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Solar Radiation Models - A Comparative Study

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ABSTRACT

Four empirical correlations, proposed by three different authors, for estimating monthly mean daily global solar radiation on a horizontal surface are tested for their applicability to Indian locations. The models compared are those developed by Glover and McCulloch (1958), Rietveld (1978), and Gopinathan (1987, 1988). The comparison is made by estimating the monthly mean daily global radiation for six widely spread stations in India. The estimated values of global radiation are then plotted together with the measured data and the errors in the estimated values are evaluated. A comparative study of the four models establishes that the method proposed by Gopinathan, connecting the regression constants of Angstrom correlation with latitude and sunshine duration, is the most accurate and is recommended for Indian locations. The estimated values from this model are accurate to about five per cent, whereas the errors from the other models can be as large as 15-20 per cent during some of the months, for some locations.

INTRODUCTION

An accurate knowledge of the irradiation incident on a horizontal surface, in a given location, is important for any solar energy application. Many locations in most of the developing countries receive appreciable amounts of irradiation; however, it is in these areas where the measurements of solar radiation are least common. The inhibiting circumstances are the high cost of the necessary equipment and the shortage of expert care which they require. For locations where no measured data on solar radiation are available, the common approach has been to estimate solar radiation from other measured meteorological parameters such as sunshine duration, rainfall, air temperature, relative humidity and cloud cover.

The most important radiation parameter, which is often needed for solar energy applications, is the long-term average daily global radiation on horizontal surface. The first correlation proposed for estimating the monthly average daily global radiation is due to Angstrom[1] connecting global radiation with sunshine duration. The relationship between sunshine duration and total radiation was later examined by numerous researchers.[1-4] Several workers[2-4] have also demonstrated that the sunshine-total radiation relationship can be based on the extraterrestrial radiation in the form

$$Q_t/Q_a = a + b\,(n/N) \qquad (1)$$

where Q_t is the monthly mean daily total radiation on a horizontal surface, Q_a is the monthly mean extraterrestrial radiation, n is the monthly average daily sunshine duration and N is the day length in hours; a and b are regression coefficients. Though a number of other correlations which include more parameters have been developed by different workers,[5,6] the Angstrom type correlation has been found to be the most convenient. The difficulty in employing the Angstrom correlation is, however, in determining the values of the regression coefficients for a given location; coefficients a and b are found to vary not only for different parts of the world but even for nearby locations having similar geographical and climatological conditions. Several methods exist for computing a and b from various parameters like latitude, elevation, sunshine duration, etc. Some of these models are claimed to have universal applicability.

Though solar radiation is measured at many places in India, due to the varying climatic and geographic conditions of the country, their distribution is not sufficient enough to give an accurate network of measured data. Solar radiation and other meteorological parameters show large variations in different parts of India. This is well demonstrated by the measured data on solar radiation reported[7,8] for various locations. One can, for example, compare the measured monthly mean daily global radiation for a particular month, say January, for various locations. Srinagar, for example, has the lowest monthly mean daily global radiation of 7.3 MJ m^{-2} for January,whereas Delhi registers a total radiation of 15.1 MJ m^{-2} day^{-1} for the same month. Bombay, on the west coast, has a radiation of 19.2 MJ m^{-2} day^{-1} while Madras, on the east coast, records 21.3 MJ m^{-2} day^{-1}, for the same month. The variation in solar radiation even for nearby locations like Delhi and Agra are considerable. Delhi receives average radiation of 15.1 MJm^{-2} day^{-1} in January whereas Agra records 13.4 MJ m^{-2} day^{-1} for the same month. During July, global radiation values for the two stations are 25.5 MJ m^{-2} day^{-1} and 20.5MJ m^{-2} day^{-1} respectively. Because of this climatic diversity, the radiation data need to be recorded independently, even for nearby locations. However, it is virtually impossible to set up so many radiation measuring stations and one has to depend on theoretical models for estimation purposes. Empirical correlations involving sunshine duration, appear to be the most useful, as this measurement exists for many stations in the country.

Attempts have already been made by various investigators to compute monthly mean daily global radiation on horizontal surfaces from various meteorological parameters, for locations in India. Reddy[9] proposed an empirical method for computing daily total solar radiation using sunshine hours, humidity and rainfall data. He tested the equation for only two locations, Poona and Trivandrum. His equation gave large errors when tested for other locations.[10] Mani and Chacko[11] plotted radiation maps with the results of solar radiation measurements made for a network of 13 stations in India. Mani and Rangarajan[12] discussed the computation of solar radiation from other meteorological parameters and presented results of the computation of monthly mean values of daily global radiation for 121 stations in India using the model proposed by Hay.[13] In his model, Hay took into account the effect of multiple reflections between the earth's surface and the atmosphere and his correlation incorporates the monthly average ground albedo, cloudless sky albedo and cloud albedo and the modified day length. Mani and Rangarajan[12] used the cloudless sky albedo and cloud albedo values assigned by Hay to Canadian locations and assumed the ground albedo to be 0.2. These may affect the accuracy of the estimated data and, as measured albedo values are not available for most of the locations, this correlation is not easy to employ. Gopinathan[14,15] recently developed two models for estimating monthly average daily global solar radiation. In one of the models, the regression coefficients a and b are estimated from the elevation of the location; in the other, a and b values are computed from latitude and per cent possible sunshine duration.

The purpose of the present study is to test the applicability of some empirical correlations for estimating global solar radiation for Indian locations. Four models suggested by Rietveld,[16] Glover and McCulloch,[4] and Gopinathan[14,15] are selected for comparison. A comparative study of the four models is carried out to select the most suitable method for Indian locations. The models by Rietveld, and Glover and McCulloch are considered to have universal applicability. The present work will also help to test the applicability of these two models to Indian conditions.

GLOBAL RADIATION CORRELATIONS

The following four models are used in the present analysis. All the four models are simple and easy to employ.

Method 1: Rietveld[16] after examining several published values of the regression coefficients has suggested the following relationships for expressing a and b in terms of the per cent possible sunshine, n/N

$$a = 0.10 + 0.24\,(\bar{n}/\bar{N}) \tag{2}$$

$$b = 0.38 + 0.08\,(\bar{N}/\bar{n}) \tag{3}$$

Method 2: From a study of the results for six locations in India, Gopinathan[14] has recommended the following quadratic relationship connecting a and b with the elevation (h) of the location above sea level, in kilometres.

$$a = 0.458 - 0.213\,h + 0.219\,h^2 \tag{4}$$

$$b = 0.288 + 0.229\,h - 0.236\,h^2 \tag{5}$$

Method 3: Gopinathan[15] has attempted to improve the accuracy of the estimated regression constants by combining the effect of latitude and sunshine duration together in a single equation. After analyzing the measured global radiation data published for 19 locations[7] he has established correlations for estimating the regression coefficients a and b of the Angstrom type correlation. By using the least squares method, he first obtained the regression coefficients a and b for each of the 19 stations, from measured values of global radiation and sunshine duration. These a and b values, along with the per cent possible sunshine and latitude of the locations, were then used in a multiple linear regression analysis to find the dependence of a and b on n/N and λ. However, none of the six locations discussed in this paper were included in the analysis to develop the equations.

Correlations of the following form were obtained to express coefficients a and b of the Angstrom type correlations

$$a = -0.110 + 0.235\cos\lambda + 0.323\,(\bar{n}/\bar{N}) \tag{6}$$

$$b = 1.449 - 0.533\cos\lambda - 0.694\,(\bar{n}/\bar{N}) \tag{7}$$

Gopinathan was able to improve the accuracy of the estimated regression constants by combining the effect of latitude and sunshine duration together. In tests of the applicability of the method, by calculating global radiation for five locations spread all around India, the model was found to be very accurate.

The calculated value of a and b from the above three methods can be substituted in Eq. (1) to estimate monthly mean daily global radiation on a horizontal surface.

Method 4: Glover and McCulloch[4] have modified the Angstrom type correlation by adding the latitude effect and have proposed the following equation,

$$Q_t/Q_a = 0.29 \cos\lambda + 0.52\,(n/N);\ \lambda < 60^\circ \tag{8}$$

Q_a and N values needed for the study were calculated from the following equations,

$$Q_a = \left(\frac{24}{\pi}\right) Q_p E_0 \sin\lambda \sin\delta \left[\left(\frac{\pi}{180}\right) W_s - \tan W_s\right] \tag{9}$$

where Q_p is the solar constant, E_0 is the eccentricity correction factor, λ is the latitude of site, δ is the solar declination and W_s is the sunshine hour angle.

$$N = \frac{2}{15} \cos^{-1}(-\tan\lambda \tan\delta) \tag{10}$$

The magnitude of the errors in the estimated value of global radiation are calculated from

$$\text{percentage error} = \frac{|Q_{tM} - Q_{tE}|}{Q_{tM}} \times 100 \tag{11}$$

where Q_{tE} and Q_{tM} were the estimated and measured total solar radiation. The twelve month average of the percentage errors for each location is shown as the mean percentage error (MPE).

RESULTS AND DISCUSSION

The stations selected for the study were Bombay, Bangalore, Jodhpur, Nagpur, Poona and Srinagar. Measured data on global radiation and sunshine duration for these locations were made available from the distribution of solar radiation reported in the literature.[7,8] The above six locations are spread all around India and have different geographical and climatological conditions. For example, Bangalore is in the southern part of the country whereas Srinagar and Nagpur are in the northern and central part of India respectively. Bombay is on the coast and Poona, Bangalore, etc. are in the interior of the country. Such locations are selected, so that the method recommended from the present study should be well acceptable for locations in all parts of the country.

Geographical parameters like elevation and latitude for the six stations, along with the average per cent possible sunshine duration ($\bar{n}/\bar{N}$) are presented in Table 1. The a and b values calculated from methods 1, 2 and 3 are also given in the same table. Global radiation is directly estimated in method 4, without obtaining the a and b constants. The estimated global radiation from all the four methods are compared with the available measured data[7,8] for these locations. The error in the calculated global radiation is evaluated from Eq. (11) and the mean percentage error (MPE) from all the four methods is shown in Table 1. The estimated global radiation from the four methods, together with the measured data, are shown in Figs. 1-6. The global radiation values presented in the figures are in MJ m^{-2} day^{-1}.

The following features emerge from a study of the results presented in Table 1 and the Figs. 1-6.

Figure 1 shows the monthly average daily global radiation for Bombay. This station is on the coast at a latitude of 18.93°N and elevation of 14 m. There is a remarkable agreement between the measured radiation and the estimated data from method 3. The mean percentage error from method 3, for this location, is only 2.2 per cent. The percentage error from this method never exceeds five per cent during any month of the year for Bombay. However, the error in the estimated values from the other three

Table 1. Latitude, elevation, regression coefficients and the mean percentage errors for the six locations in India.

Station	Elevation km	Latitude degrees	$\bar{n}/\bar{N}$	Method 1				Method 2				Method 3				Method 4
				a	b	a+b	MPE	a	b	a+b	MPE	a	b	a+b	MPE	MPE
Bombay	0.014	18.93	0.62	0.249	0.509	0.758	9.7	0.455	0.291	0.746	7.9	0.313	0.515	0.828	2.2	4.5
Bangalore	0.897	12.97	0.58	0.239	0.518	0.757	12.6	0.443	0.303	0.746	7.5	0.306	0.527	0.833	1.7	5.3
Jodhpur	0.224	26.30	0.75	0.280	0.487	0.767	8.3	0.421	0.327	0.748	5.4	0.343	0.451	0.804	3.0	7.3
Nagpur	0.310	21.15	0.64	0.254	0.505	0.759	9.0	0.413	0.336	0.749	6.0	0.316	0.508	0.824	1.8	4.8
Poona	0.559	18.53	0.67	0.261	0.499	0.760	8.1	0.407	0.342	0.749	5.8	0.329	0.479	0.808	3.1	5.2
Srinagar	1.593	34.08	0.50	0.220	0.540	0.760	11.2	0.674	0.054	0.728	31.7	0.246	0.661	0.907	6.2	9.2

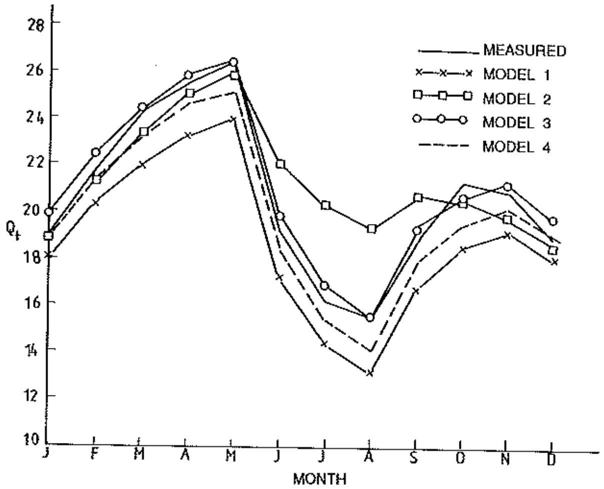

Fig. 1. Measured and calculated global radiation on a horizontal surface for Bombay in MJ m^{-2} day^{-1}.

methods are high as compared to the results from method 3. The difference between measured data and those estimated from methods 1, 2 and 4, is large, especially during the months of June-September. Results from method 2 are higher than the measured values and those from methods 1 and 4 are lower. Between methods 1 and 4, method 4 found to be the more accurate. The mean percentage errors for Bombay from the four methods are 9.7, 7.9, 2.2 and 4.5 respectively.

Figure 2 gives the monthly mean daily global radiation for Bangalore. This station is in the interior of the country at a latitude of 12.97°N and altitude of 897m. Again, the measured and the estimated radiation from method 3 agree very well during all the months of the year. Estimated global radiation from method 2 is again higher than the measured values whereas methods 1 and 4 give lower estimates. The differences between measured and estimated values are large, especially during the months of July-November. The MPE values from the four models are 12.6, 7.5, 1.7, and 5.3 respectively.

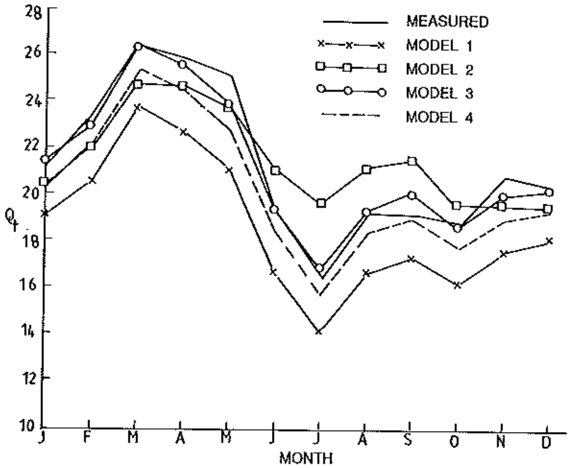

Fig. 2. Measured and calculated global radiation on a horizontal surface for Bangalore in MJ m^{-2} day^{-1}.

Figure 3 presents the monthly variation of global radiation for Jodhpur. Once again there is an excellent agreement between measured radiation values and those estimated from method 3. The deviation of the estimated data from the other three methods is as large as observed for Bombay and Bangalore. The MPE values from the four methods are 8.3, 5.4, 3.0 and 7.3 respectively.

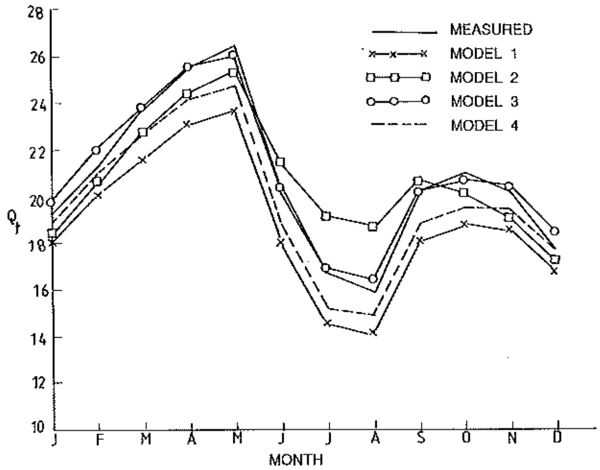

Fig. 3. Measured and calculated global radiation on a horizontal surface for Jodhpur in MJ m^{-2} day^{-1}.

Figures 4-6 compare the estimated and measured total radiation values for Nagpur, Poona, and Srinagar, respectively. The results presented in these figures together with the MPE values reported in the table, support the observations made earlier. Method 3 gives the most accurate estimation of global radiation for all these locations. The percentage error from this method never exceeds five per cent during any month of the year for any location. However, the MPE from other methods can be as

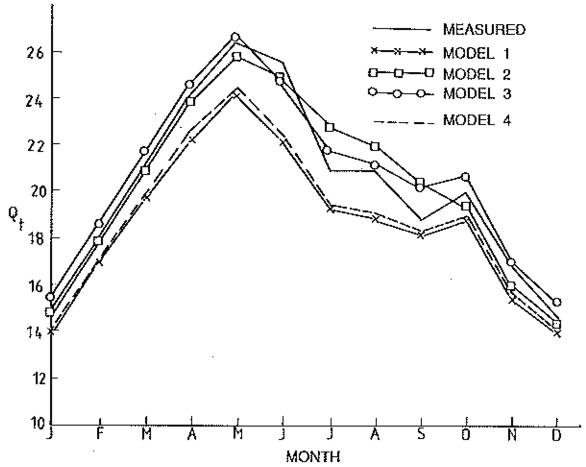

Fig. 4. Measured and calculated global radiation on a horizontal surface for Nagpur in MJ m^{-2} day^{-1}.

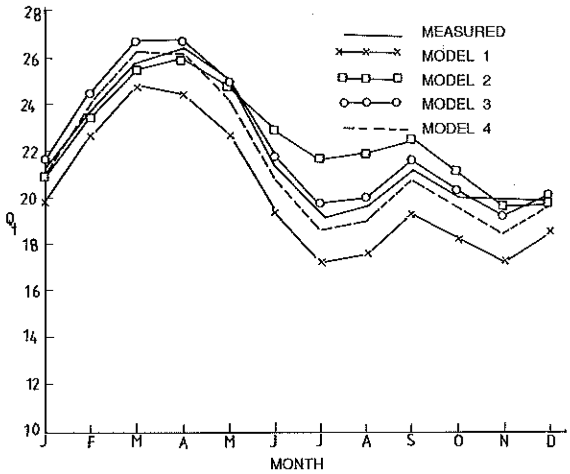

Fig. 5. Measured and calculated global radiation on a horizontal surface for Poona in MJ m⁻² day⁻¹.

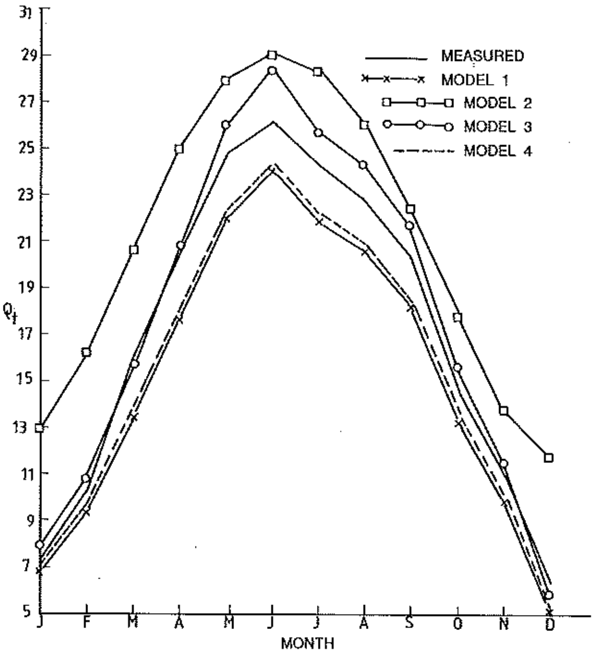

Fig. 6. Measured and calculated global radiation on a horizontal surface for Srinagar in MJ m⁻² day⁻¹.

high as 15-20 per cent during some of the months. This is observed more with the results from method 1. However, the average error from all the four methods is below 10 per cent. Among the methods 1, 2 and 4, method 4 shows better agreement with the experimental data and method 2 comes next. The errors in the calculated values from method 1 are quite high in many cases and the method is not suitable for Indian locations.

The success of method 3 over others can be attributed to the following reasons: Methods 1 and 4, though claimed to have universal applicability, are not developed for Indian conditions. They are developed from data elsewhere and their accuracy cannot be expected to be very high under Indian conditions. Furthermore, method 1 has only one variable, the sunshine duration, in the estimation correlation. Method 2, though developed from Indian data again calculates a and b from only one parameter, the elevation of the station. Further, method 2 was obtained from the data of 19 widely spread locations in India. It has been observed[17-19] that the accuracy of the estimated a and b values and solar radiation in general, can be improved by incorporating more variables in the estimation correlations. Method 3 employs two variables, namely n/N and λ in the estimation correlation, and these together have helped to improve the accuracy of the estimated data. Method 4 with two variables, is less accurate as it was not developed for Indian conditions.

CONCLUSIONS

Of the four methods compared to test their applicability to Indian locations, the method proposed by Gopinathan connecting the regression coefficients with latitude and sunshine duration is found to be the most accurate one; coefficients a and b calculated from the equations are:

$$a = -0.110 + 0.235 \cos\lambda + 0.323\,(\bar{n}/\bar{N})$$

$$b = 1.449 - 0.553 \cos\lambda - 0.694\,(\bar{n}/\bar{N})$$

when substituted in

$$Q_t/Q_a = a + b\,(n/N)$$

are capable of estimating monthly mean daily global radiation on a horizontal surface to an accuracy of five per cent. This procedure is applicable to any location in India and is recommended for solar energy applications in the country.

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