar radiation

Month	**Hm**	H_1	H_2	H_3	H_4	H_5	H_6	H_7
Jan	16.48	15.19	20.36	15.42	19.24	17.07	17.14	17.11
Feb	17.32	17.34	22.35	15.96	19.47	17.62	18.14	18.11
Mar	18.31	19.18	23.46	16.48	23.89	17.97	18.67	18.67
Apr	18.28	18.87	24.53	16.97	23.84	17.72	18.29	18.31
May	17.45	17.41	23.32	17.08	21.67	16.86	17.08	17.11
Jun	16.24	16.10	20.66	17.20	20.58	16.36	16.40	16.43
Jul	15.01	15.54	18.63	17.40	20.78	15.87	15.39	15.38
Aug	14.35	15.40	17.48	17.65	21.10	15.57	14.46	14.39
Sep	16.67	15.70	19.13	17.56	21.11	16.49	16.55	16.57
Oct	17.98	15.56	20.28	16.54	19.78	16.38	16.90	16.92
Nov	18.41	15.59	20.83	15.68	19.70	17.61	17.43	17.41
Dec	16.59	15.12	20.07	15.15	19.91	17.48	16.61	16.64

From Table 1, it is observed that the highest and lowest temperatures occurred in March and December, respectively. This is expected, since the month of March is characterized by heavy sunshine and dry atmosphere, and the month of December is characterized by harmattan haze which greatly reduces the intensity of solar radiation (Babatunde, 2001; Ekpe and Nnabuchi, 2012). It is also observed that global solar radiation was highest in the month of November while the lowest value was recorded in August. This is attributed to the highest and lowest values of clearness index obtained for these months, respectively. This again, is expected as the mean daily relative sunshine value is highest in November and lowest in August.

Table 3 indicates the regression constants obtained for each of the seven models used. From Table 4, it is observed that the values of the global solar radiation predicted by models 1, 5, 6 and 7 are closely related to the measured values. The values predicted by models 2, 3 and four are either highly overestimated or underestimated. This again, is reflected in Table 5, where the MBE and RMSE values are lowest for models 1, 5, 6 and 7. Also the MPE values for these models are low with the exception of model 1 which indicates overestimation. Models 2 and 4 have the highest MBE, RMSE and MPE values and therefore are the worst performed models. Models 1, 5, 6 and 7 are adequately fit for predicting global solar radiation in Minna.

Figures 1 to 7 show the comparison between the measured and predicted values of global solar radiation. It is seen in Fig. 1 that model 1 underestimated the global solar radiation in the months of January, September, October, November and December and overestimated in the month of August. A high level of overestimation was observed throughout the months of the year in Figures 2 and 4. It is observed in Fig. 3 that model 3 indicates underestimation from the months of January to April and from

October to December. It also indicated overestimation from June to September. Figure 5 indicates overestimation in August and underestimation in October by model 5. As shown in Figures 6 and 7, models 6 and 7 indicate overestimation in February and underestimation in October and November. Therefore, both quadratic and cubic models using temperature ratio as the independent variable, are the best models for predicting global solar radiation in Minna location.

Table 5 statistical error indicators of the models

Models	R	R^2	MBE	RMSE	MPE
1	0.704	0.495	-0.50917	1.325317	2.795879
2	0.862	0.743	3.998472	4.202236	-23.5965
3	0.228	0.052	-0.33428	1.782569	1.248158
4	0.643	0.413	3.997332	4.333162	-24.1678
5	0.894	0.799	-0.00852	0.790105	-0.24579
6	0.946	0.895	-0.00368	0.556763	-0.07647
7	0.948	0.899	-0.004	0.547281	-0.06739

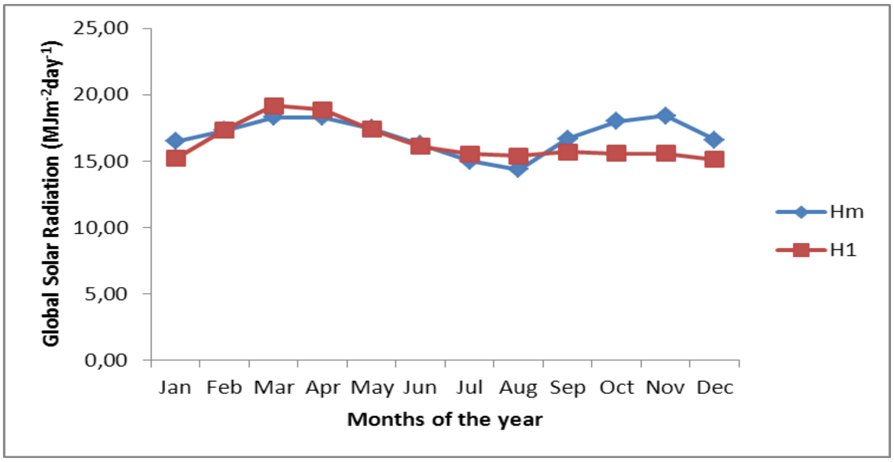

Fig. 1 Comparison between the measured and model 1 values of solar radiation

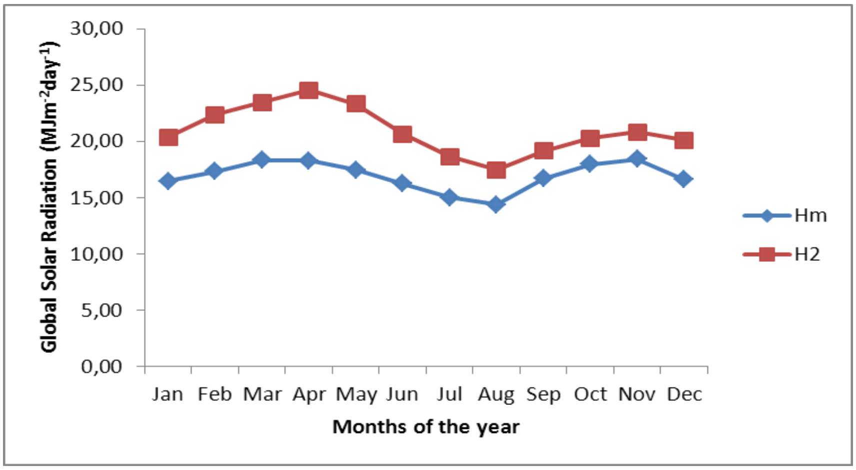

Fig. 2 Comparison between measured and model 2 values of solar radiation

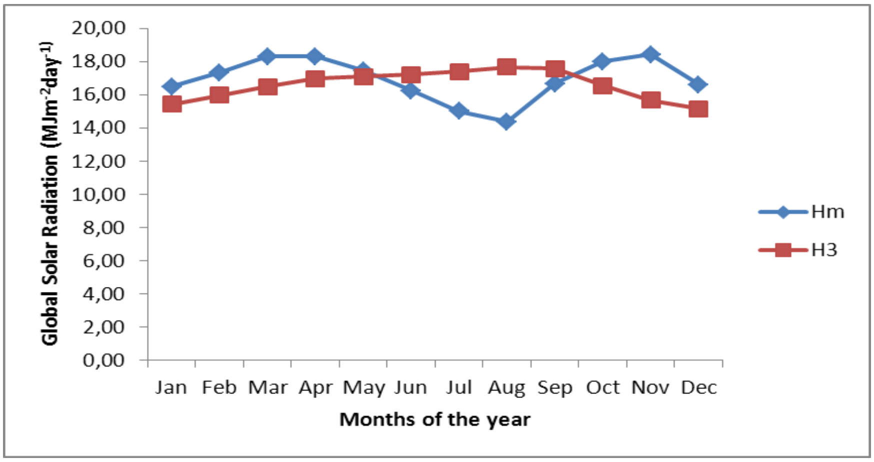

Fig. 3 Comparison between measured and model 3 values of solar radiation

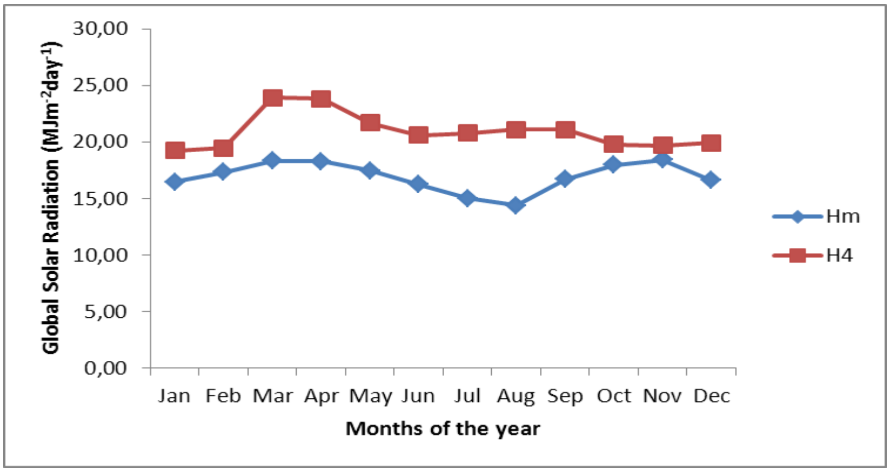

Fig. 4 Comparison between measured and model 4 values of solar radiation

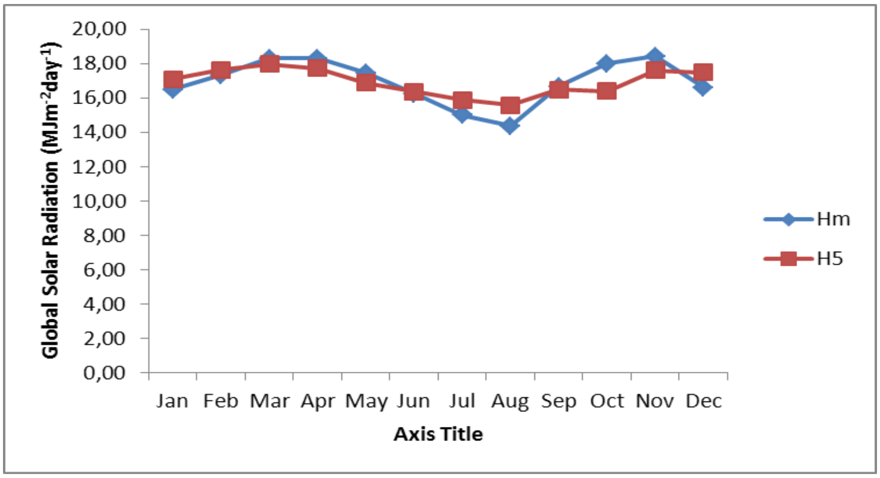

Fig. 5 Comparison between measured and model 5 values of solar radiation

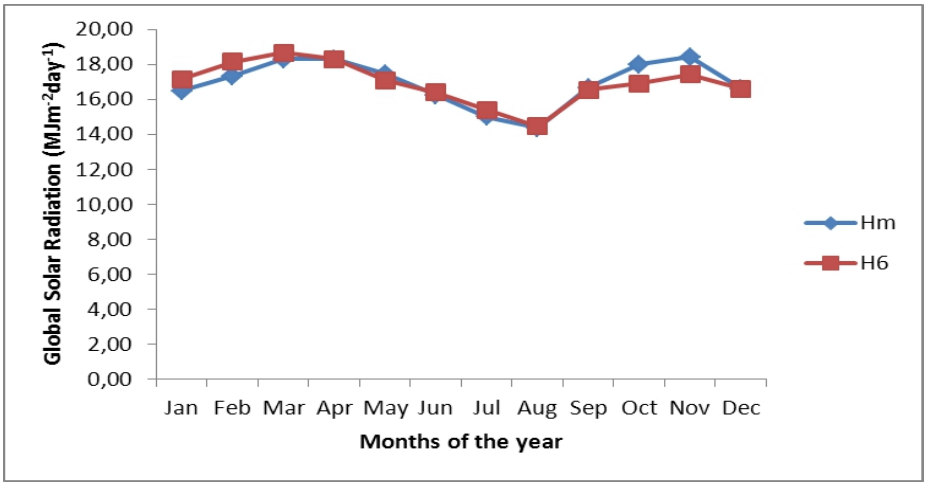

Fig. 6 Comparison between measured and model 6 values of solar radiation

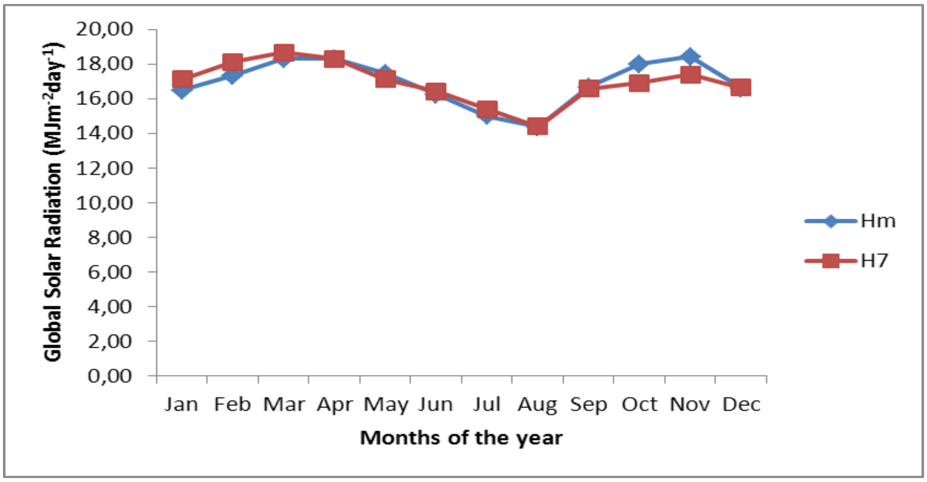

Fig. 7 Comparison between measured and model 7 values of solar radiation

4. Conclusion

The monthly mean daily global solar radiation and temperature data (maximum, minimum and temperature ratio) have been employed to develop the Angstrom-Prescott type equations (models) for estimating global solar radiation in Minna.

It was observed that models 1, 5, 6 and 7, gave a very good result in predicting global solar radiation, considering their MBE, RMSE and MPE values. However, judging from the values of correlation coefficient, R and RMSE, models 6 and 7 gave better predictions of R which indicate that about 95% of variation in the monthly mean daily solar radiation $\overline{H}_M$ on a horizontal surface can be accounted for, by the models. Therefore, either the quadratic or cubic model based on temperature ratio, is adequately fit for estimating global solar radiation in Minna and its environs.

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