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Measurements of Diffuse Solar Radiation at Delhi and Poona

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ABSTRACT. The paper discusses the diurnal and seasonal variations of diffuse solar radiation on a horizontal surface from measurements made during 1958 and 1959 at Poona and Delhi. Diffuse radiation is maximum during the summer and monsoon months, May to September as a result of increased turbidity in summer and clouding during monsoon. On the whole, diffuse radiation at Poona is more than that at Delhi. The paper discusses also the ratio of diffuse radiation to total radiation at the two stations. The proportion of diffuse to total radiation is higher at Poona than at Delhi throughout the year except during December to March.

1. Introduction

Diffuse solar or sky radiation is the short-wave energy component of solar origin, scattered and diffused downwards by the gas molecules, water vapour, dust particles and clouds in the atmosphere. Measurements of diffuse radiation are of value in the estimation of the other radiation components and of daylight illumination, where such measurements are non-existent. They are also of great importance to illumination engineers and architects in interior illumination studies and building research particularly in the tropics, and in problems of utilisation of solar energy.

While measurements of total incoming solar radiation over the earth's surface have been made at a large number of stations, observations of sky radiation have not been so extensive. Routine measurements of diffuse radiation have been made for many years at a number of stations in South Africa (Drummond 1956) and the Belgian Congo (Schuepp 1952), and at the Blue Hill (Hand and Wollaston 1952) and Kew (Blackwell 1954) Observatories. Observations of sky radiation were not made in India till the IGY. The present paper summarises the results of the measurements of diffuse radiation at Poona and Delhi during the years 1958 and 1959.

2. Method of measurement

2.1. The instrumental equipment used for the continuous registration of diffuse (sky) radiation, is the same as that used (Mani, Chacko and Venkiteshwaran 1962) for recording the total incoming solar radiation on a horizontal surface, *viz.*, a Moll Gorczynski solarimeter and Cambridge thread recorder with the addition of a shading ring to shade the thermopile element and the two hemispherical glass domes from direct sunshine. The shading ring is so mounted that it shades the thermopile with its domes at all times and permits the solarimeter to measure only the scattered radiation received from the sky.

The exposure was the same as those for the total solarimeters—an unobstructed horizon over an azimuth range of 360°. The two instruments were installed about 1 metre apart, the diffuse solarimeter being mounted poleward of the total instrument,

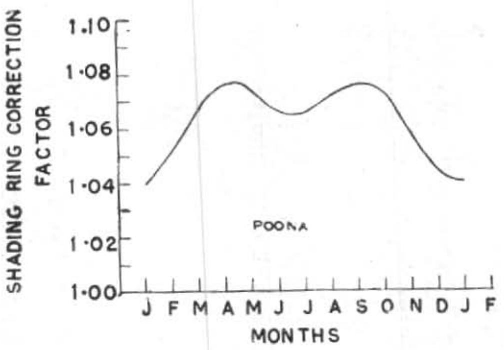

Fig. 1(a). Shading ring correction factor for Poona ($\phi = 18° 32'$)
(Radius=445 mm, width=51 mm)

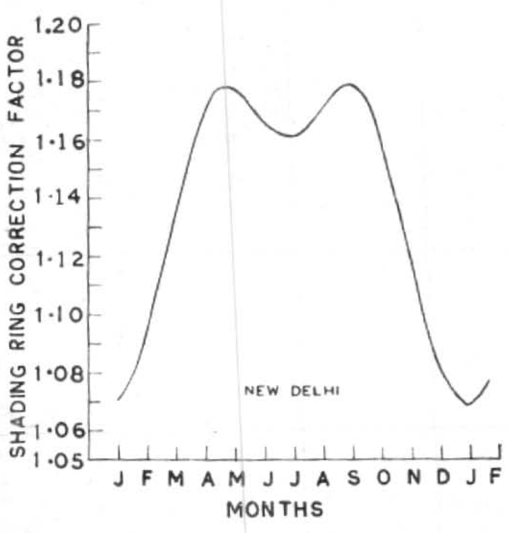

Fig. 1(b). Shading ring correction factor for New Delhi ($\phi = 28° 35'$)
(Radius=203 mm, width=51 mm)

so that mutual interference was a minimum and not more than 1 per cent of the diffuse radiation at the total instrument is intercepted by the shadow ring of the diffuse instrument.

The shading ring installed at Poona was built on the Schuepp (1952) model and had a width of 5·1 cm and a radius of 44·5 cm. The shading ring used at Delhi had a width of 5·1 cm and a much smaller radius of 20·3 cm.

2.2. *Shadow ring correction*—Corrections to compensate for the sky energy intercepted by the ring simultaneously with the eclipsing of the sun's disc, were computed on the basis of the formula derived by Drummond (1956).

$$\frac{X}{T} = \frac{2b}{\pi r} \cos^3 \delta \, (t_0 \sin \phi \sin \delta + \cos \phi \cos \delta \sin t_0)$$

where $t_0 =$ the hour angle of the sun at sunset, $\phi =$ the latitude of the recorder, $\delta =$ the sun's declination, $b =$ the width of the shadow ring, $r =$ the radius of the shadow ring, $T =$ the energy intensity on a horizontal plane receiver from the whole sky and $X =$ the energy intensity on a horizontal plane receiver for the part of the ring above the horizon.

The correction factor is $1/(1-X/T)$, for a sky of uniform brightness and where b is small compared with r. Fig. 1 gives the variations throughout the year of the computed shadow-ring correction factor for isotropic conditions for Poona and Delhi. It will be seen that corrections vary from 4 to 8 per cent for Poona and from 7 to 18 per cent for Delhi, the correction factor being least in January and highest in April and September with a secondary minimum in July.

The correction factor to compensate for the diffuse energy intercepted by the shading ring is as stated above, based on the assumption that the diffuse radiation from the sky is uniform and the receiver is an ideal one. Corrections for the non-uniform nature of the sky radiation, which includes the marked variations in the intensity of the circumsolar radiation have, however, to be made. Drummond (1956) found that theoretically derived corrections for this standard ring (5·1 cm wide and 30·5 cm in diameter), expressed as a percentage of the measured diffuse radiation, required the addition of 7 per cent for completely cloudless skies and 3 per cent for completely cloudy skies. Schuepp (1952) found an addition of 3—5 per cent necessary for clear skies and no addition for cloudy and overcast skies. The exact corrections to be applied for Indian conditions are under experimental investigation.

2·3. *Standardization of the equipment*—The solarimeters and recorders were standardized initially at the Central Radiation Unit at Poona before installation and later at the stations themselves during annual inspection, (1) by direct standardization against a working standard Angstorm pyrheliometer and (2) by comparison over a suitable period with a standardized solarimeter under natural conditions of exposure, as for the total radiation instruments (Mani, Chacko and Venkiteshwaran 1962).

3. Discussion of data

The monthly means of the total and diffuse daily radiation T and D in cal/cm²/day, received on a horizontal surface from the sun and sky and from the sky alone, for the years 1958 and 1959 at Delhi are given in Tables 1 (a) and 1 (b). The corresponding 1959 values for Poona are given in Table 2. The monthly means of the difference T—D, *viz.*, direct radiation I_H received on a horizontal surface, the monthly mean values of the proportion of diffuse to the total radiations D/T, the mean values of the duration of sunshine SS, the mean hours of cloudiness per day C in each month (possible hours of bright sunshine *minus* actual hours of bright sunshine), the maximum and minimum values of D for each month and the ratio maximum/minimum D are also given. Similar mean values of T, D, I_H, D/T, SS and C on both clear and cloudy days are given separately, with the number of occasions of each type.

In Figs. 2(a) and 2(b) are shown the values month by month of the mean daily total and diffuse radiation incomes T and D in cal/cm²/day for the year 1959 at Delhi and Poona. The values of the ratio D/T and the hours of bright sunshine SS and cloudiness C are also plotted. While data for all the 12 months are available for both 1958 and 1959 at Delhi, for Poona only the data from October 1958 to December 1959 were available. For comparative purposes, only the data for 1959 are discussed.

It will be seen from Table 1 that diffuse radiation at Delhi constituted 33 per cent of the total solar and sky radiation received on a horizontal surface during 1958 and 1959. The ratio D/T for Poona for 1959 was 37 per cent. The daily totals of diffuse radiation averaged 152 cal/cm² for Delhi and 179 cal/cm² for Poona for the year 1959. Over the year as a whole, 58 kcal/cm² were received indirectly at Delhi and 66 kcal/cm² at Poona. This compares with annual values of 49 kcal/cm² at Kew, 47 at Brussels, 43 at Berlin, 70 at Tananarive, and 45—50 over most of South Africa (Drummond 1956).

3·1. *Total and diffuse daily radiation month by month*—The mean daily diffuse radiation D attains its maximum value at Poona in August (303 cal/cm²) and at Delhi in July (282), the highest diffuse radiation recorded on any day being 356 cal/cm² for Delhi in July and 378 cal/cm² for Poona, in November. The mean total radiation on the other hand, reaches the maximum in May at both Poona (637) and Delhi (668). The mean duration of bright sunshine, is, however, least during July at both Poona (1·8 hours) and Delhi (4·2 hours). There were no clear days in July at both Poona and Delhi and the observed high values of D in July are the direct result of this monsoon clouding.

The mean daily diffuse radiation reaches its minimum value in November at Delhi

TABLE 1(a)

Mean values of total T and diffuse D solar radiation on a horizontal surface (cal/cm²/day) on all days and on clear and cloudy days at New Delhi

1958	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
All days													
Mean T	362	435	561	608	641	620	245	452	491	501	413	345	473
Mean D	107	104	145	207	257	280	179	212	219	88	79	86	164
Ratio D/T	·29	·24	·26	·34	·40	·45	·73	·47	·45	·17	·19	·25	·35
Mean $T-D=I_H$	255	331	416	401	384	340	66	240	272	413	334	259	309
Max. values of D	205	166	244	315	401	334	323	319	301	119	146	171	401
Min. values of D	59	71	87	93	134	156	41	94	137	63	50	55	41
Ratio max./min. D	3·5	2·3	2·8	3·4	3·0	2·1	7·9	3·4	2·2	1·9	2·9	3·1	9·8
Mean hours of sunshine SS	8·0	9·6	8·2	8·4	8·7	8·5	1·4	5·9	5·3	9·7	9·1	8·0	7·6
Mean hours of cloudiness C	2·4	1·5	3·6	4·3	4·8	5·6	12·5	7·4	7·2	1·7	1·7	1·7	4·5
Number of days	15	13	24	27	25	22	10	19	2	17	29	24	..
Clear days													
Mean T	422	455	587	655	741	684	..	..	..	498	431	380	539
Mean D	73	90	120	153	149	222	..	..	..	86	74	67	115
Ratio D/T	·17	·20	·20	·23	·20	·32	..	..	..	·17	·17	·18	·21
Mean $T-D=I_H$	349	365	467	502	592	462	..	..	..	412	357	313	424
Mean hours of sunshine SS	9·9	9·9	9·5	10·4	11·9	10·9	..	..	..	10·2	9·9	9·3	9·9
Number of days	4	7	14	9	5	6	0	0	0	8	22	9	..
Cloudy days													
Mean T	341	442	542	585	616	596	245	452	491	503	356	324	456
Mean D	110	121	181	234	283	299	179	212	219	90	95	98	177
Ratio D/T	·32	·27	·35	·40	·46	·50	·73	·47	·45	·18	·27	·30	·39
Mean $T-D=I_H$	231	321	343	351	333	297	66	240	272	413	261	226	279
Mean hours of sunshine SS	7·3	9·4	6·7	7·4	8·0	7·6	1·5	5·9	5·3	9·3	6·2	7·2	6·8
Mean hours of cloudiness C	3·1	1·7	5·1	5·3	5·5	6·5	12·4	7·4	7·2	2·3	4·6	3·1	5·3
Number of days	11	6	10	18	20	16	10	19	2	9	7	15	..

TABLE 1(b)

Mean values of total T and diffuse D solar radiation on a horizontal surface (cal/cm^2/day) on all days and on clear and cloudy days at New Delhi

1959	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
All days													
Mean T	368	497	569	595	668	597	445	449	431	445	389	336	482
Mean D	83	107	139	163	202	252	282	203	152	101	61	83	152
Ratio D/T	·23	·21	·24	·27	·30	·42	·63	·45	·35	·23	·16	·25	·31
Mean $T—D=I_H$	285	390	430	432	446	346	163	246	279	344	328	253	330
Max. values of D	138	245	301	294	342	339	356	293	262	184	143	139	356
Min. values of D	54	69	87	95	100	122	211	73	95	69	45	49	45
Ratio max./min. D	2·5	3·5	3·5	3·1	3·4	2·8	1·7	4·0	2·7	2·7	3·2	2·8	7·9
Mean hours of sunshine SS	7·6	9·4	8·7	9·3	10·7	8·8	4·2	6·0	6·4	9·3	9·5	8·3	8·2
Mean hours of cloudiness C	2·8	1·7	3·7	3·4	2·8	5·3	9·7	7·3	6·1	2·3	1·3	2·0	4·0
Number of days	17	17	28	24	24	20	9	18	9	27	25	29	..
Clear days													
Mean T	419	525	592	655	695	656	..	623	567	479	400	363	543
Mean D	63	85	108	119	166	210	..	73	100	87	56	60	103
Ratio D/T	·15	·16	·18	·18	·24	·32	..	·12	·18	·18	·14	·17	·19
Mean $T—D=I_H$	356	440	484	536	529	446	..	550	467	392	344	303	440
Mean hours of sunshine SS	9·8	10·3	9·3	10·7	11·7	11·0	..	12·0	9·7	10·0	9·9	9·5	10·4
Number of days	6	9	14	7	11	7	0	1	2	12	14	12	..
Cloudy days													
Mean T	341	465	545	471	643	564	445	438	393	418	374	317	459
Mean D	94	132	169	181	233	274	282	210	167	112	67	100	168
Ratio D/T	·28	·28	·31	·32	·36	·49	·63	·48	·42	·27	·19	·31	·37
Mean $T—D=I_H$	247	333	376	390	410	290	163	228	226	306	307	217	291
Mean hours of sunshine SS	6·4	8·4	8·0	8·7	9·9	7·5	4·2	5·6	5·4	8·7	9·0	7·4	7·4
Mean hours of cloudiness C	4·0	2·7	3·8	4·0	3·6	6·6	9·6	7·7	7·1	2·9	1·8	2·9	4·7
Number of days	11	8	14	17	13	13	9	17	7	15	11	17	..

TABLE 2

Mean values of total T and diffuse D radiation on a horizontal surface (cal/cm²/day) on all days and on clear and cloudy days at Poona

1959	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
All days													
Mean T	458	549	612	594	637	526	354	380	409	465	416	429	486
Mean D	97	93	129	179	205	268	293	303	238	151	117	70	179
Ratio D/T	·21	·17	·21	·30	·32	·51	·83	·80	·58	·32	·23	·16	·37
Mean $T—D=I_H$	361	456	483	415	432	258	61	77	171	314	299	359	307
Max. values of D	199	137	187	324	334	371	373	367	350	320	378	125	378
Min. values of D	51	68	90	114	114	163	155	194	131	60	54	49	49
Ratio max./min. D	3·9	2·0	2·1	2·8	2·9	2·3	2·4	1·9	2·7	5·3	7·0	2·5	7·7
Mean hours of sunshine SS	9·9	10·7	10·3	9·7	9·7	7·1	1·8	3·1	4·7	8·3	8·1	10·2	7·8
Mean hours of cloudiness C	1·2	0·8	1·8	2·8	3·3	6·2	11·4	9·8	7·6	3·5	3·3	0·8	4·4
Number of days	29	25	28	27	26	20	29	31	27	30	27	31	..
Clear days													
Mean T	490	551	617	671	661	653	..	..	..	531	479	432	565
Mean D	70	91	127	135	155	210	..	..	..	63	62	57	108
Ratio D/T	·14	·17	·19	·20	·23	·32	..	..	..	·12	·13	·13	·19
Mean $T—D=I_H$	420	460	490	536	506	443	..	..	..	468	417	375	457
Mean hours of sunshine SS	10·5	10·6	10·5	10·7	11·5	11·4	..	..	..	10·8	10·4	10·4	10·8
Number of days	12	24	24	5	3	1	0	0	0	4	9	14	..
Cloudy days													
Mean T	435	522	580	577	630	519	354	380	409	455	385	427	473
Mean D	116	137	147	190	211	271	293	303	238	164	146	81	190
Ratio D/T	·27	·26	·25	·33	·33	·52	·83	·80	·58	·36	·38	·19	·40
Mean $T—D=I_H$	319	385	433	387	419	248	61	77	171	291	239	346	283
Mean hours of sunshine SS	9·6	10·3	9·6	9·5	9·4	6·8	1·8	3·1	4·7	7·9	6·9	10·0	7·5
Mean hours of cloudiness C	1·5	1·2	2·3	3·0	3·6	6·5	11·4	9·8	7·6	3·9	4·4	1·0	4·7
Number of days	17	1	4	22	23	19	29	31	27	26	18	17	..

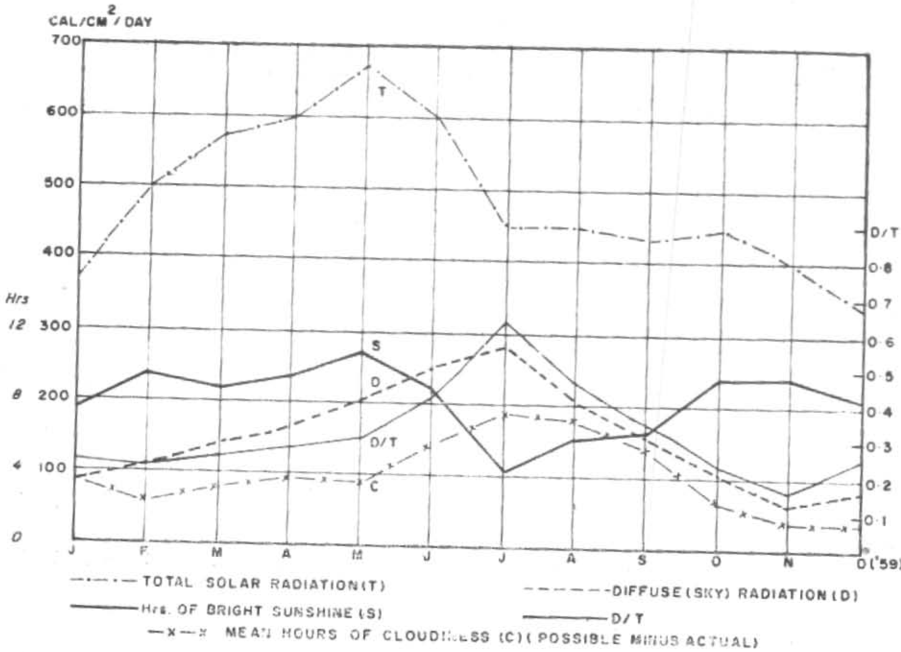

Fig. 2(a). Annual march of diffuse (sky) radiation (all days)—Delhi

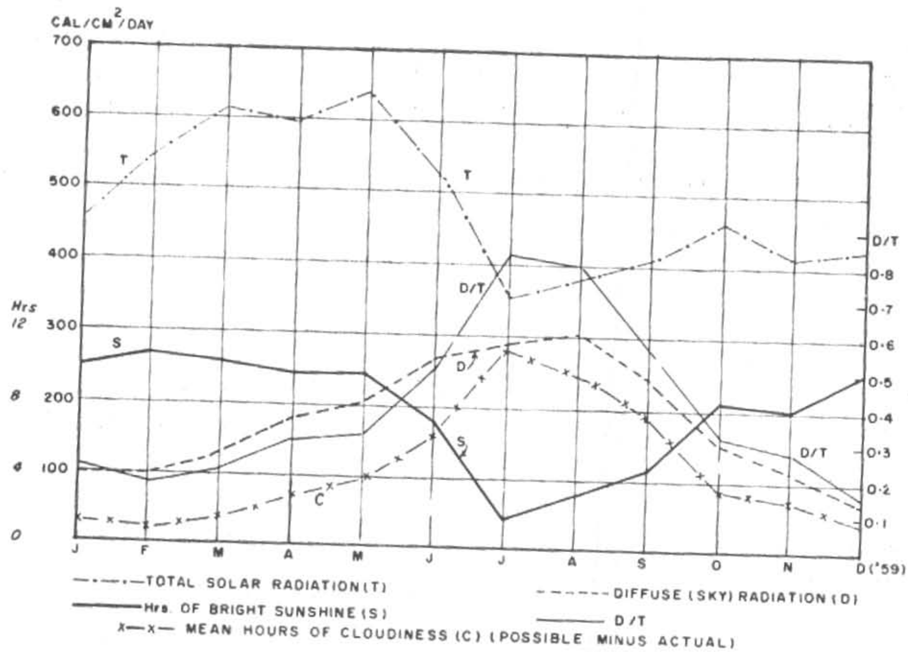

Fig. 2(b). Annual march of diffuse (sky) radiation (all days)—Poona

(61 cal/cm^2) and in December at Poona (70), the lowest diffuse radiation recorded on any day being 49 in December at Poona and 45 in November at Delhi. These are also the months when the duration of bright sunshine is a maximum, 9·5 hours at Delhi and 10·2 hours at Poona and cloudiness is at a minimum.

On the whole, diffuse radiation is maximum during the summer and monsoon months, May to September as a result of the increased turbidity in summer and clouding during the monsoon months and minimum during the clear winter months November to February. The values of total solar radiation are on the other hand, highest during the summer months March to June and least during the monsoon and winter seasons. The mean daily diffuse radiation is less than 100 cal/cm^2 during winter and about 250-300 cal/cm^2 during the monsoon.

A comparative study of the annual variation of the mean daily diffuse radiation D at Poona and Delhi shows that Poona received more diffuse radiation throughout the year than Delhi except during February and March, the two clearest months at Poona, when it is slightly less (see table in col. 2). This is obviously due to the greater clouding at Poona during the monsoon months June to September, when the proportion of diffuse to total radiation is 68 and 46 per cent respectively for Poona and Delhi, and the higher values of T at Poona during the remaining winter and summer months October to April, when D/T is the same for both stations, about 25 per cent. The rates of increase and decrease in the diffuse radiation values during the year are naturally higher at Poona than at Delhi.

The mean values of D in cal/cm^2/day for the three main seasons of the year, October to January, February to May and June to September are tabulated below, with the percentage of annual diffuse radiation received in each of the seasons at both Poona and Delhi.

	Oct—Jan		Feb—May		Jun—Sep	
	D	%	D	%	D	%
Poona	109	21	151	28	275	51
Delhi	82	18	153	34	222	48

It is interesting to note that 50 per cent of the diffuse radiation received during the year is received during the monsoon months and about one-third during summer. The percentage of annual radiation received at both stations during the different seasons is roughly the same, the percentage being slightly higher during winter and monsoon at Poona and in summer at Delhi.

3.2. *Total and diffuse radiation on clear days*—Tables 1 and 2 contain representative mean daily sums of T and D for the three categories of days, cloudy, clear and all days of record. There were 95 clear and 152 cloudy days of observations during 1959 at Delhi and 96 clear and 234 cloudy days at Poona. It will be noted that (1) the maxima and minima for T and D in all three categories fall generally in the same months at both stations, May for T and July—August for D, (2) under clear sky conditions alone, T maximum occurs in May (695 cal/cm^2/day at Delhi and 671 in April at Poona) and the T minimum in December (363 and 432 cal/cm^2/day at Delhi and Poona respectively). The corresponding D values are 210 cal/cm^2/day (June) and 56 cal/cm^2/day (November) for average cloudless skies for Delhi and 210 and 57 in June and December for Poona (Fig. 3). The two trends are similar. The clearest atmospheric conditions, therefore, occur during the winter months (November to January at Delhi and October to January at Poona) when diffuse radiation is a minimum and the most turbid in the hot summer months May and June, when diffuse radiation is a maximum. The diffuse radiation received at Poona and Delhi throughout the year on clear days alone is roughly the same.

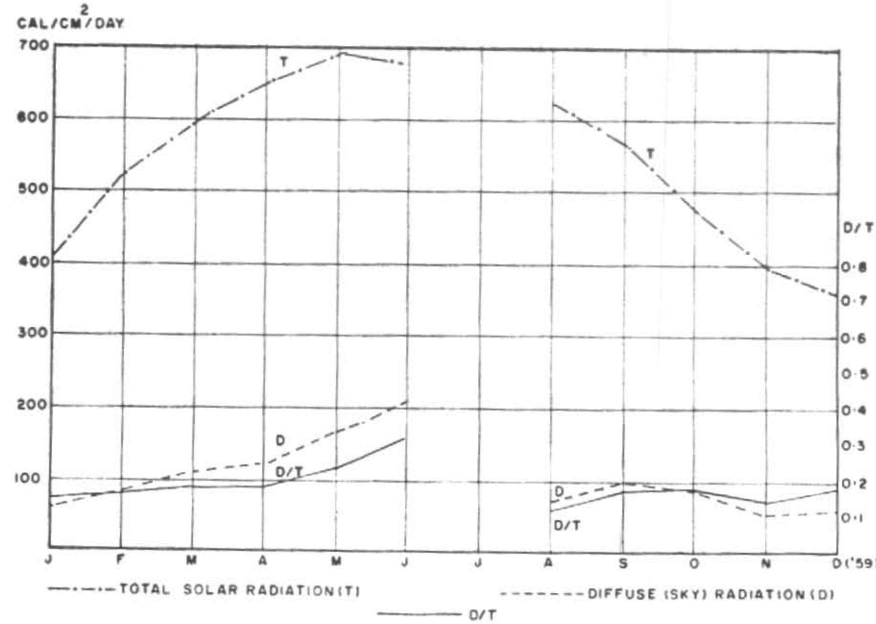

Fig. 3(a). Annual march of diffuse (sky) radiation (clear days)—Delhi

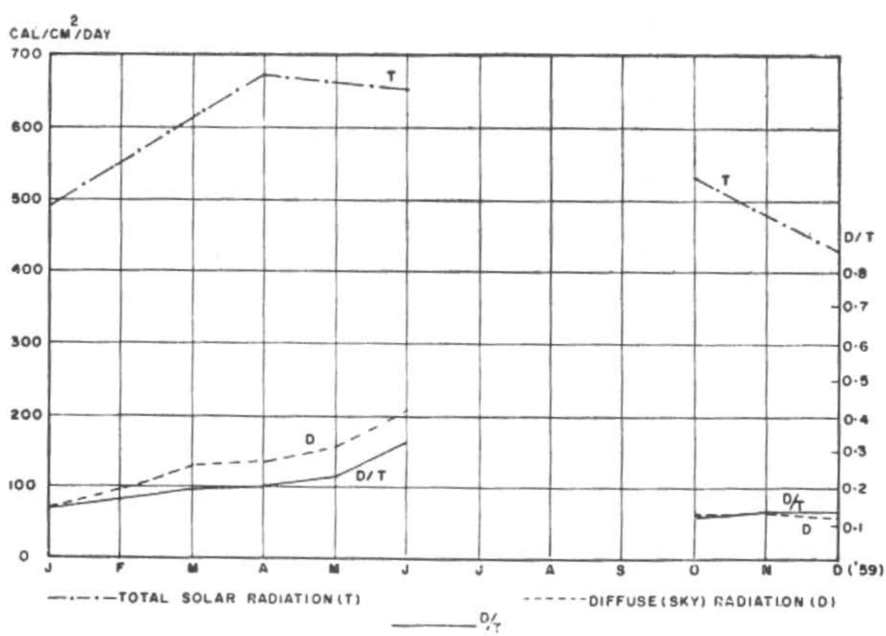

Fig. 3(b). Annual march of diffuse (sky) radiation (clear days)—Poona

TABLE 3

Highest and lowest daily sums of T and D (cal/cm²) at Delhi and Poona during 1959

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
							DELHI							
T	Highest	464	558	634	681	747	693	570	623	597	500	432	377	747
	Lowest	87	389	418	190	608	300	238	198	249	246	303	265	87
	Highest/Lowest	5·3	1·4	1·5	3·6	1·2	2·3	2·4	3·1	2·4	2·0	1·4	1·4	8·6
D	Highest	138	245	201	294	342	339	356	293	262	184	143	139	356
	Lowest	54	69	87	95	100	122	211	73	95	69	45	49	45
	Highest/Lowest	2·5	3·6	3·5	3·1	3·4	2·8	1·7	4·0	2·8	2·7	3·2	2·8	7·9
							POONA							
T	Highest	551	600	669	699	722	679	539	590	609	575	502	447	722
	Lowest	303	504	469	277	344	191	160	196	145	217	190	350	145
	Highest/Lowest	1·8	1·2	1·4	2·5	2·1	3·6	3·3	3·0	4·2	2·6	2·6	1·3	5·0
D	Highest	199	137	187	324	334	371	373	367	350	320	378	125	378
	Lowest	51	68	90	114	114	163	155	194	131	60	54	49	49
	Highest/Lowest	3·9	2·0	2·0	2·8	2·9	2·3	2·4	1·9	2·7	5·3	7·0	2·5	7·7

The upper limiting daily value of cloudless sky T radiation is about 747 cal/cm² in May, of which the D component accounts for 13 per cent at Delhi. The corresponding values for Poona are 722 cal/cm² in May and 16 per cent respectively. The lowest value of T is 145 cal/cm² in September at Poona in which a flux of about 94 per cent is contributed from the sky. The corresponding value for Delhi is 87 in January. No record of D was, however, available for the day.

Considering the daily totals of T for all days, the highest and lowest daily means occur during the same months as for cloudless sky conditions, the values being naturally higher for the latter. Table 3 gives the highest and lowest daily sums of T and D during 1959 at Delhi and Poona. The entries in Tables 1 to 3 show the remarkable constancy in the daily total radiation fluxes during November and December at Delhi and during February at Poona, the difference between the highest value and the average of all days being only 40—50 cal/cm² or 8 per cent of the total. Although the lowest value of mean T is recorded in December at Delhi and July at Poona, January exhibits the greatest variability at Delhi and September at Poona.

Similarly the month of most constant daily diffuse flux is July at Delhi and August at Poona, the ratio between the highest and lowest values being only 1·7 and 1·9 respectively. The greatest variability in D is shown during August at Delhi and November at Poona.

3·3. *Ratio of diffuse to total radiation D/T* —The ratio of diffuse to total radiation D/T month by month for the year 1958 and 1959 for Delhi and Poona are given in Tables 1 and 2 and its annual march is illustrated in Figs. 2(a) and 2(b) for all days of the year and in Figs. 3(a) and 3(b) for clear days alone.

It will be seen that the maximum value of D/T occurs in July at both Poona (83 per cent) and Delhi (63 per cent) and the minimum (16 per cent) in December at Poona and in November at Delhi. For the whole

TABLE 4

Mean annual values of the ratio D/T at representative set of stations of the world

S. No.	Station	Latitude	Longitude	D/T	Altitude (m)
1	Kew	51° 28′ N	00° 19′ W	0·56	5
2	Blue Hill, Boston	42 22 N	71 01 E	0·38	195
3	Uccle	50 48 N	04 21 E	0·54	104
4	Paris	48 54 N	02 25 E	0·45	60
5	Nice	43 39 N	07 12 E	0·30	10
6	Windhock	22 34 N	17 06 E	0·23	1728
7	Cape Town	33 54 S	18 32 E	0·29	11
8	Pretoria	25 45 S	28 14 E	0·28	1368
9	Leopoldville	04 19 S	15 18 E	0·58	1260
10	Elizabethville	11 39 S	27 25 E	0·41	1276
11	Bulawayo	20 09 S	28 37 E	0·31	1343
12	Tananarive	18 54 S	47 32 E	0·36	1310
13	Stanleyville	00 31 N	25 11 E	0·52	415
14	Berlin	52 32 N	13 24 E	0·55	30
15	Mount Evans, Co.	40 24 N	104 45 W	0·05	4355
16	Delhi	28 35 N	77 12 E	0·33	216
17	Poona	18 32 N	73 51 E	0·37	559

year, the trend is similar to that of D being highest during the monsoon months and least during t hewinter months. The average value during June to September is 68 per cent at Poona and 46 per cent at Delhi and only about 25 per cent during the remaining eight months. It is generally higher at Poona than at Delhi throughout the year, except during December to March.

On clear days alone (Fig. 3), the trend is markedly different with a maximum of 32 per cent in June and a minimum of 12 per cent in August for Delhi and October for Poona. The mean value for the whole year is only 19 per cent at both stations. The annual variation at Delhi and Poona is similar with a maximum in the turbid summer months and a minimum in the clear winter months. D/T is slightly higher at Delhi than at Poona during the winter months, indicating atmosphere over Delhi to be less transparent, since on clear days, D/T is a function mainly of the turbidity and water vapour content of the atmosphere. The increased pollution and the result of increased convective effects which disperse dust and water vapour in the atmosphere during summer, account for the higher values of D/T in summer at both stations.

Values of D/T for a number of stations in the world are tabulated in Table 4 with those for Poona and Delhi. The ratio D/T is a function of various factors as mentioned earlier and varies from 0·05 at Mount Evans to 0·58 at Leopoldville.

3·4. *Frequency distribution of daily totals*— Tables 5 (a) and 5(b) summarise the percentage frequency distribution of daily sums of diffuse radiation for all days at Delhi and Poona for each month, in steps of 50 cal/cm². More than 60 per cent of the values of D exceeded 300 cal/cm² during the monsoon months July and August at Poona, less than 5 per cent being below 200 cal/cm². During December to March at Poona, nearly 80 per cent lies in the group 51—150 cal/cm². At Delhi nearly 100 per cent lies in the range 51—150 cal/cm² during the winter months and 201—350 cal/cm² during the monsoons.

TABLE 5(a)

Percentage frequency distribution of daily values of diffuse (sky) radiation for each month at New Delhi

	<50	51-100	101-150	151-200	201-250	251-300	301-350	351-400	401-450
1958									
Jan		45	21	21	13				
Feb		50	26	24					
Mar		13	34	39	14				
Apr		2	13	13	33	28	11		
May			6	8	25	22	21	12	6
Jun				6	15	32	47		
Jul	2	5	22	22	*	31	18		
Aug		2	7	22	34	27	8		
Sep			31	*	*	*	69		
Oct		92	8						
Nov	2	78	20						
Dec		73	19	8					
1959									
Jan		58	42						
Feb		51	27	9	13				
Mar		19	33	17	23		8		
Apr		5	32	31	11	21			
May		2	11	30	33	11	13		
Jun			2	3	31	38	26		
Jul					27	33	26	14	
Aug		7	7	10	46	30			
Sep		7	37	37	*	19			
Oct		59	28	13					
Nov	19	72	9						
Dec	2	53	45						

*Discontinuity in this month is due to lack of data

TABLE 5(b)

Percentage frequency distribution of daily values of diffuse (sky) radiation for each month at Poona

	<50	51-100	101-150	151-200	201-250	251-300	301-350	351-400
1959								
Jan		49	39	12				
Feb		72	28					
Mar		5	81	14				
Apr			27	25	26	16	6	
May			15	27	25	21	12	
Jun				12	11	43	22	12
Jul				6	13	19	41	21
Aug				4	5	21	59	11
Sep			6	13	18	35	28	
Oct		23	12	8	25	18	14	
Nov		27	17	19	13	14		10
Dec	4	80	16					

Taking the year as a whole, maximum diffuse radiation is received in the interval 51—100 cal/cm^2 at both stations, followed by that in the intervals 101—150 cal/cm^2.

3·5. *Mean hourly variation of D during different months of the year*—For many practical purposes, it is desirable to have knowledge of the diurnal variation of T and D through all seasons of the year. In Tables 6(a) and 6(b) the mean values of T, D and D/T during each hour of the day during the different months of the year for Delhi and Poona are tabulated. The values refer to total and diffuse radiation received during the hour ending at each hour L.A.T. and are the mean of all days of record, irrespective of whether they are cloudy or not. The information contained in these tables is illustrated in Figs. 4(a) and 4(b) and the isopleth diagrams in Figs. 5(a) and 5(b) for Delhi and Poona, where lines of equal intensity of radiation in cal/cm^2/hr have been drawn for both the stations.

3·5.1. *Delhi*—It will be noticed that the intensity of diffuse radiation shows a maximum between 12—14 L.A.T., increasing from sunrise and decreasing till after sunset. During the months May to September, the variations are irregular, showing fluctuations in intensity throughout the day with the maximum around 13 L.A.T. The intensity during each hour increases from January to March by nearly 2 cal/cm^2 per month, till June by about 4 cal/cm^2 per month and falls after July at about the same rate with a sudden drop of about 8 cal/cm^2 from September to October.

The maximum values of hourly diffuse radiation received vary from 10·6 cal/cm^2/hr in January to 36·2 cal/cm^2/hr in July, the average value around 13 L.A.T. being about 18 cal/cm^2/hr.

3·5·2. *Poona*—The intensity is generally symmetrical around noon during the months May to September and around 13 L.A.T. during the months October to April. The variations are large as at Delhi during the summer and monsoon months, while during the winter months December to February the curve is flatter and more regular. The intensity of diffuse radiation in each hour increases month to month by about 2 cal/cm^2 from January to March, 4 from April to June, 8 from July to September and then falls again by about 3 from October to December.

The maximum value reached by the hourly diffuse radiation is 40 cal/cm^2 in July—August, 30 in June, 20 in April—May and October—November, 10 in January—March and 9 in December, the average value being about 20 cal/cm^2.

The hourly means around noon are highest in May for T (83 cal/cm^2) and in July for D (36 cal/cm^2) at Delhi. The corresponding values for Poona are 84 cal/cm^2 in March and 39 cal/cm^2 in August respectively. The lowest hourly value for T and D at Delhi were 53 and 7 cal/cm^2. The corresponding values at Poona were 48 and 8 cal/cm^2. Over the whole year T and D reached 82·3 and 21·6 cal/cm^2 when the sun was highest in the sky.

3·6. *Hourly values of D/T*—The variations of the ratio D/T hour by hour for all the months for 1959 are given in Table 6 for Delhi and for Poona and illustrated in Figs. 4(a) and 4(b). It will be seen that the progression in values of the ratio from 07 to 18 hours is a very smooth one during the winter, and summer months October to May. They are very irregular from June to September during the monsoon at both Delhi and Poona. The variations are symmetrical around noon, minimum at noon during October to March. The minimum occurs from 10—14 L.A.T. during the remaining months. The maxima are about sunrise and sunset, since with low solar elevations much of the energy received then is indirectly from the sky.

3·7. *Direct solar radiation*—Direct solar radiation I_H received on a horizontal surface is given by T—D and the mean values I_H month by month for both Delhi and

TABLE 6(a)

Mean hourly values of total T and diffuse D solar radiation on a horizontal surface at New Delhi

	Hrs	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19
								(cal/cm²/hr)							
1959															
	T		0·4	9·7	25·8	40·2	53·0	58·4	57·3	49·5	38·9	24·8	9·1	0·5	
Jan	D		0·2	3·5	6·9	9·3	10·0	10·3	10·6	10·6	9·3	7·5	4·1	0·3	
	D/T		·50	·36	·27	·23	·19	·18	·18	·21	·24	·30	·45	·60	
	T		2·5	17·8	38·7	55·3	66·6	72·5	72·1	65·1	53·2	33·8	16·0	2·9	
Feb	D		1·3	6·3	9·3	10·6	11·8	12·3	13·1	12·6	12·3	10·4	6·3	1·5	
	D/T		·52	·35	·24	·19	·18	·17	·18	·19	·23	·31	·39	·52	
	T		6·4	24·6	44·2	60·9	71·3	77·7	77·5	71·7	59·2	43·9	24·6	6·7	
Mar	D		3·6	8·4	10·9	13·5	14·6	15·7	16·3	16·3	15·3	11·9	8·8	3·4	
	D/T		·56	·34	·25	·22	·20	·20	·31	·23	·26	·27	·36	·51	
	T	1·1	12·3	30·4	49·9	61·4	72·4	76·3	75·3	71·6	61·5	45·2	28·4	11·9	1·3
Apr	D	0·8	5·8	9·6	13·1	15·1	16·6	16·5	17·3	17·3	16·5	15·1	11·7	6·4	0·7
	D/T	·73	·47	·32	·26	·25	·23	·22	·23	·24	·27	·33	·41	·53	·54
	T	3·0	16·4	33·9	52·5	67·1	77·4	83·0	82·5	76·7	66·3	52·4	35·3	17·6	3·7
May	D	2·0	10·4	10·5	16·7	15·3	19·7	20·3	20·9	20·5	19·6	17·2	13·8	8·9	2·3
	D/T	·67	·63	·31	·32	·23	·25	·24	·25	·27	·29	·33	·39	·50	·62
	T	3·3	15·0	31·2	47·1	58·6	66·9	72·7	74·4	68·9	59·8	45·7	32·0	16·6	4·2
Jun	D	2·5	9·2	14·9	18·4	21·7	23·6	25·8	28·2	27·6	25·8	22·3	14·6	10·9	3·1
	D/T	·76	·61	·45	·39	·37	·35	·35	·38	·40	·43	·49	·46	·66	·74
	T	1·6	9·4	22·6	35·7	46·3	57·9	60·4	58·2	54·2	40·7	28·3	17·8	10·1	2·4
Jul	D	1·2	7·7	16·8	25·6	28·8	31·5	31·1	36·2	29·9	25·3	20·4	14·7	8·5	1·9
	D/T	·75	·83	·74	·72	·62	·54	·51	·62	·55	·62	·72	·83	·84	·79
	T	0·8	8·2	20·1	33·3	43·4	51·3	62·2	60·9	57·1	42·8	33·4	23·0	10·8	1·6
Aug	D	0·5	4·8	10·3	15·3	20·1	22·9	25·9	27·6	23·7	18·3	14·4	11·0	6·3	1·0
	D/T	·63	·59	·50	·46	·46	·45	·42	·45	·41	·43	·43	·48	·58	·63
	T	0·2	6·5	19·9	33·1	46·6	54·6	62·9	52·0	49·9	47·1	32·3	21·4	5·7	0·2
Sep	D	0·1	3·2	7·2	9·8	13·1	18·7	21·6	19·0	18·0	16·2	11·6	9·2	3·4	0·1
	D/T	·50	·50	·36	·30	·28	·34	·35	·37	·36	·34	·36	·43	·60	·50
	T		3·3	17·5	35·3	49·0	58·8	64·7	62·3	57·2	46·6	32·0	15·0	2·7	
Oct	D		2·0	6·3	9·0	10·8	11·9	12·2	12·0	11·1	10·0	8·5	6·1	1·5	
	D/T		·61	·36	·25	·22	·20	·19	·19	·19	·21	·27	·40	·55	
	T		0·9	11·5	28·4	42·6	56·3	59·8	59·3	52·9	41·5	25·4	10·3	0·5	
Nov	D		0·4	3·7	5·7	6·9	6·8	7·3	7·1	7·3	6·8	5·8	3·2	0·2	
	D/T		·44	·32	·20	·16	·12	·12	·12	·14	·16	·23	·31	·40	
	T		0·2	7·6	22·5	36·8	47·3	53·3	52·9	47·4	36·3	23·2	8·1	0·3	
Dec	D		0·1	3·5	6·4	8·7	10·7	11·8	12·1	10·4	9·1	7·0	3·5	0·1	
	D/T		·50	·46	·28	·24	·23	·22	·23	·22	·25	·30	·43	·33	

TABLE 6(b)

Mean hourly values of total T and diffuse D solar radiation on horizontal surface at Poona

	Hrs	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19
							(cal cm² hr)								
1959															
Jan	T		1·8	15·9	34·1	49·9	59·7	67·9	68·3	59·4	48·6	31·9	16·1	2·1	
	D		1·2	5·5	8·0	9·3	11·3	11·1	11·2	12·0	10·5	9·2	6·4	1·2	
	D/T		·67	·34	·23	·19	·19	·16	·16	·20	·22	·29	·40	·57	
Feb	T		3·4	20·4	40·7	58·2	70·6	77·4	78·3	72·3	60·6	43·7	23·1	4·8	
	D		2·1	6·4	8·7	9·6	9·9	9·9	9·9	9·9	9·2	8·1	6·3	2·6	
	D/T		·62	·31	·21	·16	·14	·13	·13	·14	·15	·19	·27	·54	
Mar	T		6·5	26·2	47·3	64·3	76·8	83·8	83·6	77·6	64·7	47·4	26·7	7·2	
	D		3·7	8·9	11·1	12·8	13·2	13·3	13·6	14·1	13·6	11·9	9·5	4·1	
	D/T		·57	·34	·23	·20	·17	·16	·16	·18	·21	·25	·35	·57	
Apr	T		9·1	29·9	48·1	65·0	74·5	82·2	81·6	65·5	53·8	42·3	28·1	10·9	
	D		5·5	11·2	14·9	17·3	17·5	19·4	20·6	20·8	18·9	12·3	12·1	6·5	
	D/T		·60	·37	·31	·27	·23	·24	·25	·32	·35	·29	·43	·60	
May	T	1·3	12·9	31·4	53·2	67·6	77·6	82·3	77·5	74·9	57·3	47·2	31·8	13·8	2·2
	D	1·2	7·5	14·2	18·3	19·5	20·5	21·6	21·3	20·5	18·7	16·6	14·3	8·5	1·9
	D/T	·92	·58	·45	·34	·29	·26	·26	·27	·27	·32	·35	·45	·61	·86
Jun	T	1·5	10·0	25·6	41·1	57·6	65·9	67·7	70·6	63·6	50·8	38·5	22·2	9·3	1·4
	D	1·1	6·4	14·1	19·3	22·1	24·2	29·0	27·9	25·1	22·6	18·4	13·6	6·8	1·1
	D/T	·73	·64	·55	·47	·38	·37	·43	·39	·39	·44	·48	·61	·73	·79
Jul	T	0·6	7·6	16·5	28·8	35·9	44·0	50·8	48·0	41·1	33·6	24·0	15·9	6·6	0·6
	D	0·6	7·2	14·7	23·5	37·1	35·5	38·7	37·1	34·5	27·3	20·5	14·3	5·9	0·5
	D/T	1·00	·95	·89	·81	·87	·81	·77	·77	·84	·81	·85	·90	·89	·83
Aug	T	0·5	6·8	18·0	31·6	41·3	50·0	52·5	48·7	44·4	38·2	26·7	14·9	5·3	0·5
	D	0·5	6·8	15·9	26·5	31·4	37·1	39·1	36·3	35·1	31·6	23·2	13·4	5·3	0·4
	D/T	1·00	1·00	·88	·84	·76	·74	·74	·75	·79	·83	·87	·90	1·00	·80
Sep	T	0·1	5·4	18·5	32·8	48·3	55·1	55·3	55·5	51·3	40·8	29·5	17·0	4·5	0·0
	D	0·1	4·3	11·1	19·2	26·2	30·3	34·8	30·1	29·4	23·3	17·6	11·1	3·7	0·0
	D/T	1·00	·80	·60	·59	·54	·55	·63	·54	·57	·57	·60	·65	·82	
Oct	T		3·6	18·4	36·2	51·7	61·5	65·0	65·1	59·5	50·2	32·6	17·4	3·5	
	D		2·3	7·1	11·2	14·4	18·0	18·9	20·0	18·5	17·2	12·6	8·0	2·2	
	D/T		·64	·37	·31	·22	·29	·29	·31	·31	·34	·39	·36	·63	
Nov	T		1·6	13·5	29·5	43·7	55·8	61·5	60·9	56·8	44·7	31·1	15·0	1·8	
	D		1·2	5·9	9·6	12·0	15·0	16·5	18·1	16·8	13·1	8·9	6·0	1·2	
	D/T		·75	·44	·33	·27	·27	·27	·30	·30	·29	·29	·40	·67	
Dec	T		1·1	2·3	30·3	46·4	57·2	62·6	64·9	57·8	47·2	31·8	13·5	1·1	
	D		·9	4·1	6·1	7·2	8·1	8·3	9·1	7·9	7·5	6·1	3·8	0·7	
	D/T		·82	·33	·20	·15	·14	·13	·14	·14	·16	·19	·28	·64	

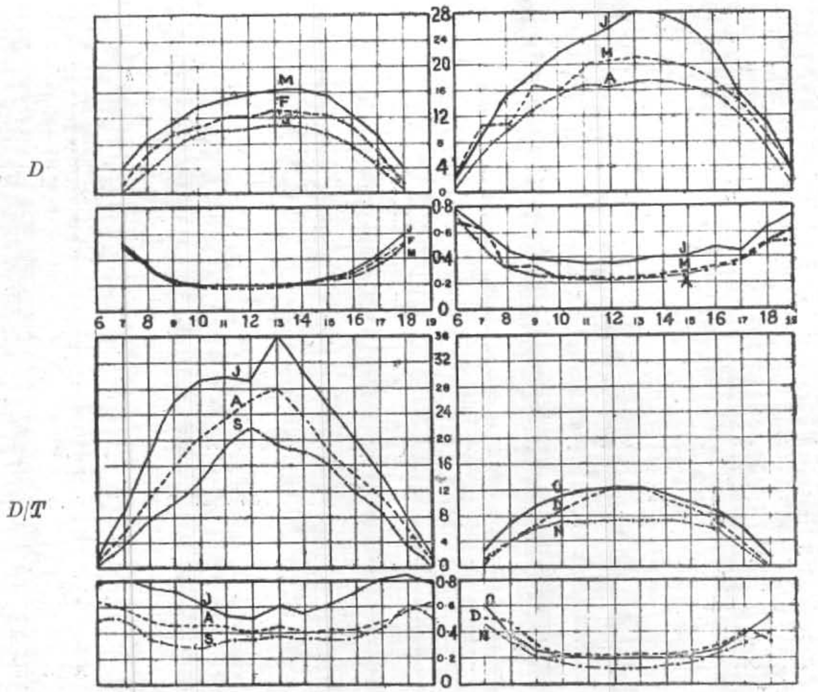

Fig. 4(a). Hourly variation of diffuse (sky) radiation D (cal/cm²/hr) and D/T—Delhi

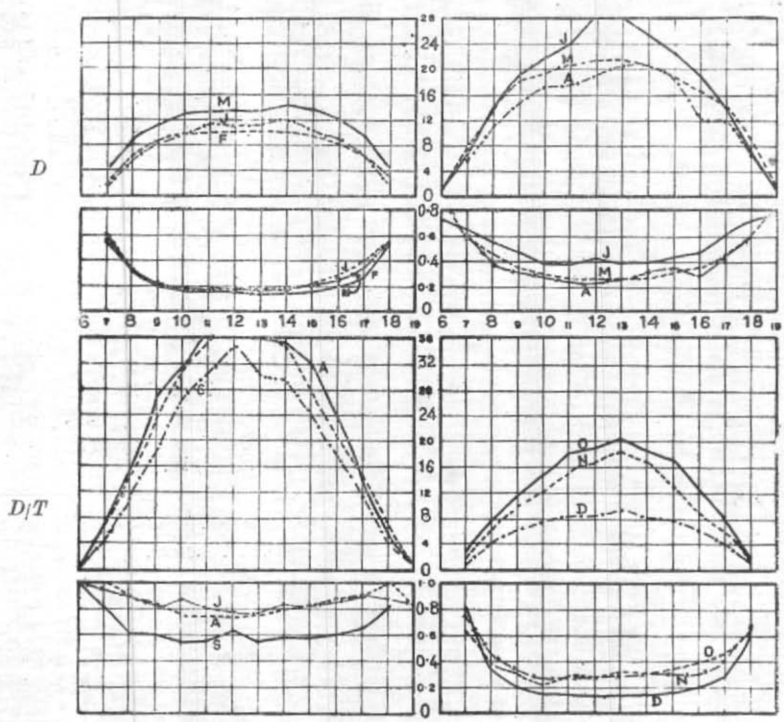

Fig. 4(b). Hourly variation of diffuse (sky) radiation D (cal/cm²/hr) and D/T—Poona

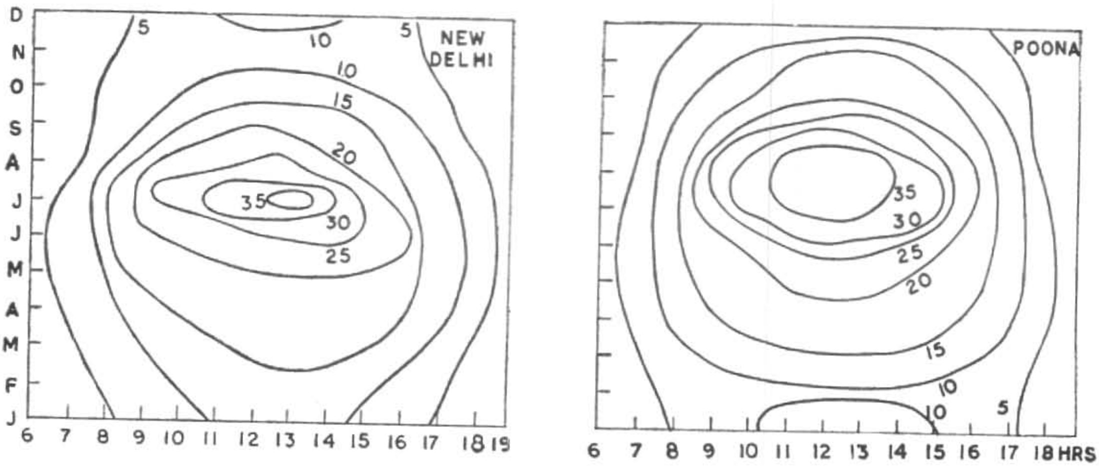

Fig. 5. Isopleths of diffuse (sky) radiation D (cal/cm^2/hr) showing hourly variation in different months

Poona are given in Tables 1 and 2. The annual variation of I is similar to that of T. The more important parameters are I_v the direct solar radiation received on a vertical surface in the direction towards the sun and I that at normal incidence. These are being discussed in a separate paper.

4. Conclusion

The paper summarises the results of measurements of diffuse radiation received on a horizontal surface at Delhi and Poona during 1958 and 1959. The results bring out clearly the importance of the diffuse sky radiation in the total radiation budget, the seasonal and diurnal variations of diffuse radiation and the proportion of diffuse to total solar radiation at two representative stations in India. As expected, the diffuse radiation on all days is directly related to the amount of cloudiness and is maximum during the monsoon season. On clear days alone it is a maximum during summer and least in winter.

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