Estimates of solar radiation over India

H. R. GANESAN
Meteorological Office, Poona
(Received 27 August 1968)

ABSTRACT. Some of the empirical relationships developed for the estimation of global solar radiation from sunshine and cloudiness data are discussed, and based on data for more than five years from a network of 10 principal radiation stations, a regression formula has been derived for the Indian area. This equation is then applied to sunshine and cloudiness data from 52 Indian stations to obtain estimated values of global solar radiation for four representative months January, May, July and October. May is considered, instead of April, as the values obtained in that month are higher than in April.

Global solar radiation is seen to be a maximum, exceeding 620 cal/cm²/day, in May over northwestern parts of the country and a minimum, less than 320 cal/cm²/day, in January over northern India.

Values of out-going longwave radiation have also been estimated, using Brunt's empirical formula and net radiation values calculated, assuming various values of albedo for various types of soil. It is seen that the distribution of outgoing radiation follows the general climatic pattern as determined by the temperature and vapour pressure and net radiation does not vary appreciably over the whole country during the summer monsoon season.

1. Introduction

In recent years considerable attention has been devoted to an understanding of the radiation climate of different areas of the world. In India, the network of radiation stations consists of 24 stations, of which 15 are equipped with Moll-Goreczynski pyranometers and the rest with Eppley pyranometers or bimetallic pyranographs to give continuous records of global solar radiation on a horizontal surface. This network is not adequate for providing a detailed picture of the distribution of global solar radiation over India. Records of sunshine have, however, been made at 52 stations over long periods in India using Campbell-Stokes sunshine recorders and sunshine and cloudiness data have been used by various authors to estimate value of global solar radiation using empirical formulae relating the two.

In the present paper values of (i) global solar radiation have been estimated from sunshine records at 52 stations using a Angstrom's modified equation and maps prepared showing the geographical distribution of global solar radiation for different seasons, (ii) outgoing longwave radiation have been calculated using Brunt's formula and maps prepared showing the geographical and seasonal variations, and (iii) net radiation calculated from the computed values of global solar and outgoing longwave radiation and assumed values of albedo. The seasonal and geographical variations are discussed.

2. Estimation of global solar radiation

2.1. Angstrom (1924) developed the following empirical relationship—

\[ Q = Q_0 \left( a' + b' n/N \right) \]  \hspace{1cm} (1)

where \( Q \) and \( Q_0 \) are the daily sums of global radiation actually received on any day and on a cloudless day respectively; \( n \) and \( N \) the actual and the maximum possible duration of sunshine respectively; \( a' \) is the coefficient equal to \( a \) on an overcast day and \( b' \) is the coefficient equal to \( b \) on a cloudless day. Since the coefficient \( a' \) in Angstrom's equation is dependent on the type and thickness of clouds and \( Q_0 \), instead of being constant, varies as a result of absorption by water vapour and scattering and diffuse reflection by aerosols, \( Q_0 \) has been replaced by \( Q_A \), which is the radiation received on a horizontal surface at the top of the atmosphere or which would be received on the surface if there were no atmospheric depletion and the relationship is given by the modified equation—

\[ Q/Q_A = a + b \left( n/N \right) \]  \hspace{1cm} (2)

The coefficients, \( a \) and \( b \) of Eq. (2) will have different values from \( a' \) and \( b' \) of (1). On an overcast day, \( a \) will be equal to \( Q/Q_A \) and this may be expected to be less than \( Q/Q_0 \) since \( Q_0 \) is smaller than \( Q_A \), due to atmospheric depletion. The coefficients \( a' \) and \( b' \) of Eq. (1) are related to coefficients \( a \) and \( b \) of Eq. (2) as follows.


<table>
<thead>
<tr>
<th>Author</th>
<th>Location</th>
<th>Latitude</th>
<th>Regression constants</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(a')</td>
<td>(b') (a) (b)</td>
</tr>
<tr>
<td>Angstrom</td>
<td>Stockholm</td>
<td>50.4°N</td>
<td>0.25</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>(Sweden)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kimball and Hand (1936)</td>
<td>Washington</td>
<td>47.3°N</td>
<td>0.22</td>
<td>0.78</td>
</tr>
<tr>
<td>Fritz and MacDonald (1949)</td>
<td>Long term data for U.S.</td>
<td>0.33</td>
<td>0.61</td>
<td>0.88</td>
</tr>
<tr>
<td>Houssain, C.E. (1956)</td>
<td>Australian data</td>
<td>0.34</td>
<td>0.66</td>
<td>0.88</td>
</tr>
<tr>
<td>Raman, P.K.</td>
<td><em>Poona</em></td>
<td>18.5°N</td>
<td>0.37</td>
<td>0.68</td>
</tr>
<tr>
<td>Mani, <em>et al.</em></td>
<td><strong>Poona</strong></td>
<td>18.5°N</td>
<td>0.44</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td><strong>New Delhi</strong></td>
<td>28.6°N</td>
<td>0.38</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td><strong>Calcutta</strong></td>
<td>22.7°N</td>
<td>0.33</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td><strong>Madras</strong></td>
<td>13.0°N</td>
<td>0.37</td>
<td>0.49</td>
</tr>
<tr>
<td>Glover McCulloch (1958)</td>
<td>Kabate (East Africa)</td>
<td>1.3°S</td>
<td>0.23</td>
<td>0.62</td>
</tr>
<tr>
<td>Black, <em>et al.</em> (1954)</td>
<td>Rothamsted (England)</td>
<td>51.8°N</td>
<td>0.18</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>Geulpho (Belgium)</td>
<td>50.6°N</td>
<td>0.15</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Versailles (France)</td>
<td>48.8°N</td>
<td>0.23</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Mt. Stromlo</td>
<td>35.3°S</td>
<td>0.25</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Dry Creek (Australia)</td>
<td>34.8°S</td>
<td>0.30</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Poona</td>
<td>18.5°N</td>
<td>0.27</td>
<td>0.61</td>
</tr>
<tr>
<td>Mooley, <em>et al.</em> (1961)</td>
<td>Madras</td>
<td>13.0°N</td>
<td>0.39</td>
<td>0.61</td>
</tr>
<tr>
<td>Yadav, B.R. (1964)</td>
<td>New Delhi</td>
<td>28.6°N</td>
<td>0.28</td>
<td>0.71</td>
</tr>
</tbody>
</table>

*Based on one year data.

**Based on daily values of 1958.

Note — Ramdas and Yogananayanan (1954) have computed the values of \(Q\) the amount of radiation from the sun and audible clear sky per sq. cm at a horizontal surface per minute at the ground surface from the isopleths of \(Q\) computed by Fritz (1949) for different values of precipitable water vapour and air masses corresponding to the different hours of the day at selected stations and for the middle of each of the months of the year. From curves showing the computed diurnal variation of \(Q\), the total mean daily radiation \(Q_0\) for cloudless skies in different months of the year was estimated by integration and the above values of \(Q_0\) were utilised by Mani, *et al.* (1956) to determine the coefficients \(a'\) and \(b'\) of Angstrom’s formula for different stations in India.

When the sky is clear \(n/N\) is nearly 1 and \(Q\) becomes \(Q_0\). Hence,

\[
Q_0/Q_A = a + b
\]

(3)

Dividing Eq. (2) by (3)

\[
Q/Q_0 = a' + b' (n/N)
\]

(4)

Thus \(a' = a/a+b\) and \(b' = b/a+b\)

The coefficients \(a'\) and \(b'\) of Angstrom equation (1) and \(a\) and \(b\) of Angstrom’s modified equation (2) obtained by various workers in India and other countries are summarised in Table 1.

### 2.2. Data utilised

Global solar radiation data recorded by Moll-Goreczynski pyranometers at 10 stations in India with 5 or more years of data up to December 1968 were used in the present study.

The mean monthly values of \(Q_A\) for the latitudes of the 10 stations were obtained by plotting values given for specific latitudes and dates by List (1958). These are based on the value of 1.94 cal/cm²/min for the solar constant. Daily values of \(N\) were obtained from the times of sunrise and sunset for the 10 stations given in the Indian
ESTIMATES OF SOLAR RADIATION OVER INDIA

Ephemeris and Nautical Almanac and thus the mean monthly values of $N$ worked out.

Regression analysis was carried out between the monthly mean values of $Q/Q_A$ and $n/N$ for each month of the year for each of the 10 stations and computed values of annual coefficients for each station and combined 10 stations. The annual values only are given below—

<table>
<thead>
<tr>
<th>Coefficients of Eq. (2)</th>
<th>No. of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>Ahmedabad</td>
<td>0.31</td>
</tr>
<tr>
<td>Calcutta</td>
<td>0.29</td>
</tr>
<tr>
<td>Jodhpur</td>
<td>0.31</td>
</tr>
<tr>
<td>Kodaikanal</td>
<td>0.32</td>
</tr>
<tr>
<td>Madras</td>
<td>0.28</td>
</tr>
<tr>
<td>Nagpur</td>
<td>0.27</td>
</tr>
<tr>
<td>New Delhi</td>
<td>0.30</td>
</tr>
<tr>
<td>Poona</td>
<td>0.33</td>
</tr>
<tr>
<td>Trivandrum</td>
<td>0.35</td>
</tr>
<tr>
<td>Visakhapatnam</td>
<td>0.29</td>
</tr>
<tr>
<td>All 10 stations</td>
<td>0.32</td>
</tr>
</tbody>
</table>

It is seen that the variations from month to month for each station and for each month between stations are rather large, because of the small sample sizes from 5 to 11 years. Taking each month of the year for the 10 stations together, the sample size ranges between 81 to 101 and the variation of coefficients between months is also not very large. $'a'$ ranges from 0.28 to 0.43 and $'b'$ from 0.21 to 0.48. (Data not presented here).

When all 12 months in the year are considered for each station, the sample size ranges between 60 to 137 and the coefficients do not show large variations, i.e., $a$ ranges from 0.27 to 0.35 and $b$ from 0.40 to 0.54.

The total of 1046 samples from all 10 stations for 12 months of the year is considered therefore for deriving a modified Angstrom formula,

$$Q/Q_A = 0.32 + 0.43 \times n/N$$  (5)

and this has been used to compute $Q$ from sunshine data in the present study.

In view of the fact that (i) there is good agreement between computed coefficients both between stations using data for all months and between months using data for all stations, (ii) the computed values of coefficients $a$ and $b$ also compare favourably with the coefficients already derived by other workers for Indian stations (vide Table 1), and (iii) the correlation coefficient between the parameters $Q/Q_A$ and $n/N$ based on 1046 samples being 0.85, the general application of the equation (5) appears to be justified. Table 2 shows the computed mean values of global solar radiation by the present author using the relationship $Q/Q_A = 0.32 + 0.43 \times n/N$ and monthly means of global solar radiation based on actual measurements for all available years up to December 1968, for different months of the year for the 10 stations. It is interesting to note that the values compare very favourably.

Until such time as a long series of observations are available for a considerably greater number of radiation stations than the existing network in India, this method may serve as the basis for estimating the global solar radiation received at the earth’s surface at a large number of stations equipped with sunshine recorders, to study the radiation climatology of India.

2.3. Distribution of global solar radiation

Several workers in India have prepared monthly and annual global solar radiation maps for the Indian subcontinent and the Indian Ocean and the adjoining area based on observed and estimated values of global solar radiation using Angstrom’s equation (Mani et al., 1959, Venkataraman and Krishnamurthy 1965, Mani et al., 1966, Desikan et al., 1967, Chacko et al. 1967). The present study confirms their observations. The main features are illustrated in Fig. 1, which shows the distribution of global solar radiation for January, May, July and October and for the whole year. The intensity of global radiation is least in winter season and highest in summer.

In January, the value of global solar radiation increases almost latitudinally from north to south, except the area south of 15° N, influenced by the northeast monsoon. Low values in the extreme north are the result of the low solar altitude and the cloudiness due to the passage of western disturbances.

In May, the area of maximum intensity is over north Gujarat, with appreciably high values over Rajasthan, Punjab and Uttar Pradesh, regions of least cloudiness. Low values over northeast Rajasthan and surrounding Uttar Pradesh are presumably due to the presence of dust in the atmosphere in this season.

In July, a typical monsoon month, lowest values are naturally observed over the regions of
maximum clouding, increasing towards Northwest India and southeast peninsula where the southwest monsoon is feeble.

In October, a month of transition between the monsoon and winter conditions, global solar radiation is a maximum over the Gujarat and Rajasthan areas.

On the whole, values of global solar radiation vary from 400 to 500 cal/cm²/day. The region of maximum radiation lies over Gujarat, Saurashtra and Kutch. The major portion of the country receives global solar radiation between 450 to 500 cal/cm²/day.

3. Distribution of outgoing long wave radiation

Mani et al. (1964) have prepared maps showing the distributions month by month of the net outgoing and downward infra-red fluxes, based on measurements made at eight stations in India during 1958-1962.

In the present paper outgoing radiation was obtained from the empirical equation (Brunt 1939) for 52 stations equipped with Campbell stokes sunshine recorders.

\[ Q_b = 1440 \times \left( 0.47 - 0.067 \frac{e_d}{T_a} \right) \times \left( 0.1 + 0.9 n/N \right) \]

where, \( Q_b = \) outgoing or back radiation in cal/cm²/day,

\( e_d = \) mean surface vapour pressure (mb),

\( T_a = \) mean air temperature in °C,

\( \sigma = \) Stefan constant.

Fig. 2 shows the estimated distribution of outgoing radiation for January, May, July and October and for the whole year using the above equation. The distribution generally follows the climatic pattern determined by the temperature and vapour pressure. The main features are given below.

In January, the outgoing longwave radiation is a maximum, exceeding 200 cal/cm²/day and is centered over the arid zones of the country comprising Gujarat and Rajasthan. It shows a gradual decrease north and southwards and attains a minimum value of about 100 cal/cm²/day in the southeast of the peninsula, where the northeast monsoon is active.

In May, the area of maximum outgoing longwave radiation extends to and covers parts of Rajasthan, Uttar Pradesh and North Madhya Pradesh, and the outgoing longwave radiation is limited to 160 cal/cm²/day. It shows a rapid decrease excep
towards north and northeastwards attaining a minimum value of about 60 cal/cm²/day, in the extreme south peninsula.

In July, the area of minimum outgoing longwave radiation, which is less than 50 cal/cm²/day, is confined to areas where the southwest monsoon is active, from the west coast to Assam across the central parts of the country. The outgoing longwave radiation exceeds 60 cal/cm²/day over the northwest and southeast where the air is relatively dry.

In October, the area of maximum outgoing longwave radiation is over the arid zone parts of the country comprising Gujarat, Rajasthan, with values of about 180 cal/cm²/day while the south of the peninsula below 14° N continues to have low values of about 60 cal/cm²/day.

On the whole, the outgoing longwave radiation is a maximum over northern Gujarat and Rajasthan. It decreases from north to south and is least over southern peninsula.

4. Distribution of net radiation

Mani et al. (1966) have presented maps of net radiation for annual and four representative months, January, April, July and October, from available observations supplemented by calculations based on other meteorological measures. Harihara Ayyar and Krishnamurthy (1967) have presented maps showing the distribution of net radiation in each month of the year over the country from estimated values of net radiation (R) by deriving the formula \( R = (0.2R_{1} - 0.6[1+2(n/N)] + 0.15) \text{ cal/cm}^2/\text{min.} \) Where \( R_{1} \) is the radiation received outside the atmosphere, \( n \) and \( N \) are the actual and maximum possible duration of sunshine respectively.

In the present study, values of net radiation were computed for 52 stations for January, May, July
and October and for the whole year, from computed values of global solar radiation, outgoing longwave radiation and albedo.

The values of albedo ranging between 0.13 to 0.30 were selected from the facing table and are based mainly on the values found by Budyko for the different types of soils and vegetation in the different regions of the country.

In January, net radiation steadily decreases almost latitudinally from south to north and is a minimum over northern India, being less than 80 cal/cm²/day. It increases southwards attaining a maximum value exceeding 280 cal/cm²/day.

In May, net radiation is high over the country with maximum values exceeding 380 cal/cm²/day observed near the coastal regions. It is less than 300 cal/cm²/day in the northwest parts of the country, while in the south peninsula it steadily increases to a value of 380 cal/cm²/day. The net

<table>
<thead>
<tr>
<th>Name of Author</th>
<th>Type of Surface</th>
<th>Values of albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angstrom (1962)</td>
<td>Sand and rocks free from vegetation</td>
<td>0.15 to 0.30</td>
</tr>
<tr>
<td>Woods, grass fields, lands covered by other forms of vegetation</td>
<td>0.05 to 0.15</td>
<td></td>
</tr>
<tr>
<td>De Vries (1959)</td>
<td>Dry land and irrigated pastures</td>
<td>0.23</td>
</tr>
<tr>
<td>Budyko (1956)</td>
<td>Bare soil</td>
<td>0.05 to 0.15</td>
</tr>
<tr>
<td>(i) dark soil</td>
<td>0.10 to 0.20</td>
<td></td>
</tr>
<tr>
<td>(iii) moist grey soil</td>
<td>0.20 to 0.35</td>
<td></td>
</tr>
<tr>
<td>(iv) dry clay or grey soil</td>
<td>0.25 to 0.45</td>
<td></td>
</tr>
<tr>
<td>(v) dry light sandy soil</td>
<td>0.10 to 0.25</td>
<td></td>
</tr>
<tr>
<td>Fields</td>
<td>0.15 to 0.25</td>
<td></td>
</tr>
<tr>
<td>(vi) Meadows</td>
<td>0.20 to 0.30</td>
<td></td>
</tr>
<tr>
<td>(vii) Dry steppe</td>
<td>0.20 to 0.30</td>
<td></td>
</tr>
</tbody>
</table>
radiation is a minimum over Rajasthan and neighbourhood as a result of the increased dust contents in the atmosphere in summer, which reduces the incoming radiation with the outgoing longwave radiation remains high and unaffected because of low humidity, clear skies and high temperatures.

In July, net radiation over the western region of Madhya Pradesh and a narrow strip in extreme southeastern part of the peninsula, is slightly in excess of 300 cal/cm²/day. Over the rest of the country it is between 280 to 300 cal/cm²/day with very little geographical variations.

In October, higher values of net radiation exceeding 280 cal/cm²/day are observed south of 20° N. To the north of 20° N, it decreases and over arid parts of the country comprising Rajasthan, it is a minimum being less than 170 cal/cm²/day.

On the whole, net radiation decreases almost latitudinally from south to north. It is least over Rajasthan and highest over southeast peninsula.

5. Acknowledgements

The author wishes to express his grateful thanks to Shri K. N. Rao, Deputy Director General of Observatories (Climatology and Geophysics), for providing necessary facilities to carry out the investigation and to Shri V.N. Antarkar, Assistant Meteorologist, for his valuable guidance during the preparation of the paper.
REFERENCES

Angstrom, A.
Blaid, J. N., Bonython, C. W. and Prescott, J. A.
Budyko, M.I.
Chacko, O., Krishnamurthy, V. and Desikan, V.
Desikan, V., Swaminathan, M. S. and Chacko, O.
De Vries
Fritz, S.
Fritz, S. and MacDonald, T. H.
Glover, J. and McGulloch, J. S. G.
Harshara Ayyar, P. S. and Krishnamurthy, V.
Hounam, C. E.
Kimbal, H. H. and Hand, I. V.
List, R. J.
Mani, Anna, Chacko, O. and Venkiteswaran, S. P.
Mani, Anna, Swaminathan, M. S. and Venkiteswaran, S. P.
Mani, Anna, Chacko, O. and Iyer, N. V.
Mani, Anna, Chacko, O., Desikan, V. and Krishnamurthy, V.
Mani, Anna, Chacko, O. Krishnamurthy, V. and Desikan, V.
Mooley, D.J.A., Bodkar, V. C. and Raghavan, S.
Raman, P. K.
Ramadas, L. A., and Yegnanarayanan, S.
Venkataaraman, S. and Krishnamurthy, V.
Yadav, B. R.

1934 Ibid., 90, p. 231.
1968 Ibid., 19, 2, pp. 149-158.
1949 Heating and Ventilating, 46, p. 69.
1949 Heating and Ventilating, 46, p. 61.
1936 Biological effects of radiation, McGraw Hill.
1962 Ibid., 13, 2, pp. 195-212.
1967 Ibid., 18, 2, pp. 171-183.
1954 Solar energy in India, Proceedings of Symposium on wind and solar energy by the Arid Zone Research Committee of UNESCO, New Delhi, p. 188.
1907 Indian J. Met. Geophys., 18, 1, pp. 39-44.