Performance Evaluation of Developed Empirical Models for Predicting Global Solar Radiation in Western Region of India

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Abstract

For the prediction of solar radiation, various models have been developed in literature with sunshine hours as prime parameter. However, an extensive amount of work is still required correlating the sunshine hours and other parameters. Seven models each for predicting mean global radiation and mean diffuse radiation has been derived in this research work for city Amravati (20.9374°N, 77.7796°E), correlating with sunshine hours, average temperature and relative humidity. Relative humidity and temperature together with sunshine can prove to be a best alternative for predicting solar radiation at places where direct measurement is unavailable. Both linear and non-linear correlations developed are compared with conventional models and measured values available for last five years from the meteorological data. The validation is done using several statistical parameters viz. mean absolute percentage error (MAPE), mean bias error (MBE), root mean square error (RMSE) and R^2. The performance evaluation of these models gives the best suitable model for both global and diffuse solar radiation for the city Amravati, Maharashtra.

Keywords: Average temperature; Relative humidity; Solar radiation; Statistical parameter; Sunshine hours.

1. Introduction

The energy demands across the globe have increased to a level where production of electricity by different sources is essential. The trend of increasing energy consumption is applicable to the Indian scenario as well [1]. The electricity consumption of India was 2666 GW, as of 31st March 2013 [2-3]. The major proportions of this energy is contributed by conventional sources of energy like coal, oil, natural gas and hydro-energy. Implementation of renewable energy sources to supply energy needs can prove to be valuable in reducing stress from these conventional sources of energy [4-6]. India has a high potential of harnessing solar energy owing to its position between Equator and Tropic of Cancer. The average value of solar radiation is observed to vary between 4 kWh/m^2-day to 7 kWh/m^2-day and annually the value of solar radiation over India is approximately 5000 trillion kWh/year [7]. Extensive work in the area of solar energy can thus be beneficial in solving energy crisis.

For prediction of solar power plant capacity and establishment of plant at a specific location, the evaluation of solar radiation flux on horizontal surface at that particular location is necessary [8]. Solar radiation data thus required is obtained from meteorological stations that are responsible for continuous monitoring of solar radiation and its various components. However, only a few meteorological stations are located at India and exact values of solar radiation at rural are not at disposal. Due to obvious reasons of high capital cost and techniques associated, meteorological stations are limited in number. Thus estimation of solar radiation at such remote locations where measured data is not available becomes tedious and development of new models for these locations is a challenging work [9-10]. Solar radiation is of uttermost importance in research area of solar energy and it can be predicted using already existing or developed correlations [11-15][38]. Most of the existing models in the literature use sunshine hour as a prime parameter for estimation of solar radiation [16]. In recent research works, other parameters such as absolute temperature and relative humidity have been examined and new techniques are implemented by various authors in developing models for various locations [17-25] [39-42].

In this research work, an effort has been made to develop several linear and non-linear models for the estimation of solar radiation at Amravati, Maharashtra. Significant research has been done for estimating global solar radiation in the tropical wet and dry climatic region around Nagpur region [20], however Amravati being an upcoming site for industrialization, more amount of work is required for estimating global and diffuse solar radiation. Seven empirical models have been proposed for predicting both mean global radiation and mean diffuse radiation. The estimated values are compared with measured data available for five years from nearest meteorological station [26]. The proposed models for mean global radiation and mean diffuse radiation are also validated by comparing with existing and widely accepted models of Angstrom-Prescott [27], Gopinathan [28], Rietveld [29] and Liu and Jordan [30], Gopinathan and Soler [31], Iqbal [32-33] respectively. The validation of derived models is done with help of statistical parameters like mean bias error (MBE), root mean square error (RMSE), mean absolute percentage error (MAPE) and regression coefficient (R^2) [34-36].

2. Methodology

The parameters required for the calculation of solar radiation such as sunshine hours, extra-terrestrial radiation and declination angle are calculated from standard expressions mentioned in the literature [27]. The value of extra-terrestrial radiation is given by

$$H_o = \frac{24}{\pi} I_{sc}\left[1 + 0.033\, cos\left(\frac{360n}{365}\right)\right][sin\omega_h . cos\emptyset . cos\delta + \omega_h . sin\emptyset . sin\delta] \quad (1)$$

Where I_{sc} is the solar constant, ϕ is the latitude of location under consideration, ω_h is hour angle and δ is the declination angle. These parameters can be expressed in the mathematical form as shown below

$$\delta = 23.45\, sin\frac{360}{365}(284 + n) \quad (2)$$

where n is the number of days starting from 1st January.

$$\omega_h = cos^{-1}(-tan\emptyset . tan\delta) \quad (3)$$

$$\vec{N} = \frac{2}{15}\omega_h \quad (4)$$

In this work, the mean global radiation and mean diffuse radiation is evaluated by considering parameters such as sunshine hours, absolute temperature and relative humidity. The values thus calculated are used for developing models by curve fitting technique for the city Amravati, Maharashtra. The proposed models for mean global radiation and mean diffuse radiation are listed in Table 1 and Table 2 respectively. In these models, H_g denotes monthly average of daily global solar radiation in MJ/m^2-day, H_o denotes value of extra-terrestrial radiation available in MJ/m^2-day, $\vec{n}$ denotes available sunshine hours at specific location, $\vec{N}$ denote maximum sunshine hours available, H_d is monthly average of daily diffuse radiation in MJ/m^2-day, T_a is the absolute temperature in ℃ and H_T denotes relative humidity of that location in percentage.

3. Performance Evaluation

For the proposed models to be adopted in practice, validation of these models is significant. The performance of all the models derived can be evaluated with help of statistical parameters viz. mean bias error (MBE), mean absolute percentage error (MAPE), root mean square error (RMSE) and regression coefficient (R^2). For better performance of the models, the values of RMSE, MAPE and MBE must be low as possible. The ideal value of these parameters is zero, indicating better performance of the models. Regression coefficient (R^2) shows the linear relationship between the estimated and measured values. Ideally the value of R^2 is one, indicating a perfect linear relation between estimated and measured values. MBE and MAPE are employed to evaluate long-term performance characteristics of the model, whereas RMSE is used to determine short-term performance characteristics. The empirical formulae of the statistical parameters are given below-

$$MBE = \frac{1}{n}\sum_1^n(H_{gc} - H_{gm}) \quad (5)$$

$$MAPE = \left|\frac{1}{n}\sum_1^n\left(\frac{H_{gc} - H_{gm}}{H_{gm}}\right) * 100\right| \quad (6)$$

$$RMSE = \left[\frac{1}{n}\sum_1^n\left(H_{gc} - H_{gm}\right)^2\right]^{\frac{1}{2}} \quad (7)$$

$$r = \frac{n\sum_1^n H_{gc}H_{gm} - \sum_1^n H_{gc}\sum_1^n H_{gm}}{\sqrt{n(\sum_1^n H_{gc}{}^2) - (\sum_1^n H_{gc})^2}\sqrt{n(\sum_1^n H_{gm}{}^2) - (\sum_1^n H_{gm})^2}} \quad (8)$$

where n is the number of readings, H_{gm} is measured mean solar radiation and H_{gc} is estimated mean solar radiation.

Table 1. The developed and conventional models for city Amravati to calculate mean global solar radiation.

Sr. No.	Model	Equations
1.	1.	$\frac{H_g}{H_0} = 0.2765 + 0.4897\left(\frac{\vec{n}}{\vec{N}}\right)$
2.	2.	$\frac{H_g}{H_0} = 0.2741 + 0.4945\left(\frac{\vec{n}}{\vec{N}}\right) - 0.0046\left(\frac{\vec{n}}{\vec{N}}\right)^2$
3.	3.	$\frac{H_g}{H_0} = 0.2785 + 0.4873\left(\frac{\vec{n}}{\vec{N}}\right) - 0.000055T_a$
4.	4.	$\frac{H_g}{H_0} = 0.2825 + 0.4821\left(\frac{\vec{n}}{\vec{N}}\right) - 0.000036H_r$

5.	5.	$\frac{H_g}{H_0} = 0.288 + 0.4793\left(\frac{\vec{n}}{\vec{N}}\right) - 0.000045H_r - 0.00011T_a$
6.	6.	$\frac{H_g}{H_0} = 0.8105 - 0.00164H_r - 0.00321T_a$
7.	7.	$\frac{H_g}{H_0} = 0.2804 + 0.5016\left(\frac{\vec{n}}{\vec{N}}\right) - 0.00668\exp\left(\frac{\vec{n}}{\vec{N}}\right)$
8.	Angstrom	$\frac{H_g}{H_0} = 0.27 + 0.50\left(\frac{\vec{n}}{\vec{N}}\right)$
9.	Rietveld	$\frac{H_g}{H_0} = 0.18 + 0.62\left(\frac{\vec{n}}{\vec{N}}\right)$
10.	Gopinathan	$\frac{H_g}{H_0} = c_1 + d_1\left(\frac{\vec{n}}{\vec{N}}\right)$ where $c_1 = -0.309 + 0.539cos\square - 0.0693h + 0.290\left(\frac{\vec{n}}{\vec{N}}\right)$ $d_1 = 1.527 - 1.027cos\square + 0.0926h + 0.359\left(\frac{\vec{n}}{\vec{N}}\right)$

Table 2. The developed models for city Amravati to calculate mean diffuse solar radiation.

Sr. No.	Model	Equations
1.	A	$\frac{H_d}{H_0} = 0.4615 - 0.3463\left(\frac{\vec{n}}{\vec{N}}\right)$
2.	B	$\frac{H_d}{H_0} = 0.45 - 0.3426\left(\frac{\vec{n}}{\vec{N}}\right) + 0.00032T_a$
3.	C	$\frac{H_d}{H_0} = 0.2695 + 0.2\left(\frac{\vec{n}}{\vec{N}}\right) - 0.3819\left(\frac{\vec{n}}{\vec{N}}\right)^2 + 0.000036T_a$
4.	D	$\frac{H_d}{H_0} = 0.2744 + 0.1637\left(\frac{\vec{n}}{\vec{N}}\right) - 0.35\left(\frac{\vec{n}}{\vec{N}}\right)^2 + 0.000117T_a + 0.000048H_r$
5.	E	$\frac{H_d}{H_0} = 0.2674 + 0.1988\left(\frac{\vec{n}}{\vec{N}}\right) - 0.3769\left(\frac{\vec{n}}{\vec{N}}\right)^2 + 0.0000355H_r$
6.	F	$\frac{H_d}{H_0} = 0.4494 - 0.3346\left(\frac{\vec{n}}{\vec{N}}\right) + 0.000072H_r$
7.	G	$\frac{H_d}{H_0} = 0.0743 - 0.00114H_r - 0.0025T_a$
8.	Liu and Jordan	$\frac{H_d}{H_g} = 1.390 - 4.027\left(\frac{H_g}{H_0}\right) + 5.531\left(\frac{H_g}{H_0}\right)^2 - 3.108\left(\frac{H_g}{H_0}\right)^3$
9.	Gopinathan and Soler	$\frac{H_d}{H_g} = 0.87813 - 0.33280\left(\frac{H_g}{H_0}\right) - 0.53039\left(\frac{\vec{n}}{\vec{N}}\right)$
10.	Iqbal	$\frac{H_d}{H_g} = 1.2547 - 1.2055\left(\frac{\vec{n}}{\vec{N}}\right)$

4. Results and Discussion

For the evaluation of monthly mean global solar radiation, seven linear as well as non-linear models have been proposed for the city Amravati. The derived models are compared with existing models and measured values on the basis of statistical parameters viz. MBE, MSE, RMSE, MAPE and R^2 as shown in Table 3. It can be verified that the value of regression coefficient (R^2) is always greater than 0.906 for the proposed models and varies between 0.906 and 0.9802. Thus it is deduced that the estimated values of mean global radiation from proposed models and measured values complement each other. The mean absolute percentage error (MAPE) ranges between 2.516% and 4.180% for the proposed models, giving judicious fit among global radiation and parameters like humidity and temperature. The negative values of mean bias error (MBE) indicates the underestimation of global radiation. Models 1, 3, 4 and 6 give negative values of MBE, whereas the maximum value of MBE is seen for Model 2 and never goes past 0.436 (MJ/m^2). The feature that estimated and measured values emulate each other can be seen from the RMSE values. The RMSE for the proposed models vary from 0.587 (MJ/m^2) to 1.030 (MJ/m^2), indicating good results for the city under consideration. From all the statistical parameters calculated, it is noted that the proposed models yield better performance characteristics than the traditional models of Angstrom, Rietveld and Gopinathan; where coefficient of regression (R^2) is considered as principle indicator.

Amongst all the seven models proposed for Amravati, the sunshine model and model having combination of sunshine hours, humidity and temperature yields better performance than the others. The correlation between the measured and estimated values of global

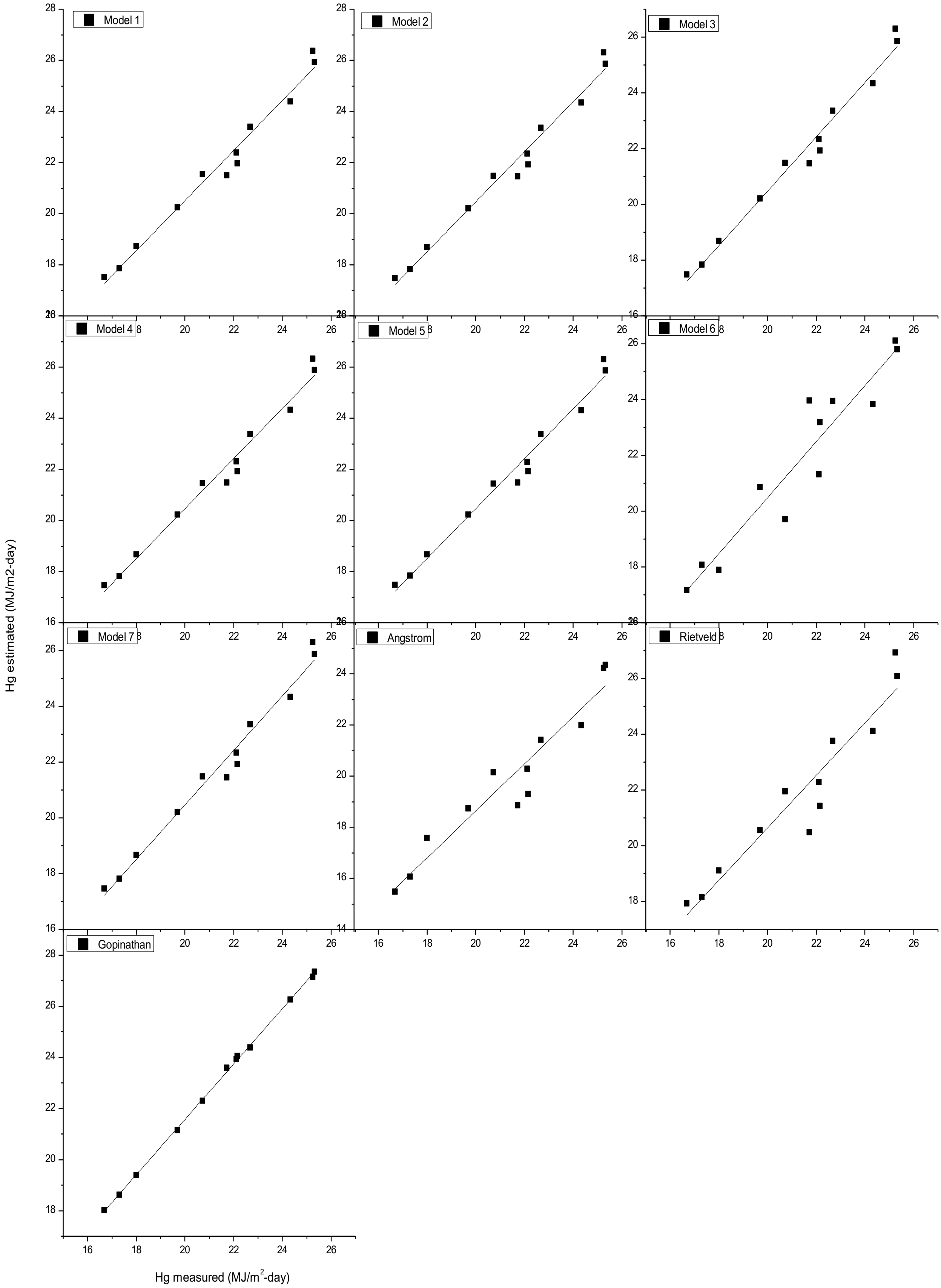

Fig 1. Estimated and measured values by Models (1) to (7) for mean global solar radiation

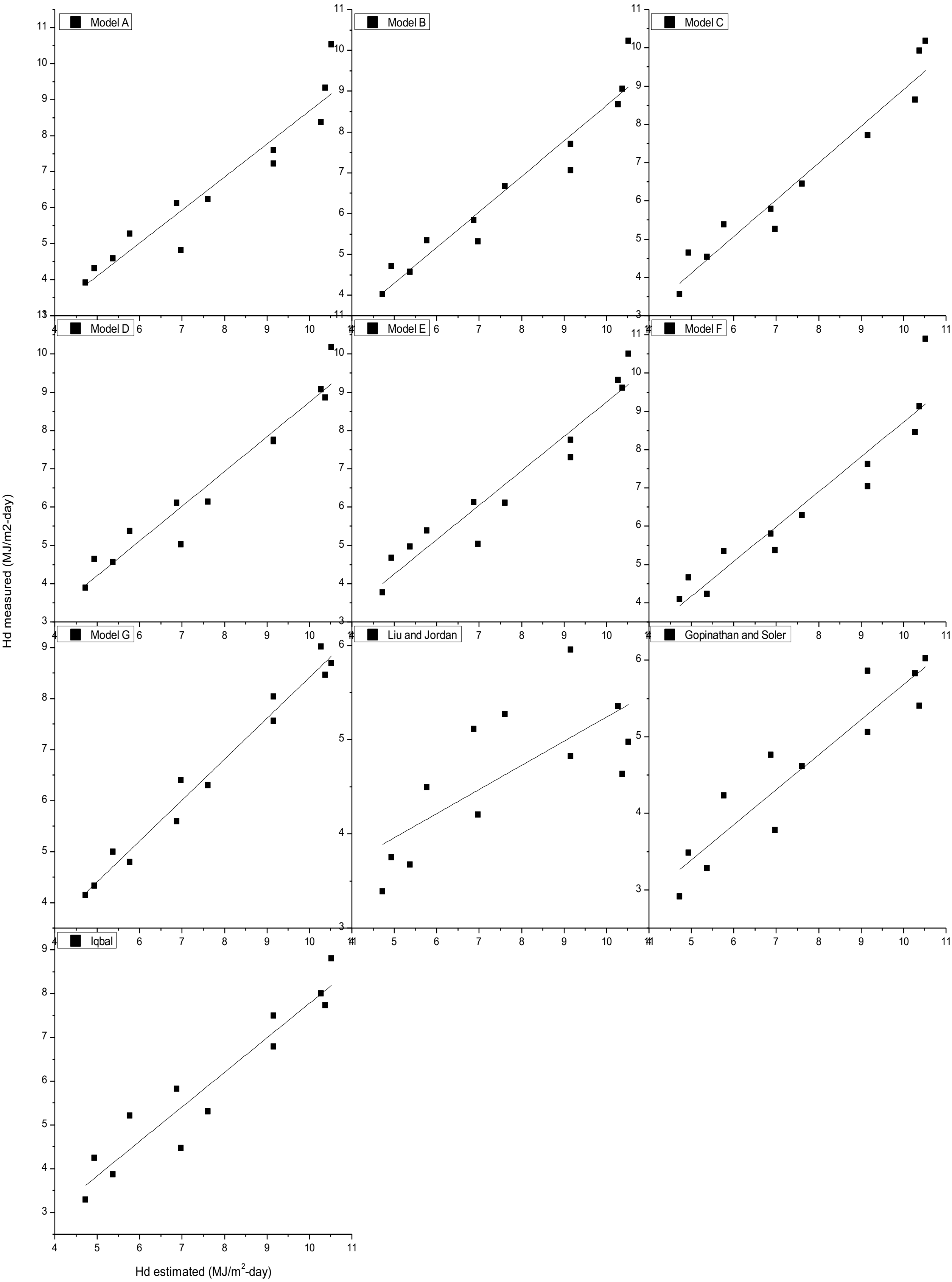

Fig 2. Estimated and measured values by Models (A) to (G) for mean diffuse solar radiation

Table 3. Performance evaluation by statistical errors for derived models for mean global radiation

Model	MBE (MJ/m^2)	MSE (MJ/m^2)	RMSE (MJ/m^2)	MAPE (%)	R^2
1.	-0.4827	0.3940	0.6277	2.6792	0.9778
2.	0.4367	0.3233	0.5912	2.5263	0.980
3.	-0.4538	0.3476	0.589	2.518	0.9802
4.	-0.4343	0.3503	0.599	2.508	0.977
5.	0.4230	0.3451	0.5875	2.501	0.98
6.	-0.488	1.0625	1.0308	4.180	0.906
7.	0.433	0.3466	0.588	2.516	0.9799
Angstrom	1.4675	2.781	1.667	6.840	0.921
Rietveld	-0.5625	1.031	1.015	4.476	0.911
Gopinathan	-1.679	2.881	1.697	7.861	0.967

Table 4. Performance evaluation by statistical errors for derived models for mean diffuse radiation

Model	MBE (MJ/m^2)	MSE (MJ/m^2)	RMSE (MJ/m^2)	MAPE (%)	R^2
A	1.118	1.658	1.288	14.948	0.903
B	1.042	1.410	1.187	13.506	0.930
C	0.996	1.243	1.115	13.614	0.943
D	1.036	1.342	1.158	13.725	0.940
E	1.017	1.341	1.158	13.367	0.931
F	1.067	1.606	1.267	14.725	0.894
G	1.120	1.494	1.222	14.208	0.917
Liu and Jordan	3.008	11.746	3.427	36.681	0.533
Gopinathan and Soler	3.042	10.688	3.269	38.666	0.876
Iqbal	1.723	3.431	1.852	22.579	0.911

radiation can be observed from Figure 1. Model 5 which is combination of various meteorological parameters gives best fit and is in good agreement with the measured values. Thus Model 5 can be adjudged as best suitable for evaluation of mean global radiation at Amravati.

Also, with the help of global radiation values, seven empirical models have been developed for estimating monthly mean diffuse radiation. The same statistical parameters viz. MBE, MSE, RMSE, MAPE and R2 are employed for comparison between derived models and conventional models as listed in Table 4. The value of regression coefficient (R2) is examined to vary in range of 0.894 to 0.943. The value of R2 is greater than 0.894 for every proposed model indicating the estimated values to be in agreement with the measured values. The mean absolute percentage error (MAPE) varies from 13.367% to 14.948%. The least value of MAPE is observed for Model 5. Considering mean bias error (MBE), Model 3 gives the least value of 0.996 (MJ/m2) whereas the maximum value is obtained for 1.120 (MJ/m2). The fact that the values of derived models and measured values are in accordance with each other can be validated from the root mean square error (RMSE). The least value is obtained for Model 3 which is 1.115 (MJ/m2) and maximum value is obtained for Model 1 which is 1.288 (MJ/m2). As in case of mean global radiation, the proposed models for mean diffuse radiation give superior results when compared with conventional models of Liu and Jordan, Gopinathan and Soler and Iqbal for the city Amravati. In this case as well, the regression coefficient (R2) has been considered as performance indicator.

The seven models for diffuse radiation were developed considering various combinations of linear and non-linear sunshine models along with other parameters such as temperature and humidity. The trend in global radiation follows in case of diffuse radiation and non-linear model with combination of sunshine hours, absolute temperature and relative humidity yields superior result than other models. The correlation between the estimated values from proposed models and measured values can be seen in Figure 2. From the statistical errors, performance of Model 3 can be deemed to be of highest quality and chosen as best suitable model for city Amravati.

5. Conclusions

With the help of statistical parameters viz. MBE, MAPE, RMSE and R2, the seven derived models for mean global radiation and mean diffuse radiation respectively can be validated. For performance verification of the proposed models they are compared with widely accepted conventional models of mean global radiation and mean diffuse radiation. A combination of various parameters have been considered while developing these models. Linear and non-linear correlations including parameters such as sunshine hours, relative humidity and absolute temperature are obtained by curve fitting. All the models developed show similar values of statistical errors and give better results when compared to existing models. Hence it can be inferred that all the suggested models for estimating mean global radiation and mean diffuse radiation can be used as generalized correlations for the considered location. All proposed models are able to give good performance characteristics, however, Model 5 for mean global radiation and Model 3 for mean diffuse radiation can be adjudged as best fit models for the city Amravati, Maharashtra.

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