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# Correlations for the estimation of monthly mean hourly diffuse solar radiation: a time dependent approach

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**Abstract**
The time dependent monthly mean hourly diffuse solar radiation on a horizontal surface has been estimated for Lucknow (latitude26.75˚, longitude 80.50˚) using least squares regression analysis. The monthly and annually regression constants are obtained. The present results are compared with the estimation of Orgill-Holands (Sol. Energy, 19 (4), 357 (1977)), Erbs et. al (Sol. Energy 28 (4), 293-304(1982)) and Spencer (Sol. Energy 29 (1), 19-32(1982)) as well as with experimental value. The proposed constant provides better estimation for the entire year over others. Spencer, who correlate hourly diffuse fraction with clearness index, estimates lowest value except in summers when insolation in this region is very high. The accuracy of the regression constants are also checked with statistical tests of root mean square error (RMSE), mean bias error (MBE) and t –statistic tests.


**Keywords:** Latitude, Hourly diffuse fraction, Regression constant, Clearness index.

## 1. Introduction
Accurate estimation of solar radiation on the earth's surface is needed for many applications such as calculation of air-conditioning loads in buildings, design and performance evaluation of passive building-heating as well as solar energy collection and conversion systems[1]. These data are beneficial in areas of agriculture, water resources, day lighting and architectural design, and climate change studies. Unfortunately, the measuring stations that provide correct data of solar radiation are very rare particularly in northern region of India. Therefore, a suitable correlation becomes important to predict the solar radiation to serve the purpose.
Orgill-Holands (2), Erbs et. al (3) , Spencer (4) and Singh et. al. (5) estimates hourly diffuse radiation on horizontal surface. Notton et al. [6] and Jacovides et al. [7] studied the variation of the diffuse component with global irradiation on an hourly basis. Srivastava et al. [8] used one month data for comparing models in clear-sky conditions. Elminar [9] also correlates the diffuse fraction with both clearness index and sunshine fraction .These correlations are based on diffuse fraction with clearness-index; bright sun shine hours etc. but do not predict the acceptable data for entire year. Singh et al. [5] and Iqbal [10] used time based correlation for global solar radiation, which fortunately estimates comparatively good results.
The aim of this paper is to analyze long term collection of global and diffuse radiation data and to present new regression constants. Therefore, a time dependent correlations have been developed and regression

constants are obtained for estimating hourly diffuse solar radiation on horizontal surface. The validity of constants has been tested by comparing present results with other theoretical models [2-4].

**2. Experimental setup**

The measurement of diffuse radiation is made for two years with a pyranometer by shading the instrument from beam radiation with a thick strip of 50 mm wide whose inner surface is black polished to avoid any extra radiation. The instrument used for continuous recording of the diffuse radiation without the positioning of shading devices. An adjustment is made after a few days by changing the declination. The global radiation is also measured with another pyranometer with calibration factor 5.37mV/cal/cm$^2$/min at same location of the Institute of Engineering & Technology, Lucknow (latitude 26.75˚, longitude 80.50˚).

**3. Data analysis and methodology**

*3.1 Orgill - Hollands correlation (1977)*

Orgill - Hollands Correlation [2] is based on the analysis of data collected at Toronto (43˚48'), Canada with the help of shadow band pyranometer. This correlation divides the sky cover into three parts depending upon the value of clearness index ($M_T$**),** and the ratio of the monthly mean hourly diffuse radiation ($I_d$) to monthly mean hourly global radiation ($I$) is given as:

$$
\begin{aligned}
I_d / I &= 1.0 - 0.249 * M_T \qquad \text{for} \quad 0 \le M_T \le 0.35 \\
&= 1.577 - 1.84 * M_T \qquad \text{for} \quad 0.35 \le M_T \le 0.75 \\
&= 0.177 \qquad \text{for} \quad M_T \rangle 0.75
\end{aligned}
\tag{1}
$$

*3.2 Erbs correlation (1982)*

Erbs [3] proposed a similar correlation model using data from five US locations which includes up to the fourth power of $M_T$ :

$$
\begin{aligned}
I_d / I &= 1.0 - 0.09 * M_T \qquad \text{for} \quad M_T \le 0.22 \\
&= 0.9511 - 0.1604 * M_T + 4.388 * M_T{}^2 - 16.638 * M_T{}^3 + 12.336 * M_T{}^4 \\
&\qquad \text{for} \quad 0.22 \le M_T \le 0.80 \\
&= 0.165 \qquad \text{for} \quad M_T \rangle 0.80
\end{aligned}
\tag{2}
$$

*3.3 Spencer correlation (1982)*

Spencer [4] used the following correlation to estimate the ratio of the monthly mean hourly diffuse fraction:

$$I_d / I = a_4 - b_4 M_T \qquad \text{for} \qquad 0.35 \le M_T \le 0.75 \tag{3}$$

$$a_4 = 0.940 + 0.0118|\phi| \quad \text{and} \quad b_4 = 1.185 + 0.0135|\phi|$$

where $\phi$ is the latitude in degree.

We have analyzed measured diffuse data of past two years of northern India using least square curve fitting and proposed the following correlations to estimate hourly diffuse solar radiation on horizontal surface

$$I_d / I = a + bt + ct^2 \qquad (6:00 \le t \le 18:00) \tag{4}$$

where‘t’ is the local time in hours and ‘a’, ‘b’ and ‘c’ are correlation constants.

The relative percentage deviation (P) was calculated using the following formula:

$$P = \frac{(I_d / I)_M - (I_d / I)_C}{(I_d / I)_M} * 100 \tag{5}$$

where $(I_d / I)_M$ and $(I_d / I)_C$ are measured and calculated ratios respectively.

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## 4. The statistical tests

In the present study the root mean square error (RMSE), mean bias error (MBE) and t –statistic tests were used to evaluate the accuracy of the correlations described above.

*4.1 Root mean square error*

The root mean square error is defined as

$$\text{RMSE}=\left(\frac{1}{n}\sum_{i=1}^{n} d_i^{\,2}\right)^{\frac{1}{2}}$$

where n is the number of data pairs and $(d_i)$ is the difference between i th estimated and measured values.

*4.2 Mean bias error*

The mean bias error is defined as

$$\text{MBE}=\left(\frac{1}{n}\sum_{i=1}^{n} d_i\right)$$

The test provides information on the long term performance .A low MBE is desired.

*4.3 The t- statistic from the RMSE and MBE*

The statistic is defined as [11]

$$t=\left[\frac{(n-1)MBE^2}{RMSE^2-MBE^2}\right]^{\frac{1}{2}}$$

The smaller is the value of t, the better is the model's performance.

## 5. Results and discussion

We used least squares regression analysis to fit equation (4) to the data for each hour of the day and obtained values of the regression constants a, b, and c for each month of the year. The month wise regression constants derived for Lucknow are summarized in Table 1. The present calculated values of $(I_d / I)$ for entire year are compared with estimation of Orgill-Holands(2), Erbs et. al.(3) and Spencer (4) along with measured data. However, for the sake of space, we presented the comparisons for four months, January, April, July and October only through Figures 1 to 4.

Table 1. The regression constants a, b, and c for each month of the year

| Month | Regression Constants | | |
|---|---|---|---|
| | a | b | c |
| January | 0.01115 | -0.2682 | 1.909 |
| February | 0.01793 | -0.4366 | 2.893 |
| March | 0.00787 | -0.1836 | 1.297 |
| April | 0.00773 | -0.1798 | 1.327 |
| May | 0.01238 | -0.2900 | 2.000 |
| June | 0.01126 | -0.2760 | 1.974 |
| July | 0.01732 | -0.3993 | 2.591 |
| August | 0.00197 | -0.0413 | 0.612 |
| September | 0.00798 | -0.1808 | 1.332 |
| October | 0.01693 | -0.3972 | 2.597 |
| November | 0.01410 | -0.3033 | 1.992 |
| December | 0.01524 | -0.3489 | 2.342 |

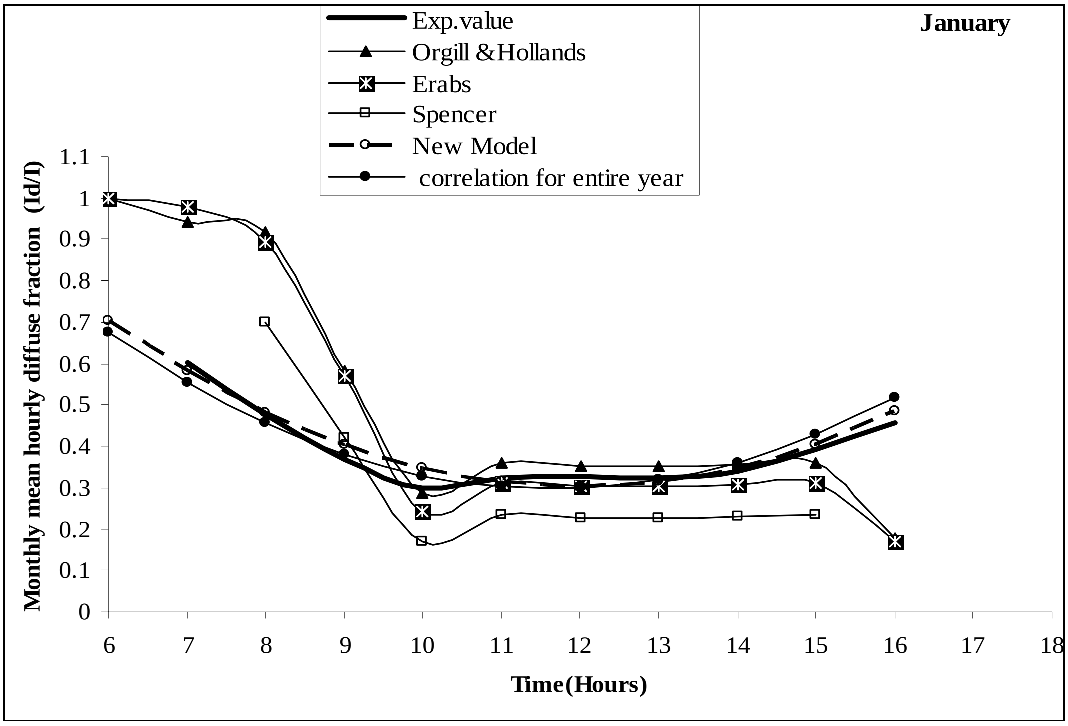


Figure 1. Variation of the monthly mean hourly diffuse radiation as a function of the time for January at Lucknow, India

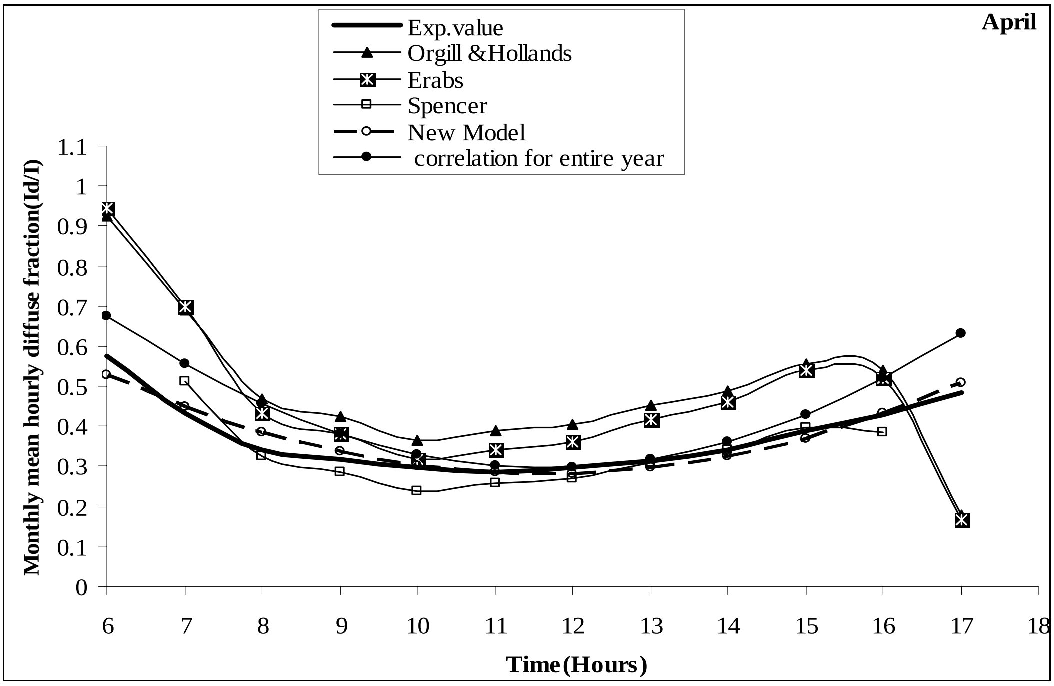


Figure 2. Variation of the monthly mean hourly diffuse radiation as a function of the time for April at Lucknow, India

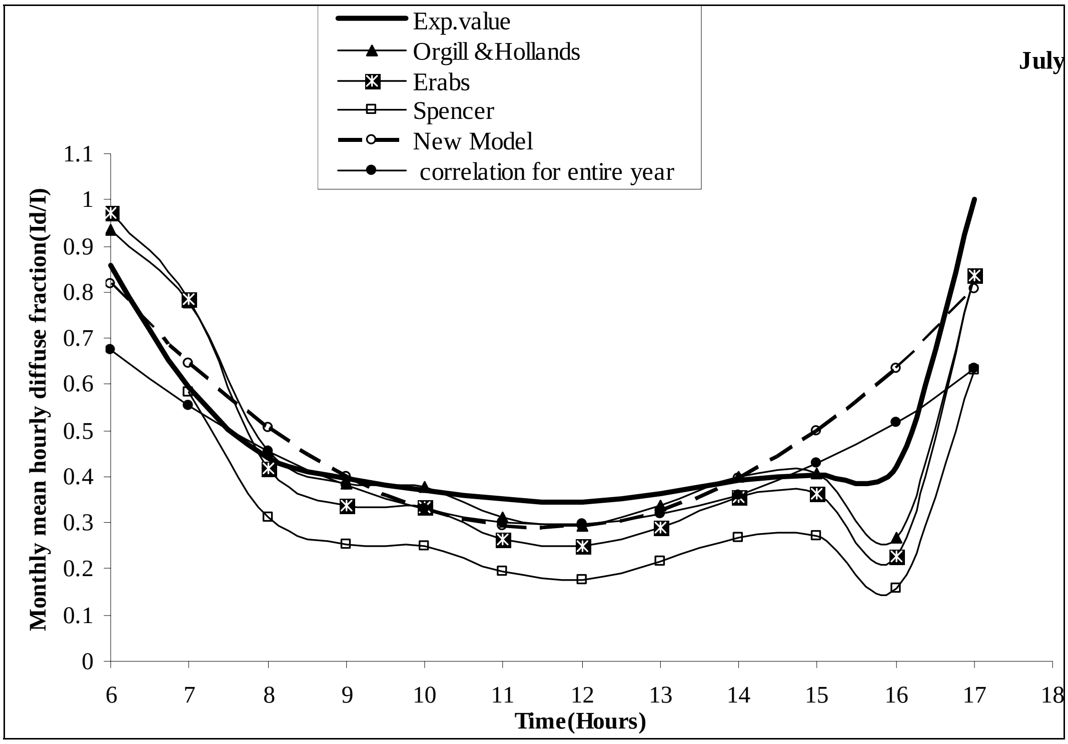


Figure 3. Variation of the monthly mean hourly diffuse radiation as a function of the time for July at Lucknow, India

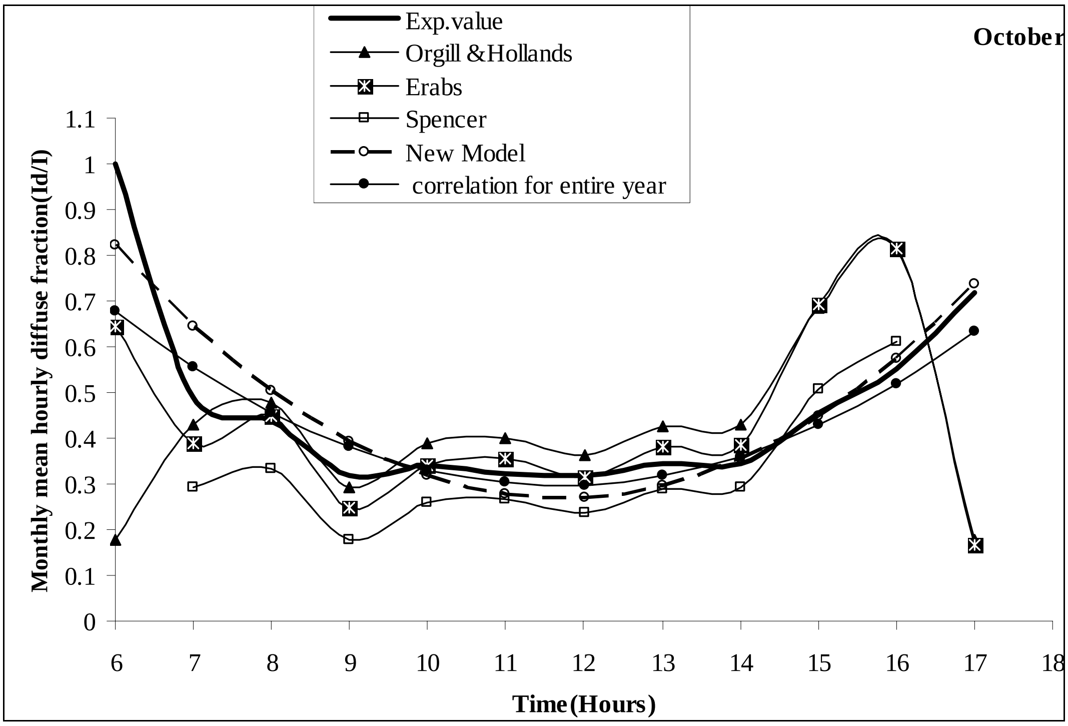


Figure 4. Variation of the monthly mean hourly diffuse radiation as a function of the time for October at Lucknow, India

From these figures, we observed that the present estimated values have close agreement with our measured diffuse fraction. The agreement is more pronounced between 9:00 and 16:00 hours for the entire year. There is small deviation from our measured values during morning and evening hours when solar insolation is quit weak. Among the other theoretical models, Orgill-Holands(2) and Erbs et. al.(3) estimation deviate more in comparison to Spencer [4] for the chosen location except during clear sky of April-May months when solar insolation is strong. In the morning up to 9 hours and in evening after 16 hours, it is very uncertain to predict theoretical results from any model.

We also averaged the hourly data of complete duration to fit equation (4) and obtained the following relation to evaluate the hourly diffuse radiation on horizontal surface.

$$(I_d / I) = 1.966 - 0.2888(t) + 0.0125(t)^2 \qquad (\text{for } 6:00 \le t \le 18:00) \qquad (6)$$

The estimated value of hourly diffuse radiation with equation (6) are also shown in the presented Figures 1-4 and observed that the estimates provide satisfactory results. It is observed that equation (6) is more appropriate for partially cloudy sky over any other correlations.

The accuracy of constants are also tested by calculating percentage estimation using equation (5) for all considered models and shown in Figure 5. The minimum variation is observed for present constants. The RMSE, MBE and t-static values for all the correlations are summarized in Table 2. A comparative study of the results shows that new constant model yield better results than all other correlations. Table 3 further validates the equation (6) for providing more accurate results of entire year.

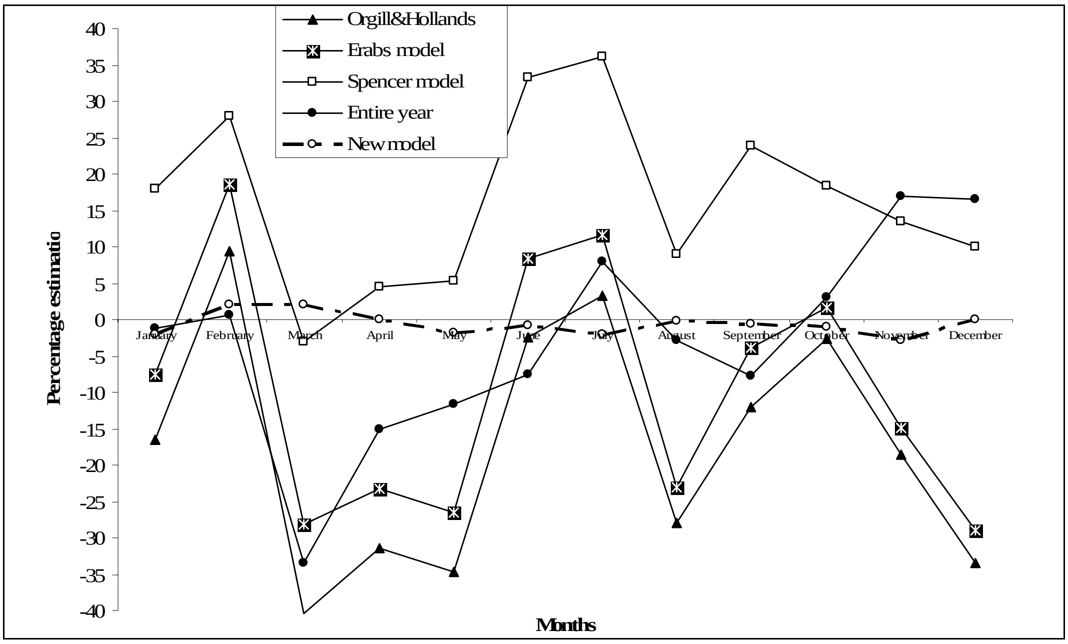


Figure 5. Month wise percentage estimation of monthly mean hourly diffuse radiation

Table 2. Comparison of root mean square error (RMSE), mean bias error (MBE) and t –statistic tests

| Month | Orgill&Hollands | | | Erbs model | | | Spencer model | | | New constant | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RMSE | MBE | t-static | RMSE | MBE | t-static | RMSE | MBE | t-static | RMSE | MBE | t-static |
| January | 0.316 | 0.077 | 0.705 | 0.362 | 0.048 | 0.438 | 0.253 | -0.146 | 1.917 | 0.213 | 0.007 | 0.107 |
| February | 0.353 | -0.11 | 1.090 | 0.359 | -0.14 | 1.350 | 0.486 | -0.324 | 2.186 | 0.121 | -0.029 | 0.807 |
| March | 0.231 | 0.113 | 1.630 | 0.219 | 0.080 | 1.200 | 0.199 | -0.034 | 0.565 | 0.052 | -0.014 | 0.912 |
| April | 0.186 | 0.114 | 2.030 | 0.179 | 0.089 | 1.653 | 0.220 | -0.098 | 1.483 | 0.023 | -0.001 | 0.145 |
| May | 0.146 | 0.124 | 2.820 | 0.133 | 0.098 | 2.454 | 0.240 | -0.086 | 1.196 | 0.059 | 0.007 | 0.402 |
| June | 0.068 | 0.012 | 0.583 | 0.086 | -0.02 | 0.933 | 0.285 | -0.185 | 2.141 | 0.072 | -0.001 | 0.041 |
| July | 0.089 | -0.07 | 2.792 | 0.109 | -0.25 | 7.716 | 0.303 | -1..31 | 14.28 | 0.095 | 0.008 | 0.272 |
| August | 0.247 | 0.102 | 1.374 | 0.248 | 0.082 | 1.099 | 0.213 | -0.038 | 0.590 | 0.200 | 0.001 | 0.015 |
| September | 0.149 | 0.040 | 0.889 | 0.158 | 0.010 | 0.220 | 0.161 | -0.099 | 2.056 | 0.356 | -0.000 | 0.001 |
| October | 0.305 | -0.04 | 0.518 | 0.219 | -0.03 | 0.572 | 0.366 | -0.198 | 1.778 | 0.079 | 0.001 | 0.017 |
| November | 0.330 | 0.090 | 0.902 | 0.332 | 0.075 | 0.746 | 0.319 | -0.057 | 0.590 | 0.045 | 0.009 | 0.699 |
| December | 0.359 | 0.159 | 1.452 | 0.345 | 0.141 | 1.355 | 0.357 | -0.221 | 2.038 | 0.036 | 0.007 | 0.089 |
| **Average** | **0.232** | **0.052** | **1.398** | **0.229** | **0.015** | **1.65** | **0.284** | **-0.135** | **2.57** | **0.113** | **0.0005** | **0.292** |

Table 3. The percentage deviation of monthly mean hourly diffuse fraction

| Month | Orgill&Hollands Model Eq(1) | Erbs model Eq(2) | Spencer model Eq(3) | Present model with New constants | Entire year Correlation model Eq(6) |
|---|---|---|---|---|---|
| January | -16.5066 | -7.5740 | 17.8767 | -2.120 | -1.1645 |
| February | 9.4760 | 18.5355 | 27.9461 | 1.9698 | 0.5500 |
| March | -40.5069 | -28.0712 | -3.0130 | 2.0864 | - 33.4300 |
| April | -31.4440 | -23.3519 | 4.4491 | 0.0637 | -15.1392 |
| May | -34.6443 | -26.5853 | 5.2288 | -1.7479 | -11.6330 |
| June | -2.3789 | 8.2664 | 33.1764 | -0.7465 | -7.4610 |
| July | 3.3482 | 11.6709 | 36.1026 | -1.9654 | 7.9518 |
| August | -27.9018 | -23.0231 | 8.9660 | -0.1561 | -2.9067 |
| September | -11.9561 | -3.9002 | 23.8013 | -0.6993 | -7.8558 |
| October | -2.5659 | 1.6524 | 18.4355 | -1.0004 | 3.0596 |
| November | -18.6669 | -14.8633 | 13.4931 | -2.7603 | 16.9859 |
| December | -33.3954 | -28.9433 | 9.9461 | 0.0079 | 16.4774 |

## 6. Conclusion

The estimated result using present regression constants and measured values are in close agreement (shown for Lucknow) which is more pronounced during bright sunshine hours. Therefore, monthly mean hourly diffuse solar radiation on horizontal surface can be satisfactory estimated for northern region of India with new regression constants. The applicability of the time dependent correlations for the other part of the world can also to be tested for further improvement.

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