Chapter 61
Statistical Analysis of Short-Term Solar Radiation Data over Aligarh (India)

Basharat Jamil and Naiem Akhtar

Abstract This study aims at exploring solar radiation in the Aligarh region of India (latitude, 27.88°N; longitude, 78.08°E), due to the fact that measured solar radiation data for this region is scarce. A new set of regression coefficients for the Angström-type correlation for estimation of monthly average daily solar radiation on horizontal surfaces in Aligarh (India) has been presented. The regression coefficients were applied to the data of bright sunshine hours obtained from the Solar Energy Laboratory, Department of Mechanical Engineering, Aligarh Muslim University, during the period of September 2013 to February 2014. The results were compared with the correlations of other researchers available in literature and solar radiation data obtained from measurements. Correlation for the estimation of monthly average diffuse solar radiation is also developed in terms of the ratio of diffuse to global radiation. The performances of the proposed correlations were analyzed by mean bias error and root mean square error. A good agreement was found between the estimated and measured values following the application of the new proposed correlations. Thus, monthly average global, diffuse, and direct solar radiation on a horizontal surface in the Aligarh region of India has been obtained.

Keywords Aligarh (India) • Experimental measurement • Horizontal surface • Regression coefficients • Solar radiation

Nomenclature

$\overline{H}$	Monthly average global solar radiation (MJ/m^2-day)
$\overline{H}_0$	Monthly average extraterrestrial solar radiation (MJ/m^2-day)
$\overline{H}_d$	Monthly average diffuse solar radiation (MJ/m^2-day)
$\overline{H}_b$	Monthly average beam solar radiation (MJ/m^2-day)
H_{sc}	Solar constant

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n	Day of the year
$\overline{S}$	Monthly average duration of bright sunshine (h)
$\overline{S}_0$	Monthly average maximum possible sunshine duration (h)
$\overline{H}_{i,e}, \overline{H}_{i,m}$	ith calculated and measured values (MJ/m^2-day)
K_T	Monthly average of daily clearness index
K_D	Monthly average of daily diffuse index
$a, b, c,$ and d	Empirical constants
$\varnothing$	Latitude (degree)
δ	Solar declination angle (degree)
ω_s	Sunset hour angle (degree)
θ	Incidence angle (degree)

61.1 Introduction

The increase in energy demands over the globe because of the dramatic rise in human population and consequent increase in fossil fuel prices have led developing countries like India to shift their focus on renewable energy sources. Additionally, severe environmental problems (like global warming) caused by the unattended use of fossil fuels release a large amount of greenhouse gases (GHGs). Worldwide concern over the issue of rapid fossil fuel depletion and environmental degradation is critical.

Solar energy is a readily available source of alternative energy and is free of cost. It is therefore among one of the top contenders of alternative energy. Since solar energy is available in abundance, it can be utilized in varied applications. For this reason the focus on solar energy research has increased tremendously in recent years. Typical applications in different areas include solar water heating and distillation, solar crop drying, photovoltaics, building energy estimation, daylighting, energy storage, desalting, meteorological forecasting, etc., to name a few. Knowledge of solar energy is fundamental for analysis of such solar energy applications.

Global solar radiation is fundamentally composed of two components, namely, direct (or beam) radiation and diffuse radiation [1]. Solar energy applications require a complete detailed analysis of these components so that the potential of the site for solar energy utilization can be evaluated.

61.2 Solar Radiation Measurements

For the purpose of analysis and further utilization in solar energy conversion systems, measurement of solar radiation at the ground level is an important issue. The radiation information at the ground level can be gathered by pyranometers because it's the best way available for the price measurement of solar radiation and its components. Also, their operational cost is quite low with easy day-to-day maintenance of the apparatus.

Solar radiation data (global and diffuse) in this study were obtained from the Solar Energy Laboratory at the Department of Mechanical Engineering, Aligarh Muslim University, Aligarh (India). The data was collected over a period of 6 months from September 2013 to February 2014. Global solar radiation was measured using Kipp & Zonen CM-11 pyranometer, and diffuse horizontal solar radiation was measured using Kipp & Zonen CM-11 pyranometer with a shading ring (CM-121B). These measurements were continuously recorded for the sunshine duration and stored in Kipp & Zonen Datalogger LogBox. The difference of the global and diffuse solar radiation data provides the beam (or direct) horizontal solar radiation.

The hourly average daily values of global, diffuse, and direct solar radiations on a horizontal surface have been obtained during sunshine hours for the 6 months and are represented in Fig. 61.1.

The daily values of solar radiation are obtained by integrating the hourly distribution. All the data used in this study are recorded live for the past 6 months which are used for the ongoing research on solar energy. The daily average values of solar radiation and its component are represented in Fig. 61.2.

It shows the monthly average daily global, direct, and diffuse solar radiation data measured for the period of study. The monthly average daily global solar radiation is observed to be the highest for the month of September of the order of 21.7 MJ/m^2-day, while it is observed to be the lowest in January (15.1 MJ/m^2-day). The maximum and minimum values of monthly average daily diffuse radiation are 8.2 MJ/m^2-day in October and 5.4 MJ/m^2-day in December, respectively. The monthly average direct solar radiation values are 14.2 MJ/m^2-day in September to 8.1 MJ/m^2-day in January. The monthly average hours of bright sunshine for the 6 months under study are also shown in Fig. 61.3.

61.3 Materials and Methods

61.3.1 Correlations for Estimation of Solar Radiation Data

Solar radiation data are commonly available in the form of monthly average daily global radiation on a horizontal surface $\left(\overline{H}\right)$ and monthly average daily diffuse radiation $\left(\overline{H}_{\mathrm{d}}\right)$.

For the estimation of monthly average global solar radiation on a horizontal surface, the modified Angström-type regression equation is the most commonly used, which is of the form

$$\frac{\overline{H}}{\overline{H}_0} = a + b\frac{\overline{S}}{\overline{S}_0} \tag{61.1}$$

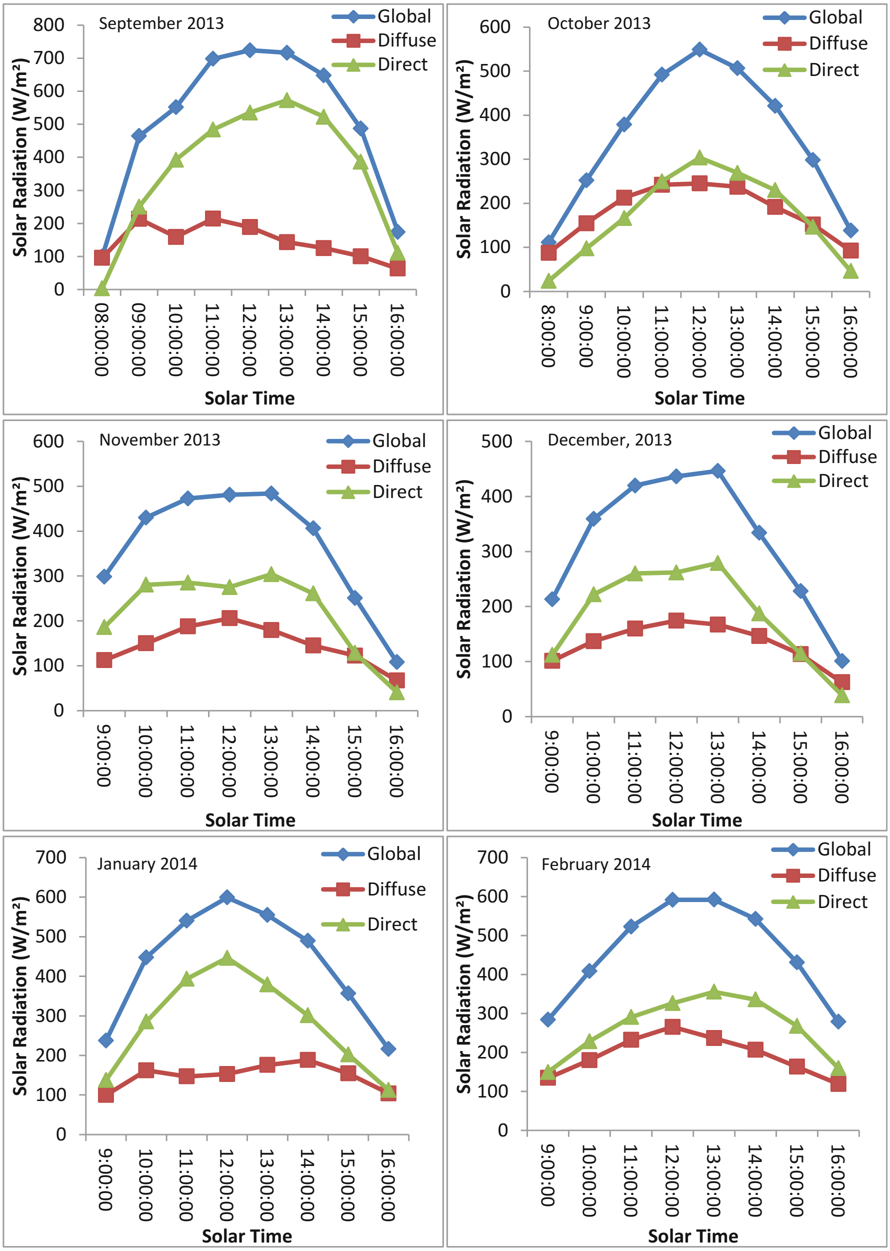

Fig. 61.1 Daily solar radiation for 6 months for the sunshine duration

where $\overline{H}$ is the monthly average global solar radiation on a horizontal surface, $\overline{H}_0$ is the monthly average extraterrestrial solar radiation, $\overline{S}$ is the monthly average duration of bright sunshine, $\overline{S}_0$ is the monthly average maximum possible sunshine duration, and a and b are the empirical coefficients [2–4].

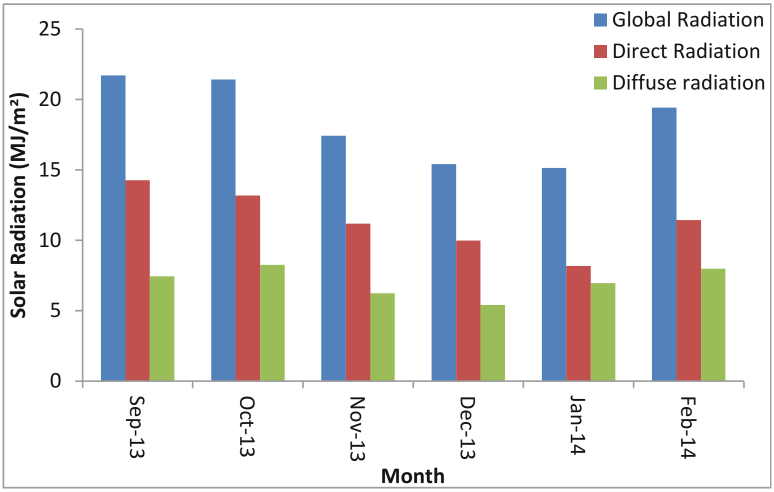

Fig. 61.2 Monthly average daily solar radiation on a horizontal surface in Aligarh

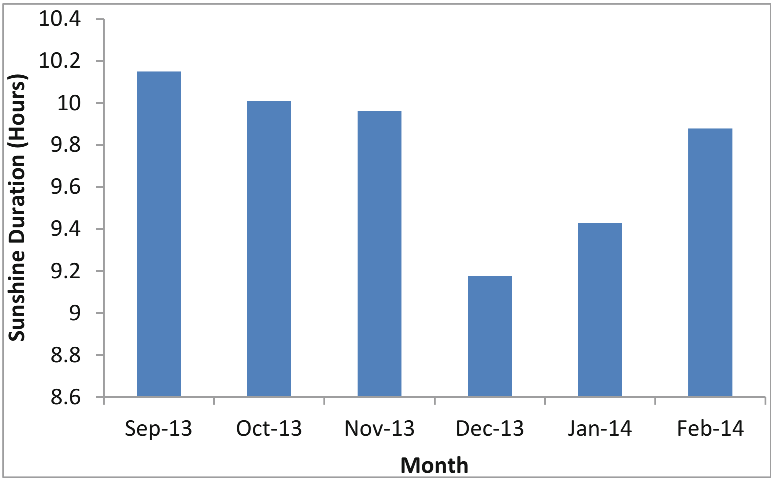

Fig. 61.3 Monthly average daily hours of sunshine in Aligarh

The monthly average extraterrestrial solar radiation $\left(\overline{H}_0\right)$ is computed from the following equation

$$\overline{H}_0 = \frac{24}{\pi} H_{sc} \left(1 + 0.033 \cos\left(\frac{360}{365} n\right)\right) \left(\cos \varnothing \cos \delta \sin \omega_s + \frac{\pi}{180} \omega_s \sin \varnothing \sin \delta\right) \tag{61.2}$$

where H_{sc} is the solar constant, n is day of the year for each month, $\varnothing$ is the latitude, and δ is the solar declination, which can be expressed as:

$$\delta = 23.45^\circ \sin\left[\frac{360(284+n)}{365}\right] \tag{61.3}$$

The maximum possible sunshine duration is given by

$$\overline{S}_0 = \frac{2}{15}\omega_s \tag{61.4}$$

where ω_s is the sunset hour angle, described in terms of inclination angle (θ) and declination angle (δ) given as:

$$\cos\omega_s = -\tan\theta\tan\delta \tag{61.5}$$

The calculation of monthly average diffuse solar radiation takes on a similar form as Eq. (61.1), with the ratio of monthly average diffuse solar radiation to global solar radiation described as a function of the ratio of monthly average global to extraterrestrial solar radiation

$$\frac{\overline{H}_d}{\overline{H}} = c + d\frac{\overline{H}}{\overline{H}_0} \tag{61.6}$$

where $\left(\overline{H}_d\right)$ is the monthly average daily diffuse radiation on a horizontal surface and c and d are the empirical coefficients.

Klein [5] has simplified the calculation of $\left(\overline{H}_0\right)$, by determining the particular day of each month for which the extraterrestrial radiation is nearly equal to the monthly mean value. These are as follows: January 17, February 16, March 16, April 15, May 15, June 11, July 17, August 16, September 15, October 15, November 14, and December 10.

The regression coefficients a and b in Eq. (61.1) have been estimated from $\overline{H}/\overline{H}_0$ and $\overline{S}/\overline{S}_0$ by fitting the data with a linear curve. Similarly, c and d in Eq. (61.6) are obtained from the linear fitting of $\overline{H}_d/\overline{H}$ and $\overline{H}/\overline{H}_0$ data points.

61.3.2 *Performance of Correlations*

The most commonly used statistical measures to analyze the performance of a correlation in estimating a value are *mean bias error* and *root mean square error*. These are described below.

61.3.2.1 Mean Bias Error

The long-term performance of a correlation for estimating a value is provided by the mean bias error (MBE). It allows the comparison of actual deviation between the estimated and measured value for each term. A smaller value of MBE is preferred and ideally it should be zero. Mathematically, it is defined as:

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}\left(\overline{H}_{i,\mathrm{e}} - \overline{H}_{i,\mathrm{m}}\right) \quad (61.7)$$

A positive value gives the average amount of overestimation in the calculated value and vice versa. One drawback of this test is that overestimation of an individual observation will cancel underestimation in a separate observation.

61.3.2.2 Root Mean Square Error

The root mean square error (RMSE) provides information on the short-term performance of the correlation. The value of RMSE is always positive and ideally it should be zero. It is mathematically represented as:

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\overline{H}_{i,\mathrm{e}} - \overline{H}_{i,\mathrm{m}}\right)^2\right]^{1/2} \quad (61.8)$$

61.4 Results and Discussion

In the present study, observations of bright sunshine hours and monthly average daily solar radiations values are utilized to compute the regression coefficients *a* and *b*. The monthly average values of $\overline{H}/\overline{H}_0, \overline{H}_\mathrm{d}/\overline{H}$, and $\overline{S}/\overline{S}_0$ during the period of 6 months from September 2013 to February 2014 are provided in Table 61.1.

Table 61.1 Monthly average values of $\overline{S}/\overline{S}_0$ and K_T and K_D in Aligarh

Month	$\frac{\overline{S}}{\overline{S}_0}$	$K_\mathrm{T} = \frac{\overline{H}}{\overline{H}_0}$	$K_\mathrm{D} = \frac{\overline{H}_\mathrm{d}}{\overline{H}}$
September 2013	0.835973	0.641421184	0.342954825
October 2013	0.886182	0.755465365	0.385027375
November 2013	0.940192	0.743277021	0.358245175
December 2013	0.894261	0.727941221	0.351644088
January 2014	0.902465	0.671231903	0.45988537
February 2014	0.894948	0.72442449	0.411624032

where K_T and K_D are the monthly average sky clearness index and monthly average diffusion index, respectively.

61.4.1 Correlations for Estimation of Monthly Average Global Solar Radiation

Many researchers have modified the Angström-type model for the conditions of solar radiation over a variety of locations all over the world and have presented the values of coefficients *a* and *b*.

Rietveld [6] proposed a model for monthly average global solar radiation that is applicable worldwide. It is given as follows:

$$\frac{\overline{H}}{\overline{H}_0} = 0.18 + 0.62\frac{\overline{S}}{\overline{S}_0} \quad (61.9)$$

Garg and Garg [7] obtained the following equation from the experimental data of 11 stations in India:

$$\frac{\overline{H}}{\overline{H}_0} = 0.3156 + 0.4520\frac{\overline{S}}{\overline{S}_0} \quad (61.10)$$

For the present case, the regression coefficients *a* and *b* of the Angström-type correlation for the monthly average daily values of solar radiation was determined and is given in Table 61.2.

To evaluate the suitability of the present correlation, the mean bias error (MBE) and root mean square error (RMSE) are evaluated and the values are shown in the table below.

The measured and estimated values of monthly average global solar radiation using the described correlations are displayed in Fig. 61.4.

It can be seen from Fig. 61.4 that a good agreement is found between estimations and actual measurement using the new correlation. This is also justified by the values of MBE and RMSE in Table 61.2.

61.4.2 Correlations for Estimation of Monthly Average Diffuse Solar Radiation

As stated earlier, for the estimation of monthly average daily diffuse radiations, the ratio of diffuse to global radiation could be correlated against the ratio of global to extraterrestrial solar radiation as given by Eq. (61.6).

Table 61.2 Performance of correlations in estimating monthly average global solar radiation

Correlation	Coefficient		MBE	RMSE
	a	*b*		
Rietveld	0.1800	0.6200	0.60	0.34
Garg and Garg	0.3156	0.4520	0.24	0.31
Present case	0.0609	0.8646	−0.01	0.25

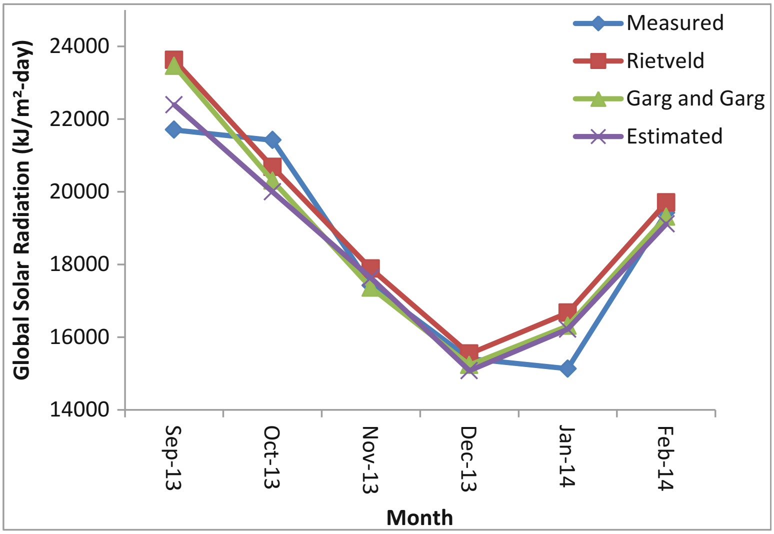

Fig. 61.4 Comparison of the measured and estimated values of monthly average global solar radiation

Table 61.3 Performance of correlations in estimating monthly average diffuse solar radiation

Correlation	Coefficient		MBE	RMSE
	c	*d*		
Modi and Sukhatme	1.411	−1.696	−1.56	0.29
Gupta et al.	1.354	−1.570	−0.73	0.26
Present Case	0.465	−0.113	0.03	0.07

Modi and Sukhatme [8] proposed a model for the monthly average diffuse solar radiation for Indian data. It is given as follows:

$$\frac{\overline{H}_{\mathrm{d}}}{\overline{H}} = 1.411 - 1.696\frac{\overline{H}}{\overline{H}_0} \tag{61.11}$$

Gupta et al. [9] obtained the following equation:

$$\frac{\overline{H}_{\mathrm{d}}}{\overline{H}} = 1.354 - 1.570\frac{\overline{H}}{\overline{H}_0} \tag{61.12}$$

Based on the measured data, a new correlation has been proposed for the estimation of monthly average diffuse radiation for the period of study. This case has been compared against the work of previous researchers described above. The results are exhibited in Table 61.3.

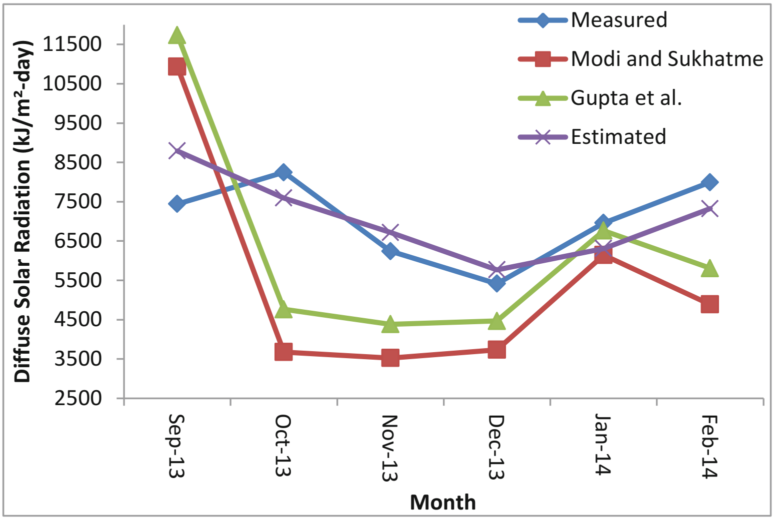

Fig. 61.5 Comparison of the measured and estimated values of monthly average diffuse solar radiation

It can be observed that the new proposed correlation is the most accurate. This statement is well supported by the fact that the values of MBE and RMSE are the least for new correlation (Fig. 61.5).

61.4.3 Estimation of Monthly Average Direct Solar Radiation

For the estimation of monthly average direct solar radiation, the difference of the monthly average global solar radiation and monthly average diffuse solar radiation (obtained from the new set of correlations) is done:

$$\overline{H}_{\mathrm{b}} = \overline{H} - \overline{H}_{\mathrm{d}} \tag{61.13}$$

The results are shown in Fig. 61.6. It can be observed that the estimated values of direct solar radiation closely follow the measured data.

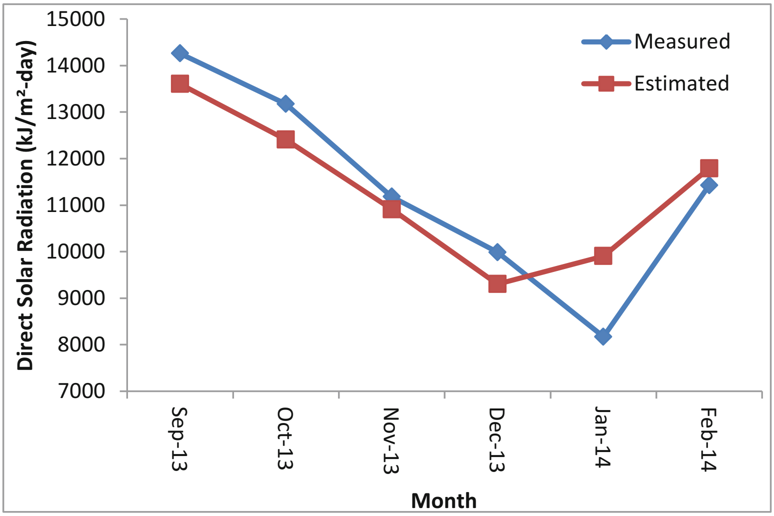

Fig. 61.6 Comparison of the measured and estimated values of monthly average direct solar radiation

61.5 Conclusions

Correlations for estimation of monthly average global solar radiation incident on a horizontal surface were applied to the sunshine hour data and compared statistically in terms of mean bias error and root mean square error. The new model correlation showed the highest level of accuracy when compared with the existing models. Also, the correlation for monthly average diffuse solar radiation on a horizontal surface was proposed. Again, the new correlation was found to be the best compared to other models. Thus, it can be concluded that the proposed correlation models are recommended for the estimation of solar radiation for the Aligarh region of India.

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