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Estimates of solar radiation over India

H. R. GANESAN

Meteorological Office, Poona

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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 at present of 24 stations, of which 15 are equipped with Moll-Gorczynski 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—

$$Q = Q_O\,(a' + b'\,n/N) \qquad (1)$$

where Q and Q_O 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 the ratio of Q/Q_O on an overcast day and b' is the coefficient equal to $1—a'$ since $Q = Q_O$ on a cloudless day. Since the coefficient a' in Angstrom's equation is dependent on the type and thickness of clouds and Q_O, instead of being constant, varies as a result of absorption by water vapour and scattering and diffuse reflection by aerosols, Q_O 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 —

$$Q/Q_A = a + b\ (n/N) \qquad (2)$$

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_O since Q_O 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 1

Author	Location	Latitude	Regression constants				Correlation coefficient
			a′	b′	a	b	
Angstrom	Stockholm (Sweden)	59·4°N	0·25	0·75			
Kimball and Hand (1936)	Washington	47·3°N	0·22	0·78			
Fritz and MacDonald (1949)	Long term data for U.S.		0·35	0·61			0·88
Hounam, C.E. (1956)	Australian data		0·34	0·66			
Raman, P.K.	*Poona	18·5°N	0·37	0·68			
Mani, *et al.*	**Poona	18·5°N	0·44	0·51			0·93
	**New Delhi	28·6°N	0·38	0·57			0·90
	**Calcutta	22·7°N	0·33	0·48			0·84
	**Madras	13·0°N	0·37	0·49			0·89
Glover McCulloch (1958)	Kabate (East Africa)	1·3°S			0·23	0·62	0·97
Black, *et al.* (1954)	Rothamsted (England)	51·8°N			0·18	0·55	0·79
	Gembloux (Belgium)	50·6°N			0·15	0·54	0·83
	Versailles (France)	48·8°N			0·23	0·50	0·90
	Mt. Stromlo	35·3°S			0·25	0·54	0·89
	Dry Creek (Australia)	34·8°S			0·30	0·50	0·95
	Poona	18·5°N			0·27	0·61	
Mooley, *et al.* (1961)	Madras	13·0°N	0·39	0·61	0·30	0·46	0·93
Yadav B.R. (1964)	New Delhi	28·6°N	0·28	0·71	0·23	0·58	0 86

*Based on one year data.

**Based on daily values of 1958.

Note— Ramdas and Yegnanarayanan (1954) have computed the values of Q the amount of radiation from the sun and sunlit clear sky per sq. cm of 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_o for cloudless skies in different months of the year was estimated by integration and the above values of Q_o were utilised by Mani, *et al.* (1959) 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,

$$Q_0/Q_A = a + b \qquad (3)$$

Dividing Eq. (2) by (3)

$$Q/Q_0 = a' + b' \; (n/N) \qquad (4)$$

Thus $a' = a \div a{+}b$ and $b' = b \div a{+}b$

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-Gorczynski pyranometers at 10 stations in India with 5 or more years of data upto 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/cm^2/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*

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—

	Coefficients of Eq. (2)		No. of samples
	a	b	(s)
Ahmedabad	0·31	0·45	76
Calcutta	0·29	0·40	131
Jodhpur	0·31	0·48	60
Kodaikanal	0·32	0·54	79
Madras	0·28	0·46	135
Nagpur	0·27	0·49	103
New Delhi	0·30	0·47	137
Poona	0·33	0·41	126
Trivandrum	0·35	0·41	108
Visakhapatnam	0·29	0·46	91
All 10 stations	0·32	0·45	1,046

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 5-11 years. Taking each month of the year for the 10 stations together, the sample size ranges between 81 to 91 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,

$$Q/Q_A = 0{\cdot}32 + 0{\cdot}43\ n/N \qquad (5)$$

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 $Q/Q_A = 0{\cdot}32+0{\cdot}43\ n/N$ and monthly means of global solar radiation based on actual measurements for all available years upto 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

TABLE 2

Station		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Ahmedabad	I	420	480	533	579	630	560	451	414	470	502	438	402	490
	II	409	493	563	622	649	565	415	409	485	495	417	392	493
Calcutta/Dum Dum	I	396	445	508	561	564	453	423	405	420	420	394	379	448
	II	357	417	480	528	542	412	393	398	371	378	388	354	418
Jodhpur	I	375	449	502	584	611	586	500	468	508	497	412	364	488
	II	399	469	552	622	645	614	511	484	524	497	423	380	510
Kodaikanal	I	456	502	525	501	451	391	359	398	422	400	370	419	433
	II	509	561	555	535	510	445	369	398	428	391	393	458	463
Madras	I	480	526	557	567	543	495	412	445	466	432	428	420	482
	II	442	539	584	581	559	498	449	474	482	425	357	377	481
Nagpur	I	428	497	540	576	602	482	393	396	425	474	472	414	475
	II	421	501	543	581	599	501	377	370	434	490	442	403	472
New Delhi	I	335	410	472	546	580	485	468	468	456	452	380	325	448
	II	341	430	518	586	627	569	445	438	474	454	389	327	467
Poona	I	451	507	558	574	580	472	386	385	430	499	445	428	477
	II	446	524	578	611	620	514	389	393	445	484	435	413	488
Trivandrum	I	480	520	545	490	472	370	400	440	472	428	424	453	458
	II	499	534	559	526	466	445	416	461	488	453	419	444	476
Visakhapatnam	I	459	510	561	567	567	423	403	432	441	448	448	439	475
	II	452	521	554	567	576	425	392	444	441	434	436	432	473

I—Computed mean monthly values of global solar radiation in cal/cm²/day using the relationship $Q/Q_A = 0\cdot32 + 0\cdot43\, n/N$

II—Monthly means of global solar radiation in cal/cm²/day based on actual measurements for available years upto December 1968

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 counrty 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.

$$Q_b = 1440\, \sigma\, T_a^4\, (0\cdot47 - 0\cdot067\sqrt{e_d}) \times \times (0\cdot1 + 0\cdot9\, n/N)$$

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

e_d = mean surface vapour pressure (mb),

T_a = mean air temperature in °K and

σ = 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 centred 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

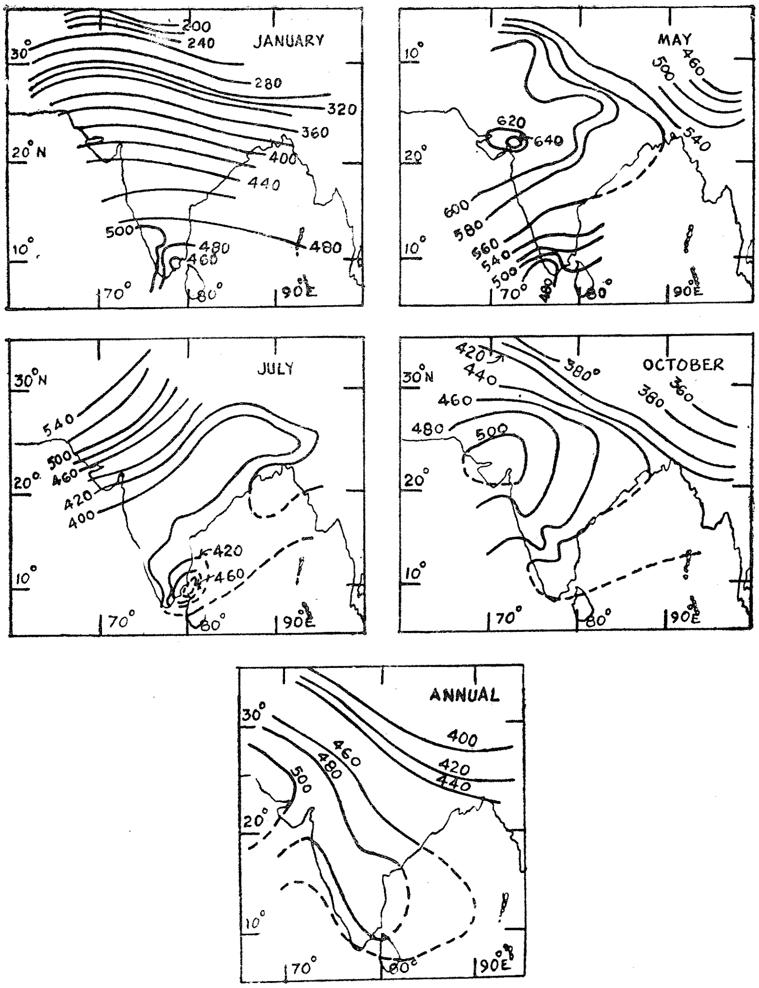

Fig. 1. Global radiation in cal/cm²/day

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 $R = (0{\cdot}2R_A - 0{\cdot}6\,[1+2(n/N)] + 0{\cdot}15)$ cal/cm²/min. Where R_A 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

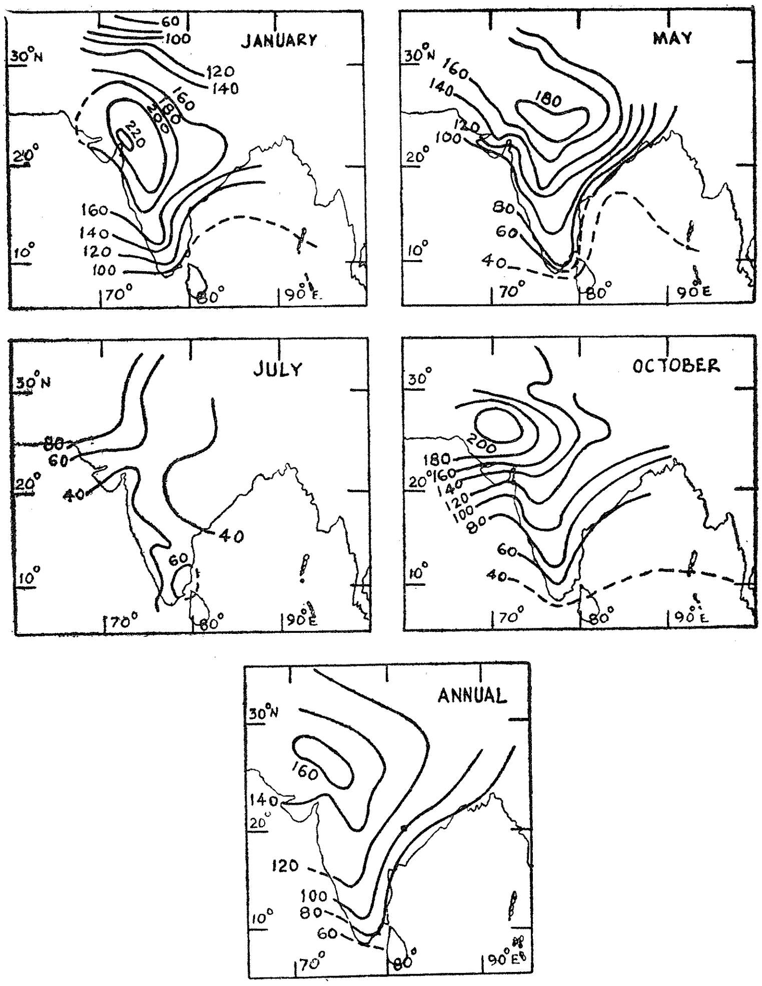

Fig. 2. Outgoing radiation in cal/cm²/day

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

Name of Author	Type of Surface	Values of albedo
Angstrom (1962)	Sand and rocks free from vegetation	0·15 to 0·30
	Woods, grass fields lands covered by other forms of vegetation	0·05 to 0·15
De Vries (1959)	Dry land and irrigated pastures	0·23
Budyko (1956)	*Bare soil*	
	(*i*) dark soil	0·05 to 0·15
	(*ii*) moist grey soil	0·10 to 0·20
	(*iii*) dry clay or grey soil	0·20 to 0·35
	(*iv*) dry light sandy soil	0·25 to 0·45
	Fields	
	(*i*) Rice and wheat fields	0·10 to 0·25
	(*ii*) Meadows	0·15 to 0·25
	(*iii*) Dry steppes	0·20 to 0·30

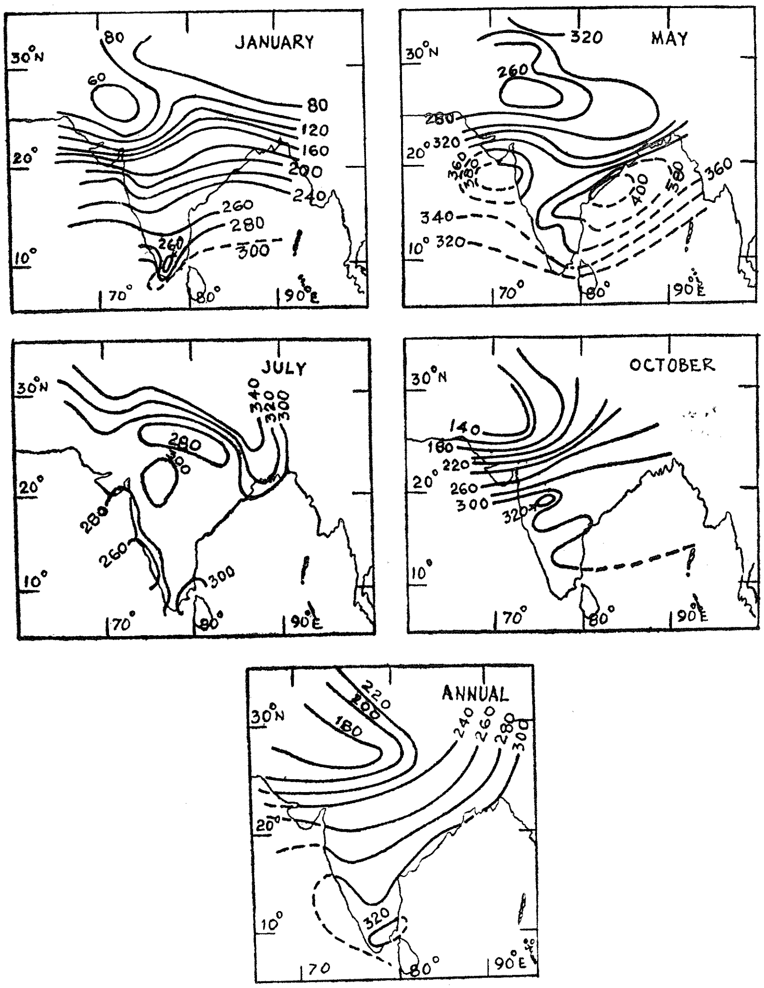

Fig. 3. Net radiation in cal/cm^2/day

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/cm^2/day. Over the rest of the country it is between 280 to 300 cal/cm^2/day with very little geographical variations.

In October, higher values of net radiation exceeding 280 cal/cm^2/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/cm^2/day.

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

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