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Absorption of short-wave radiation in the atmosphere over India in winter

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सार — विश्व मौसम संगठन के विश्व जलवायु कार्यक्रम के लिए विकिरण अध्ययनों की महता को ध्यान में रखते हुए विभिन्न ऋतुओं में भारत पर सौर और पार्थिव विकिरणों द्वारा वायुमंडलीय स्तंभ के उष्णक/शीतलक का जलवायु संबंधी अध्ययन किया गया। इस शोध पत्र में (भारत में) जनवरी माह में पृथ्वी से सूर्य और विसरित लघु तंरग विकिरण द्वारा प्रत्यक्ष लघु-तरंग विकिरण के वायुमंडल में अवचूषण (सोखने) को प्रस्तुत किया गया है। इससे पता चलता है कि आपतित प्रत्यक्ष और विकिरण अर्थात उष्मांक (अधिकम 1360W/m²) का लगभग केवल 25 प्रतिशत भाग वायु मंडल में (345W/m²) अवचूषित होता है और वायु मंडल के ऊपर स्थित कुल मात्रा का मात्र लगभग एक प्रतिशत 500 मि. बार तक अवचूषित होता है। 500 और 850 मि. बार के मध्य, इसका लगभग 26 प्रतिशत अवचूषण होता है किन्तु 850 मि. बार और सतह के मध्य यह 34 प्रतिशत होता है। इस प्रकार, वायु मंडल का सबसे नीचे के आधे भाग (500 मि. बार के नीचे) वायु मंडल में कुल लघु तरंग विकिरण के अवचूषित भाग का करीब-करीब 60 प्रतिशत सोख लेता है और इसका प्रमुख भाग सबसे नीचे के 1500 मीटर में सोख लिया जाता है।

ABSTRACT. Considering the importance of radiation studies for the World Climate Programme (WCP) of WMO, a climatic study of warming/cooling of the atmospheric column by solar and terrestrial radiations over India in different seasons has been undertaken. In this paper the absorption in the atmosphere of direct short-wave radiation from the sun and diffuse short-wave radiation from the earth in the month of January (over India) is presented. It shows that only about 25 per cent of the incident direct solar radiation, *viz.*, solar constant (Approx. 1360 W/m^2), is absorbed in the atmosphere (345 W/m^2) and upto 500 mb absorption is just about 1 per cent of the amount at the top of the atmosphere. Between 500 and 850 mb the absorption is about 26 per cent of it, but between 850 mb and the surface it is 34 per cent. Thus, the lowest-half of the atmosphere (below 500 mb) absorbs almost 60 per cent of the absorbed part of total short-wave radiation in the atmosphere and of this the major portion is absorbed in the lowest 1500 metres.

1. Introduction

It is well established that radiation processes play a very effective role in controlling the weather in tropics. For instance, the differential heating of the Indian sub-continent in summer has now been recognised as the main mechanism for triggering the monsoon (Krishnamurti 1979). It is also being recognised that for complete understanding of trade inversions, monsoons, African disturbances and many other weather processes in the tropics, the role of radiation must be fully understood.

In India, climatic study of radiation has been carried out since long based on sunshine records and later on radiation instruments' data (Mani *et al.* 1963, 1968, 1971, 1981). Recently Mani and Rangarajan (1982) studied the radiation climate of India for the entire year. Their study, however, gives the heat balance at the surface only. The effect of radiation processes in the atmosphere has not been given by them. In fact, studies on radiation budget of the troposphere are very few. Katayama's (1966, 1967, 1972) work which coveres the whole northern hemisphere seems to be one of the few.

In our effort to study the heat balance of the atmosphere over India we present here the climatic study of the short-wave radiation flux only over the country during winter season. In this study, only the effect of water vapour present in the atmosphere is considered. The contribution of other atmospheric constituents like ozone, CO_2, aerosols including dust particles which is of significance specially in the lower troposphere is not considered. The study will be extended finally to derive the heat budget of the troposphere over India throughout the year.

2. Data

For this study, mean monthly upper air data for the month of January for three years (1978-80) for all the nineteen Indian radiosonde stations (Table 1) published by WMO in the monthly climatic data of the world were used. From these data, three years' mean monthly temperature and dew point values, were worked out for surface, 850, 700, 600, 500, 400, 300, 200 and 100 mb levels for each station using both 0000 and 1200 UT observations. Using these mean temperature and dew point values, mixing ratios at all these levels were picked out with the help of tephigrams for each station.

Dew point temperatures were mostly available upto 500 mb level only. In order to estimate dew point temperature values at higher levels, one of the schemes proposed by Katayama (1966) was followed. The dew point curve was extended above 500 mb assuming that it

TABLE 1

Computation of absorbed part in incident solar radiation at top of the atmosphere during January (declination for January =22.2°, solar constant $S_0 \approx 1360$ W/m² and time of observation taken as 0060 GMT)

Station	Long. (°E)	Lat. (°N)	S^a (W/m²)
Srinagar	74° 50′	34° 05′	250.035
Delhi	77° 12′	28° 35′	291.477
Jodhpur	73° 01′	26° 18′	296.868
Lucknow	81° 00′	27° 00′	305.701
Gauhati	91° 36′	26° 06′	316.272
Ahmedabad	72° 38′	23° 04′	316.272
Calcutta	88° 20′	22° 32′	337.279
Nagpur	79° 03′	21° 06′	338.456
Bhubaneshwar	85° 30′	20° 15′	350.968
Bombay	72° 51′	19° 00	338.395
Hyderabad	78° 12′	17° 12′	358.395
Visakhapatnam	83° 18′	17° 41′	361.529
Goa	73° 49′	15° 29′	357.590
Madras	80° 11′	13° 00′	386.560
Mangalore	74° 53′	12° 55′	381.164
Port Blair	92° 43′	11° 40′	393.960
Cochin	76° 12′	9° 54′	389.640
Minicoy	73° 00′	8° 18	390.330
Trivandrum	76° 57′	8° 29′	395.610

(dew point curve) runs parallel to the air temperature curve upto tropopause and that the mixing ratio remains constant in the stratosphere. The mixing ratio (specific humidity) was thus calculated upto 100 mb level.

3. Numerical calculations

In dealing with tropical weather systems (Krishnamurti 1979) the following calculations are important with respect to position and time :

(*i*) Rate of warming of the atmosphere by short-wave (solar) radiation,

(*ii*) Rate of warming/cooling of the atmosphere by long wave (terrestrial) radiation and

(*iii*) Heat balance of the earth's surface.

In such calculations, prevailing conditions such as the vertical distribution of temperature, moisture, temperature of the underlying surface, nature of the surface, cloud-cover, cloud height, cloud thickness, vertical extension of dust and other atmospheric constituents like ozone, water vapour, CO_2 and nature of the earth's surface are important.

Here we have calculated only the effect of short wave radiation on the atmosphere over India during the month of January, assuming that the atmosphere in this month is mainly cloudless and free of dust in the climatological sense. Effect of surface topography and soil moisture have been ignored. Effects of ozone and other rare constituents of the atmosphere have also not been taken into consideration though important in the lower troposphere. Only the effect of water vapour (moisture content) in the atmosphere has been considered.

It is well known that scattering and absorption are the two main mechanisms which deplete the incident solar radiation in the atmosphere. The solar radiation incident at the top of the atmosphere is represented by solar constant (S_o) which has the value $S_o \approx 1360$ W/m². The expression for scattered and absorbed part of the incident solar radiation is given Katayama (1972) by

$$\text{Scattered part } S^s = 0.651 \; S_o \times \cos \nu \qquad (1)$$

$$\text{Absorbed part } S^a = 0.349 \, S_o \times \cos \nu \qquad (2)$$

where ν is the zenith angle of the sun. In this study 0600 GMT has been taken as time of observations.

4. Calculation of incident solar radiation at various levels

Assuming the top of the atmosphere at 0 mb the absorbed parts in the incident solar radiation at the top of the atmosphere (S_o) were worked out for each station (Table 1).

For calculation of the absorbed part of the incident solar radiation through different layers of the atmosphere the atmosphere has been divided into 100 mb thick layers down to 700 mb after which the two layers are 850 mb and surface (average pressure 1000 mb). For these calculations use has been made of concept of optical depth of the atmosphere which is a function of the mixing ratio, pressure and temperature distribution in the atmosphere. It is expressed by the relation (Kuhn 1963) :

$$W_p = \frac{1}{g} \int_0^p q \left(\frac{p}{p_o}\right)^{0.85} \left(\frac{T_o}{T}\right)^{0.5} dp \qquad (3)$$

where W_p is the 'optical depth' of the atmosphere at a reference level (p) estimated from the top of the atmosphere ($p \neq 0$). p_o, T_o are the normal pressure and absolute temperature (1013.2 mb and 288°K) at the surface, and. p, T are the pressure and temperature of the reference layer. q is the mixing ratio of the layer and dp is the depth of the layer in millibars. With the help of this equation, optical path length at the pressure levels, 100, 200, 300, 400, 500, 600, 700, 850 and the surface were calculated.

For calculation of absorption in incident solar radiation in each layer, use has been made of Joseph's (1966) absorptivity function [($A(W)$)] which gives the value of incident radiation depleted by the absorbing constituent, *viz.*, water vapour. Here :

$$A(W)_p = 0.271 \; (W_p \sec \nu)^{0.303} \qquad (4)$$

where "$W_p \sec \nu$" is the effective path length through which solar radiation has passed.

Hence, the incident radiation reaching a reference level p is written as :

$$(\text{DSR})_p = S^a \; [1 - A\,(W)_p \; (W_p \sec \nu)] \qquad (5)$$

where S^a is the absorbed part in the solar radiation incident at the top of the atmosphere (0 mb level) and "W_p sec ν" the effective path length in the layer. Using this expression, the amounts of absorbed part (S^a) of direct solar radiation (DSR) reaching various levels of

TABLE 2

The amount of absorbed part (S^a) in solar radiation reaching at various levels over India during the month of January (W/m²) from top of the atmosphere

Station	Surface	850 mb	700 mb	600 mb	500 mb	400 mb	300 mb	200 mb	100 mb	0 mb (Top of atmosphere)
Srinagar	..	200.619	235.290	242.124	245.067	245.887	249.839	249.960	250.044	250.045
Delhi	169.083	230.472	268.452	282.633	288.920	290.855	291.248	291.362	291.441	291.477
Jodhpur	156.893	224.551	273.155	288.080	294.333	296.249	296.638	296.751	296.831	296.868
Lucknow	188.207	250.144	290.394	299.708	303.605	305.106	305.472	305.584	305.664	305.701
Gauhati	149.474	248.869	300.042	310.067	313.324	315.615	316.047	316.157	316.235	316.272
Ahmedabad	140.001	233.547	285.120	300.974	311.529	315.133	316.011	316.197	316.275	316.286
Calcutta	151.451	267.420	316.600	328.877	334.238	336.466	337.059	337.166	337.243	337.279
Nagpur	144.893	227.386	300.960	321.523	333.220	336.747	337.897	338.343	338.420	338.456
Bhubaneshwar	164.748	274.299	325.691	340.499	347.528	349.712	350.297	350.557	350.932	350.968
Bombay	115.791	246.036	310.053	327.421	335.383	337.588	338.177	338.284	338.360	338.395
Hyderabad	189.369	251.289	324.895	344.407	353.356	356.709	357.550	357.987	358.062	358.097
Visakhapatnam	93.470	266.891	331.793	346.265	358.159	360.732	361.308	361.412	361.494	361.529
Goa	88.085	255.774	330.469	345.841	353.378	356.369	357.224	357.480	357.555	357.590
Madras	101.181	292.092	360.304	375.351	382.724	385.641	386.203	386.452	386.526	386.560
Mangalore	88.238	277.547	358.071	371.694	378.503	380.621	380.954	381.056	381.130	381.164
Port Blair	86.814	282.233	364.757	382.126	390.062	393.043	393.603	393.853	393.926	393.960
Cochin	67.497	225.809	329.217	365.030	381.536	387.188	388.916	389.523	389.606	389.640
Minicoy	64.318	243.615	346.091	373.420	384.496	387.826	388.912	390.222	390.295	390.330
Trivandrum	83.523	306.868	370.982	386.000	392.751	394.844	395.402	395.503	395.576	395.610

the atmosphere from the immediate upper levels were worked out for the whole atmosphere from top to surface and level by level for the month of January as shown in Table 2. This table shows that the absorbed part of solar radiation gets very much absorbed by water vapour on reaching 850 mb level with respect to the top of atmosphere.

5. Calculations of diffuse solar radiation at various levels

On reaching the earth's surface a part the incident solar radiation gets reflected back into the atmosphere as reflected radiation depending on the albedo of the earth surface. In this case we have assumed the earth surface to be covered with green grass for which average surface albedo $^*\alpha_s$ is taken to be 0.2. Thus the incident solar radiation reflected back to space by the earth's surface will be given by :

$$(\mathrm{DFR})_{\mathrm{surface}} = S_o^a \; [1 - A \; W_o \, ^*(W_o \sec \nu)] \, ^*\alpha_s \qquad (6)$$

The reflected short wave radiation experiences in general a longer path length than the direct solar radiation. Joseph (1966) suggested that the path length of the reflected radiation be increased by a factor of 1.66. Then the amount of reflected short wave radiation reaching a reference pressure level (p) from the earth's surface may be given by :

$$(\mathrm{DFR})_p = S_o^a \, [1 - A \; W_o \, (W_o \sec \nu) \, ^*\alpha_s] \times [1 - AW_p \, \{1.66 \, (W_o - W_p)\}] \qquad (7)$$

In this expression the first part accounts for the total reflected solar radiation for the earth's surface (albedo) and the second part represents the absorption of reflected radiation due to the increased path length between the earth's surface and the reference level (p).

With the help of this expression, reflected solar radiation energy from surface reaching at 850, 700, 600, 500, 400, 300, 200 and 100 mb levels has been calculated for each station. In this case reflected radiation at the lower level has been considered as the source for the higher level. The result of this computation has been given in Table 3.

6. Calculation of net downward short-wave radiation

The net downward solar radiation flux (SRF) at any level (p) in the atmosphere was obtained as the algebraic difference between the direct solar radiation and the reflected radiation at that level :

$$(\mathrm{SRF})_p = (\mathrm{DSR})_p - (\mathrm{DFR})_p \qquad (8)$$

The net downward flux of solar radiation calculated for 19 stations over the country is given in Table 4.

7. Analysis

7.1. Direct solar radiation

The analysis of the data shows that only about 25 per cent of the incident solar radiation at the top of the atmosphere gets absorbed in the atmosphere, *i.e.*, only 345 W/m² out of the incident solar energy of about 1360 W/m² (solar constant) is absorbed in the atmosphere.

The absorbed part of energy at the top of the atmosphere is almost undiminished upto 500 mb level (99%) below which attenuation starts. Still nearly 73% of the energy reaches 850 mb level. The real attenuation starts in the lowest part of the atmosphere, *i.e.*, below 850 mb due to large amount of moisture present in the lowest layers. The atmosphere above 500 mb is almost transparent to incident solar radiation with absorption just

TABLE 3

Amount of reflected solar radiation reaching various levels (W/m²) from earth's surface after reflection during the month of January over India

Stations	Surface	850 mb	700 mb	600 mb	500 mb	400 mb	300 mb	200 mb	100 mb
Srinagar	..	40.124	37.593	37.655	38.097	38.378	38.774	38.880	39.089
Delhi	33.817	30.767	29.317	29.436	30.153	31.176	31.816	31.975	32.276
Jodhpur	31.379	30.681	26.548	26.773	27.571	30.851	29.310	30.619	29.779
Lucknow	37.641	34.510	32.742	33.110	33.832	34.805	35.463	35.627	35.762
Gauhati	29.895	24.702	23.606	24.585	24.935	26.428	27.342	27.535	27.913
Ahmedabad	28.000	23.286	21.889	22.062	22.927	24.178	25.606	25.783	26.139
Calcutta	30.290	23.679	22.859	23.662	24.664	26.044	27.408	27.621	28.052
Nagpur	28.979	26.009	22.859	22.950	23.869	24.893	25.655	26.746	27.103
Bhubaneshwar	32.950	26.311	25.057	25.689	27.054	28.498	29.235	30.151	30·599
Bombay	23.158	17.163	16.114	16.708	18.114	19.367	20.587	20.777	21.163
Hyderabad	37.874	37.162	32.257	32.191	32.825	34.022	34.527	35.626	35.982
Visakhapatnam	18.694	11.703	11.570	11.790	13.485	14.936	16.149	16.336	16.713
Goa	17.617	11.316	10.069	11.569	12.556	13.683	14.676	15.398	15.752
Madras	20.236	12.335	12.216	13.077	14.257	16.059	16.765	17.618	18.145
Mangalore	17.648	10.543	10.374	11.076	12.534	14.259	15.065	15.250	15.639
Port Blair	17.363	10.803	9.658	10.558	12.238	13.469	14.120	14.916	15.311
Cochin	13.499	8.580	7.143	7.548	8.491	9.591	10.401	11.599	11.903
Minicoy	12.864	7.605	6.595	7.288	8.426	9.378	10.123	10.981	11.278
Trivandrum	16.705	8.657	9.091	10.063	11.475	12.800	14.067	14.257	14.650

Fig. 1. Direct short-wave radiation (DSR) and net amount of downward short-wave radiation flux (SRF) at various levels over India during the month of January

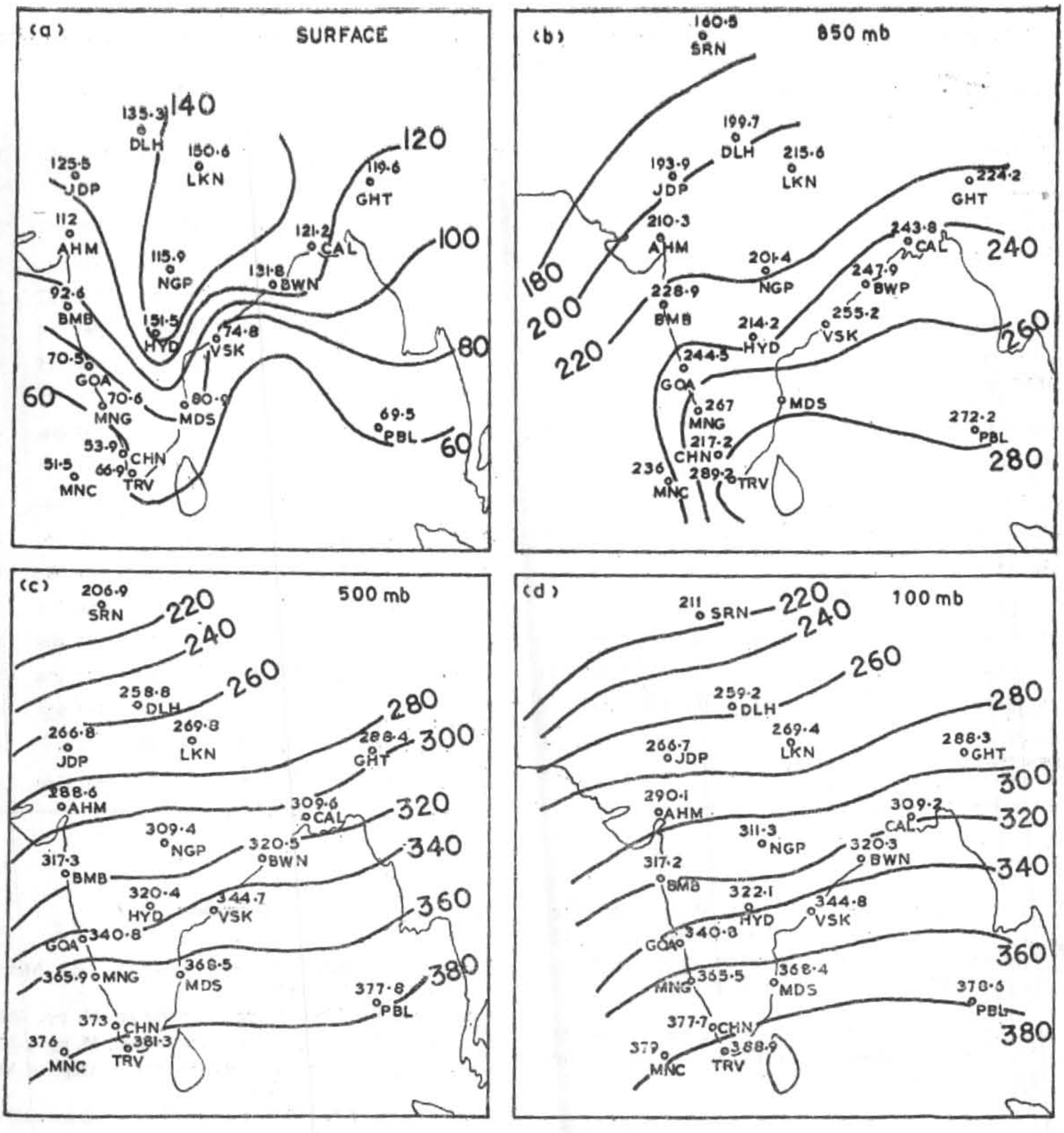
about 1% of the energy received at the top of the atmosphere. Below 500 mb the absorption is higher upto 850 mb (26%) but between 850 mb and the surface it is maximum. Fig. 1 brings out very clearly how fast the attenuation takes place in the first 1500 m of the atmosphere.

7.2. *Net solar radiation*

Table 4 gives the net solar radiation reaching various levels of the atmosphere after taking into account the loss due to reflection. It is also shown in Fig. 1. From a comparison of direct and net solar radiation curves (Fig. 1), it is apparent that loss due to reflection is high in lower layers and very little or even slight increase in higher layers which may be due to absorption by dust and aerosol particles. In fact, it is quite high upto 850 mb (Table 3) level, then decreases slowly upto 700 mb level and becomes almost *nil* or shows slight rise above 600 mb. Depletion is again due to absorption of a part of reflected short-wave radiation from the surface by the moisture in lower levels.

7.3. *Spatial distribution of net solar radiation over India*

Fig. 2 shows the spatial distribution of net solar radiation at surface, 850, 700, 500 and 100 mb levels. It can be seen that at 100 mb the net incident solar radiation is almost zonal decreasing from south to north as is natural with sun being south of equator



Figs. 2(a-d). Net amount of downward flux of short-wave radiation (W/m^2) during January

in this month. This condition continues right upto 500 mb with little change. Below 500 mb, the attenuation due to moisture becomes apparent, first at southern coastal stations, particularly at the west coast. At the surface levels, however, the picture is quite interesting. The landmass of central and north India receives the maximum radiation due to cloudless condition and coastal belts the least. The decrease in coastal belts is due to relatively high amount of moisture at coastal stations in lower levels when inland stations are almost dry.

An analysis of inland and coastal stations separately shows that the average net solar radiation reaching surface for land stations (Hyderabad, Nagpur, Ahmedabad, Jodhpur, Delhi, Srinagar, Lucknow and Gauhati) is $130 W/m^2$ and for coastal stations (remaining stations in Table 2) it is $81 W/m^2$.

8. Conclusion

The following broad conclusions can be derived from this study :

(*i*) Only about 25% of the incident direct solar radiation, (*i.e.,* solar constant of about 1360 W/m^2), is absorbed by the water vapour of atmosphere (345 W/m^2).

(*ii*) Atmosphere is almost transparent to incoming solar radiation upto 500 mb levels.

(*iii*) Between 500 mb and 850 mb levels the absorption is 26% and between 850 mb and surface, it is 34%. Thus, 60% of the solar radiation at the top of the atmosphere gets absorbed in the lowest half of the atmosphere below 500 mb, of which about 58% in the lowest 1500 metres.

TABLE 4

Net amount of downward flux of solar radiation (W/m²) at various levels of the atmosphere over India during the month of January

Stations	Surface	850 mb	700 mb	600 mb	500 mb	400 mb	300 mb	200 mb	100 mb
Srinagar	..	160.495	197.697	204.469	206.970	207.509	211.066	211.080	210.955
Delhi	135.266	199.705	239.135	253.197	258.769	259.679	259.432	259.387	259.155
Jodhpur	125.514	193.870	246.607	261.307	266.762	265.398	267.328	266.132	266.663
Lucknow	150.566	215.634	257.652	266.590	269.773	270.305	270.009	269.957	269.902
Gauhati	119.579	224.167	276.436	285.482	288.389	239.187	288.705	288.622	288.322
Ahmedabad	112.001	210.261	263.320	278.912	288.602	290.955	290.405	290.414	290.136
Calcutta	121.161	243.791	293.741	305.215	309.574	310.422	309.651	309.545	309.191
Nagpur	115.914	201.377	278.101	298.572	309.351	311.854	312.242	311.599	311.317
Bhubaneshwar	131.798	247.988	300.634	314.809	320.474	321.214	321.062	320.406	320.333
Bombay	92.633	228.873	293.939	310.713	317.269	318.221	317.590	317.507	317.187
Hyderabad	151.495	214.127	292.638	312.216	320.431	322.687	323.023	322.361	322.079
Visakhapatnam	74.776	255.188	320.223	334.475	344.674	345.796	345.159	345.076	344.781
Goa	70.468	244.458	319.600	334.272	340.822	342.686	342.549	342.082	341.803
Madras	80.945	279.757	348.088	362.275	368.467	369.583	369.438	368.834	368.381
Mangalore	70.590	267.004	347.657	360.618	365.970	366.362	365.889	365.806	365.491
Port Blair	69.451	272.229	355.099	371.568	377.824	398.575	379.483	378.938	378.615
Cochin	53.998	217.229	322.074	357.482	373.045	377.597	378.515	377.923	377.703
Minicoy	51.454	236.009	339.496	366.132	376.070	378.448	378.789	379.241	379.017
Trivandrum	66.818	298.211	361.897	375.938	381.276	382.044	381.334	381.246	380.926

(*iv*) Approximately 40% (*i.e.,* 135 W/m²) of the direct solar radiation entering the atmosphere (345 W/m²) ultimately reaches the surface on an average. It is just about 10% of the solar constant.

(*v*) The reflected radiation (reflected solar radiation from the surface) decreases upward layerwise. The loss is high in lower levels.

(*vi*) The net downward solar radiation flux decreases from south to north over India in January upto 850 mb levels. At the surface, however, the picture becomes quite distorted with coastal stations showing much less incident short-wave radiation than the inland stations. The average incident radiation at coastal stations is 81 W/m² whereas over inland stations it is 130 W/m². This is because of strong absorption by water vapour present in lower levels at coastal stations, inland stations being drier at the surface in this month.

(*vii*) The water vapour emerges as a strong absorber of incident solar radiation both direct as well as reflected.

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