Annals of Arid Zone 29(2) : 73-80, 1990

ESTIMATION OF TOTAL SOLAR RADIATION FROM LATITUDE AND SUNSHINE DURATION

K.K. GOPINATHAN

Department of Physics, National University of Lesotho
Roma, Lesotho, Southern Africa

ABSTRACT

Correlations are suggested for calculating the regression coefficients a and b of equation $H' = H_o (a+b\ S/S'_o)$ suggested by Hay (Solar Energy, 23, 301, 1979) for global solar radiation. The proposed correlations calculate a and b constants from latitude and sunshine duration for a given station. The correlations are developed from the latitude, the reported regression parameters and sunshine duration for twelve locations spread all around India. The applicability of the proposed equations is tested by calculating the regression coefficients and hence the global solar radiation for three new locations in India. The remarkable agreement between the measured and estimated values of global radiation suggests the wide applicability of the method for locations in India

INTRODUCTION

Information on global solar radiation is needed in many fields dealing with the exploitation of solar energy. However, long term measured data on global radiation on a horizontal surface exist for relatively few meteorological stations. For places where no measured data are available, solar radiation can be estimated from theoretical models. A host of empirical formulae exist in the literature for the estimation of solar radiation from various meteorological parameters. Among the various empirical correlations, for estimating global radiation, the most widely used relationship is the linear regression due to Angstrom (1924) and Black et al. (1954) between global radiation and the duration of sunshine. In spite of its simplicity the relationship of the following form has been found useful for the analysis and estimation of global radiation in many parts of the world having different climatological and geographical conditions.

$$H/H_0 = a + b\ (S/S_0) \qquad (1)$$

were

H = monthly mean daily global radiation on a horizontal surface.

H_0 = monthly mean extra terrestrial radiation on a horizontal surface.

S = monthly average daily sunshine duration.

S_0 = maximum possible monthly average daily sunshine duration.

a and b are the regression coefficients.

Hay (1979) modified Angstrom equation to account for multiple reflections between the earth's surface and the atmosphere as well as for the Campbell-Stokes sunshine recorder at sun elevation less than 5°. His correlation incorporates the monthly average ground albedo (ρ) cloudless sky albedo (ρa) clould albedo (ρc) and modified day length. Hay obtained a correlation of the following form:

$$H' = H_0 (a + b\, S/S_0') \tag{2}$$

H′ is the global radiation that first hits the ground before undergoing multiple reflections and S_0' is the new maximum possible sunshine duration obtained from

$$S_0 = \frac{2}{15} \cos^{-1} \left[\frac{\cos 85 - \sin \phi \sin \delta}{\cos \phi \cos \delta} \right] \tag{3}$$

instead of the usual relationship

$$S_0' = \frac{2}{15} \cos^{-1} (-\tan \phi \tan \delta) \tag{4}$$

where ϕ is the latitude and δ is the declination.

The values of H can be obtained from H′ using the relationship

$$H' = H \left[1 - \rho \left\{ \rho_a \left(\frac{S}{S_0'}\right) + \rho_c \left(1 - \frac{S}{S_0'}\right) \right\} \right] \tag{5}$$

Hay has assigned a value of 0.25 to clouldless sky albedo and 0.6 to cloud albedo.

The only variable in equation (2) is the sunshine duration which is measured in most of the meteorological stations. H_0 and S_0' values can be calculated. However, the main problem is using the above type of correlation is in obtaining the proper values of a and b constants suited for a given location. a and b values are found to vary not only in different parts of the world but even for nearby locations having similar geographical and climatological conditions. Attempts have already been made by many investigators to calculate the coefficients of equation (1) from various parameters. Rietveld (1978) has proposed the following relationship between the regression coefficients and the percent possible sunshine duration (S/S_0), such as

$$a = 0.10 + 0.24\, (S/S_0) \tag{6}$$

$$b = 0.38 + 0.08\, (S_0/S) \tag{7}$$

Substituting equations (6) and (7) into equation (1), the following is obtained

$$H/H_0 = 0.18 + 0.62\, (S/S_0) \tag{8}$$

Glover and McCulloch (1958) have included the latitude effect and have presented the following formula :

$$H/H_0 = 0.29 \cos \phi + 0.52\, (S/S_0); \; \phi < 60° \tag{9}$$

Having already established the dependence of the regression parameters a and b on latitude and sunshine duration, an attempt is made here to develop correlations for a and b of equation (2) for Indian locations by combining the effect of both latitude and sunshine duration to single equation. The accuracy of the estimated regression coefficients is expected to improve by adding the effect of both latitude and sunshine duration together.

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 (1971) 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, Pune and Trivendrum. His equation gave large errors when tested to other locations (Vijay Modi et al. 1979). Mani and Chacko (1972) plotted radiation maps with results of solar radiation measurements made for a network of 13 stations in India. Mani and Rangarajan (1983) have discussed the computation of solar radiation from meteorological parameters and have presented results of computation of monthly mean values of daily global radiation for 121 stations in India using the model proposed by Hay (1979). Mani and Rangarajan (1983) have used the cloudless sky albedo and cloud albedo values assigned by Hay to Canadian locations and have assumed the ground an albedo to be 0.2 and have reported good agreement between measured and estimated values. The purpose of this paper is to develop an estimation equation based on Hay's model for computing monthly mean daily total solar radiation for locations in India. Correlations connecting a and b constants with latitude and mean percent sunshine duration are suggested to calculate the regression coefficients of Hay's correlations. The estimated a and b values can be used to calculate global radiation.

MATERIAL AND METHODS

Reported data for twelve locations spread throughout India are used in the study. The data on regression parameters a and b and S/S_0' for these 12 locations were made available from the work published by Mani and Rangarajan (1983). The a and b values thus obtained together with the latitude and S/S_0' data for these stations are then used in a multiple linear regression to express the dependence of a and b on these Parameters. Correlations of the following form are used to show the dependence of the coefficients on latitude and percent possible sunshine.

$$a = A_0 + A_1 \cos\phi + A_2 (S/S'_0) \tag{10}$$

$$b = B_0 + B_1 \cos\phi + B_2 (S/S'_0) \tag{11}$$

where ϕ is the latitute of the location in degrees and

A_0, A_1, A_2 and B_0, B_1, B_2 are all constants.

The applicability of the developed equations is then tested by calculating the regression coefficients and global radiation for three widely spread new locations in India. These three stations were not included in the regression analysis for obtaining the constants of equation (10) and (11). The monthly mean daily values of extraterrestrial radiations (H_0) were calculated using the following equation.

$$H_0 = \frac{24}{\pi} (r\, I_{sc}) (\cos\delta \cos\phi \sin W_s + \frac{2\pi}{360} W_s \sin\phi \sin\delta \qquad (12)$$

where W_s the sunset hour angle, is given by

$$\cos W_s = -\tan\phi \tan\delta \qquad (13)$$

$$\text{and } r = 1 + 0.033 \cos \left[\frac{360 \text{ x } n}{365}\right] \qquad (14)$$

the declination δ is given by

$$\delta = 23.45 \sin \left[360 \text{ x } \frac{284 + n}{365}\right] \qquad (15)$$

I_{sc} is the solar constant and n is the day of the year, S/S_0' values are derived from the calculated global radiation reported for these 12 stations by Mani and Rangaranjan (1983).

The accuracy of the estimated data on global radiation was tested by calculating the mean bias, root mean square and mean percentage errors. The mean bias error (MBE), the root mean square (RMES) and the mean percentage error (MPE) are defined as below.

$$MBE = [\Sigma (H_{ical} - H_{imeas})]/ n \qquad (16)$$

$$RMSE = \left\{ \left[\Sigma \left(H_{ical} - H_{imeas} \right)^2 \right] / n \right\}^{\frac{1}{2}} \qquad (17)$$

$$MPE = \left[\Sigma \left(\frac{H_{i,\,meas} - H_{ical}}{H_{j,\,meas}} \text{ x } 100 \right) \right] n \qquad (18)$$

where $H_{i,\,cal}$ is the ith calculated value, $H_{i,\,meas}$ is the ith measured value, and n is the total number of observations. The lower the RMES, the more accurate the estimate is. The positive MBE shows an overestimation while a negative MBE shows an under estimation. While calculating the MPE values, the sign of the errors are neglected and the percentage errors added up to calculate the mean.

RESULTS AND DISCUSSION

Reported values of the regression parameters a and b alongwith S/S_0' data are utilized in a multiple linear regression analysis to obtain the constants of equation (10) and (11). The following twelve stations in the latitude range 8°N to 29°N are selected for study. Bhavnagar, Calcutta, Goa, Jodhpur, Kodaikanal, Madras, Mangalore, Nagpur, New Delhi, Pune, Shilong, and Vishakhapatnam. From the computer analysis the following relationship is established.

$$a = 0.295 - 0.101 \cos \phi + 0.082 (S/S_0') \quad (19)$$
$$b = 0.456 + 0.136 \cos \phi - 0.214 (S/S_0') \quad (20)$$

Equations (19) and (20) are then used to calculate a and b for three new locations. The three stations selected for study are Ahmedabad, Bombay, and Trivandrum a and b values for the three locations, calculated from equations (19) and (20), alongwith their lattitude and mean S/S_0' values are presented in Table 1. a and b values from Table 1. are then employed to estimate monthly mean daily global radiation on a horizontal surface for these locations using equations (2) and (5). The accuracy of the estimated data radiation is tested by comparing them with the measured values reported by Mani and Rangarajan (1983). The MPE, MBE and RMSE errors in the calculated value are also shown in Table 1. The calculated values are compared with experimental data in Figure 1-3. The values of global radiation presented in figures 1-3 are in MJm^{-2} day^{-1}. The following observations can be made from a study of the results presented in the figures and Table. Figure 1 gives the

Table 1. Latitude, mean percent possible sunshine, regression coefficients and the mean percentage errors for three stations in India.

Location	Latitude ϕ Degrees	Mean S/So'	a	b	a+b	MPE	MBE %	RMSE %
Ahmedabad	23.03	0.783	0.266	0,414	0.680	3.4	1.9	5.0
Bombay	18.94	0.685	0.256	0.438	0.694	3.5	2.0	3.8
Trivandrum	8.48	0.573	0.224	0.468	0.710	4.5	4.1	6.2

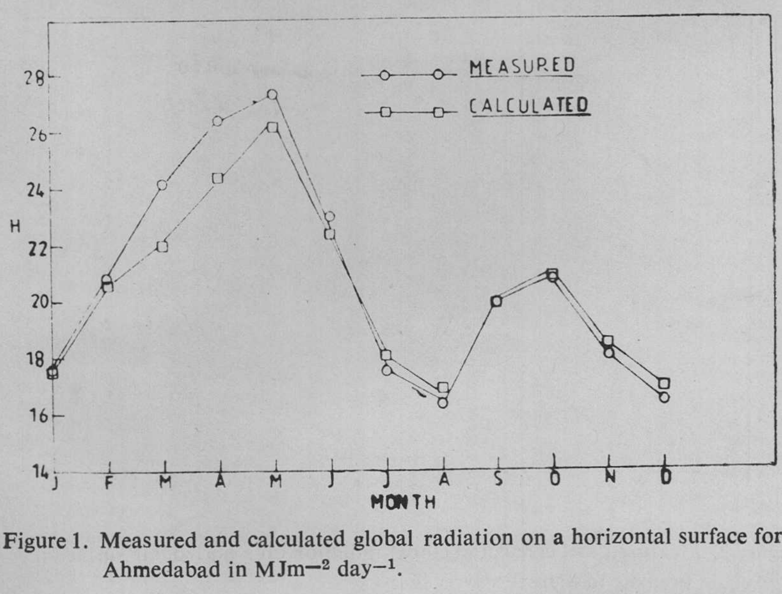

Figure 1. Measured and calculated global radiation on a horizontal surface for Ahmedabad in MJm^{-2} day^{-1}.

measured and estimated monthly average daily global solar radirtion, on a horizontol surface, for Ahmedabad. This station is at latitude 23.03°N, longitude 72.6°E and of elevation 55 m. The relative percentage error in the estimated global solar radiation, for the twelve months of the year, for this station are 0.6, 1.3, 9.4, 7.2, 4.5, 3.1, 3.8, 4.0, 1.8, 0.5, 3.0 and 2.0 respectively. the relative percentage error (e) values are calculated from experession.

$$e = \frac{H_{i,\,meas} - H_{i\,cal}}{H_{i,\,meas}} \times 100$$

The maximum percentage error of 9.4 percent is during March for this station. Only during the months of March and April the error is above five percent. In all the remaining months, the percent error values are very low. The MPE, MBE and RMSE values of the estimated data, for Ahmedabad, are 3.4, 1.9 and 5.0 percent respectively. Fig. 2 represents the estimated and measured global radiation values for Bombay. This station, in the sea coast, is at latituce 18.93°N, longitude 72.83°E and elevation 14 m. The relative percent errors for months from January to December, for this station, are 3.3, 3.0, 1.0, 1.4, 3.9, 4.0, 2.9, 2.5, 1.7, 5.0, 6.8 and 7.1. The percentage error never exceeds five percent except for the months of November, and December, when they are 6.8 and 7.1 percent respectively. The MPE, MBE and RMSE values for Bombay are 3.5, 2.0 and 3.8 respectively. Finally the measured and estimated global radiation values for Trivandrum are presented in Figure 3. Trivandrum is at latitude 8.48°N, longitude 76.97°E and elevation 64 m. The error in the estimated data for various months, for Trivandrum, are 0.6, 0.1, 3.6, 4.5, 2.1, 14.5, 9.5, 6.3, 8.1, 1.9, 1.0 and 2.0 percent respectively. The MPE, MBE and RMSE values are 4.5, 4.1 and 6.2 percent, for Trivandrum.

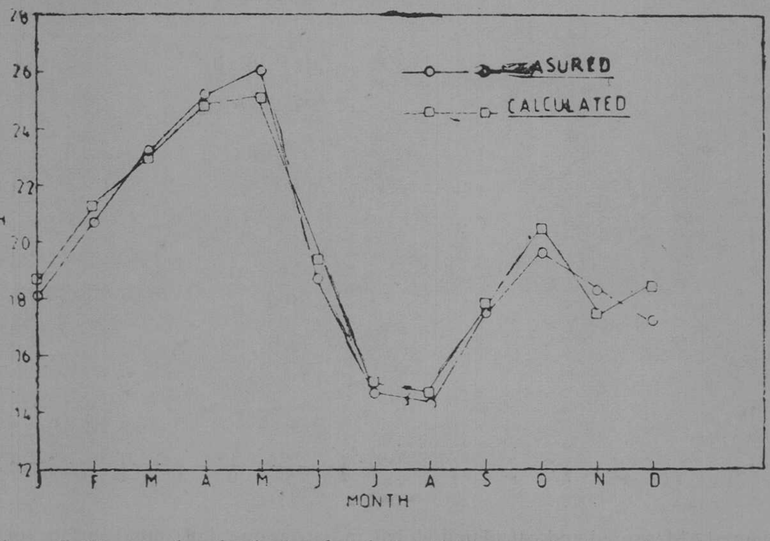

Figure 2. Measured and calculated global radiation on a horizontal surface for Bombay in MJm^{-2} day^{-1}.

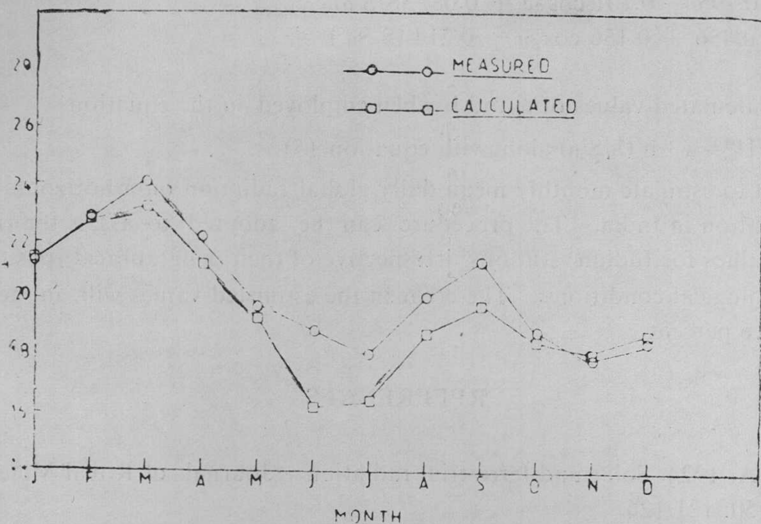

Figure 3. Measured and calculated global radiation on a horizontal surface for Trivandrum in $MJm^{-2} day^{-1}$.

As is seen from the results, there is a remarkable agreement between the measured and theoretical global radiation for all the stations during all the months of the year. The two values always agree well. The mean percentage errors given in Table 1 clearly demonstrate the accuracy of the estimated data. The percentage errors seldom exceed five percent and they are very low for most of the months, for all the stations. Such low values of mean percentage errors show the accuracy of the estimated data. The above observations are supported by the low MBE and RMSE values.

It should be remembered that none of these three locations were used in the linear regression analysis for obtaining the constants of equations (19) and (20). The fact that the estimated values of global radiation for these locations lie within five percent of the measure data during most of the months shows the wide applicability of the whole procedure for locations in India. The three locations selected to test the applicability of the developed equations are having different geographical and climatological conditions. These locations lie in the latitude range from 8.5°N for Trivandrum to 23°03N for Ahmedabad. Locations like Bombay and Trivandrum are in the sea coast while Ahmedabad is in the interior and the climate of the locations are different. However, the geographical position or the climatological conditions have not affected the accuracy of the estimated data and the model is applicable to any location in India irrespective of their geographical position or climatological conditions.

Correlations of the following form are recommended for calculating the regression coefficients a and b of Hay's type correlation for a global radiation.

$$a = 0.295 - 0.101 \cos \Phi + 0.082 (S/S'_0)$$
$$b = 0.456 + 0.136 \cos \Phi - 0.214 (S/S_0')$$

The calculated values of a and b when employed in the equation

$H'/H^0 = a + b (S/S'_0)$ alongwith equation (5)

can be used to estimate monthly mean daily global radiation on a horizontal surface for any location in India. The procedure can be adopted to assess the the global radiation values for Indian stations irrespective of their geographical positions and and climatological conditions. The error in the estimsted values will, in general, be of about five percent.

REFERENCES

Angstorm, A. 1924. Solar and terrestrial radiation. Journal of Royal Meterological Society 50: 121-126.

Black, J.R., Bonython, C.W. and Prescott, J.A. 1954. Solar radiation and duration of sunshine. Journal of Royal Meteorological Society 80 : 231-235.

Glover, J. and McCulloch, J.D.G. 1958. The empirical reletion between solar radiation and hour of bright sunshine. Journal of Royal Meteorological Society 84 : 172-175.

Hay, J.E. 1979. Calculation of monthly mean solar radiation for horizontal and inclined surfaces. Solar Energy 23 : 301-307.

Jeevananda Reddy, S. 1971. An empirical method for the estimation of total solar radtation. Solar Energy. 13 : 289-390.

Mani, A. and Chacko, O. 1972. Solar radiation climate of India, Solar energy 14:139.

Mani, A. and Rangarajan, S. 1983. Techniques for the precise n estimation of hourly values of global, diffuse and direct solar radiation. Solar Energy 31 : 577-599.

Rietveld, M.R. 1978. A new method for estimating the regression coefficient in the formula relating solar radiation to sunshine. Agricultural Meteorology 19 : 243-252.

Vijay Modi and Sukhatme, S.P. 1979. Estimation of daily total and diffuse insolation in India from weather data. Solar Energy 22 : 407-411.