551·521(545·5)

A study of five years' of Atmospheric Radiation measurements at Delhi

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(*Received 2 June 1967*)

ABSTRACT. A study of the results of five years of observations of downward atmospheric radiation and net atmospheric radiation at New Delhi from 1958—1962 has been made. Downward atmospheric radiation is maximum during the cloudy monsoon months and minimum during winter. High values occur also in winter associated with Western Disturbances and summer due to increased dust content in the atmosphere. Net radiation is maximum during the cloud free winter and summer months and minimum during the cloudy months. Due to the continental semi-arid character of its climate and the extreme dryness of the atmosphere over Delhi, the annual variations in both downward and net atmospheric radiation are compared to those at Madras except during the monsoon months.

1. Introduction

Results of measurements with Ångström compensation pyrgeometers of atmospheric radiation at New Delhi during the IGY have been presented by Mani and Chacko (1963). Maps showing the distribution of terrestrial radiation fluxes at the ground in India have also been published (Mani *et al*. 1965). The present paper analyses the results of five years of observations of downward atmospheric radiation and net atmospheric radiation at Delhi from 1958–1962.

2. Observations

The method of measurement of net atmospheric radiation with Ångström pyrgeometers has been described in earlier papers. If E is the outgoing longwave radiation at the temperature T°A of the black strips of the pyrgeometer ($E = \sigma\ T^4$, where σ is the Stefan-Boltzman constant) and S is the downward atmospheric radiation, N the effective longwave outgoing radiation or net atmospheric radiation, is given by $N = E - S$. N was directly measured with the pyrgeometer, which was exposed horizontally on the roof of the radiation laboratory at New Delhi and had a practically free exposure to the whole sky. Regular observations were made every night at 2030 IST whenever there was no rain or duststorms. An Assmann psychrometer was used to record the air temperature and humidity in the vicinity of the pyrgeometer.

3. Discussion of results

Table 1 gives the mean monthly values of downward atmospheric radiation S, net atmospheric radiation N and blackbody radiation E at Delhi, with values of air temperature T in °A and vapour pressure VP in mm of Hg for all nights, clear as well as cloudy, for the five years 1958—62. The last column gives the ratios of the downward radiation to the black body radiation. Similar tables for clear nights alone are given in Table 2, with maximum and minimum values of N and S, for each month. All nights with high cloud, or medium or low cloud near the horizon with cloud amounts less than one octa, are taken as clear nights, since clouds very near the horizon have little effect on the atmospheric radiation measured. In Fig. 1 are plotted the mean monthly values of downward atmospheric radiation S, net atmospheric radiation N, vapour pressure VP and air temperature T, for all nights for the years 1958—1962. Fig. 2 gives similar curves for clear nights alone. Fig. 3 shows the actual and possible hours of bright sunshine at Delhi during 1961. The area between the two curves represents the duration of cloudiness.

3.1. *Downward atmospheric radiation*

All nights—It will be seen from Figs. 1 and 3 that at New Delhi, temperatures are highest in June and least in December, and water vapour content and cloudiness highest during the months June to September. Blackbody radiation E is accordingly a maximum in June and a minimum in December with high values (·715 cal/cm²/min) from May to July. The downward atmospheric radiation S is also maximum in June and least in December. It shows a rapid increase after March till the maximum (0·655 cal/cm²/min) is reached in June, and falls rapidly again after September. The mean seasonal value from May to September is 0·630 cal/cm²/min and for the winter months 0·474 cal/cm²/min. This is to be expected, since the downward atmospheric radiation during cloudy days is mainly a function of cloudiness and depends mainly on the amount and type of cloud. During the winter months the skies are again cloudy (*see* Fig. 3), due to the passage of winter

TABLE 1

Mean monthly values of atmospheric radiation during 1958-62 at New Delhi (All nights)

	Number of obsns. (n)	Air temp. (T)	Vapour pressure (mm of Hg) (VP)	Blackbody radiation (cal/cm²/min) (E)	Net atmospheric radiation (cal/cm²/min) (N)	Downward atmospheric radiation (cal/cm²/min) (S)	S/E
Jan	143	286·4	9·7	·556	·096	·460	·827
Feb	122	290·5	8·3	·588	·101	·487	·828
Mar	150	293·2	9·2	·611	·114	·497	·814
Apr	144	301·9	10·7	·686	·118	·568	·828
May	150	303·7	9·9	·703	·111	·592	·842
Jun	122	307·6	15·6	·740	·085	·655	·885
Jul	140	303·8	20·9	·703	·049	·654	·930
Aug	104	302·3	20·6	·690	·047	·643	·932
Sep	137	302·0	19·8	·687	·064	·623	·907
Oct	149	296·9	14·0	·642	·103	·539	·840
Nov	148	290·1	9·1	·585	·112	·473	·809
Dec	121	286·0	7·3	·553	·101	·452	·817
Annual		297·0	12·8	·643	·092	·554	·862

TABLE 2

Mean values of atmospheric radiation on clear nights at New Delhi during 1958-62

	Number of obsns.	Air temp. (Å)	Vapour pressure (mm of Hg)	Black-body radiation (cal/cm²/min)	Net atmospheric radiation (N) (cal/cm²/min)			Downward atmospheric radiation (S) (cal/cm²/min)			S/E
					Mean	Max.	Min.	Mean	Max.	Min.	
Jan	94	285·9	7·9	·552	·103	·149	·041	·448	·542	·368	·810
Feb	90	290·4	8·2	·587	·106	·175	·047	·481	·552	·405	·823
Mar	92	292·8	9·3	·607	·125	·189	·081	·511	·579	·428	·795
Apr	81	301·8	10·3	·685	·129	·175	·077	·556	·636	·485	·812
May	105	306·1	11·0	·725	·122	·186	·048	·603	·699	·510	·832
Jun	77	307·5	15·9	·738	·089	·143	·041	·649	·707	·555	·879
Jul	42	304·5	19·9	·710	·058	·088	·014	·656	·698	·629	·924
Aug	21	302·8	23·1	·694	·065	·111	·037	·636	·673	·570	·916
Sep	62	305·2	19·1	·693	·076	·129	·051	·617	·549	·508	·893
Oct	123	296·1	13·7	·635	·111	·172	·064	·525	·612	·445	·827
Nov	129	290·0	9·1	·584	·114	·192	·029	·469	·601	·363	·803
Dec	85	285·6	7·1	·549	·105	·172	·041	·442	·551	·366	·805
Mean		297·4	12·9	·647	·100			·549			·849

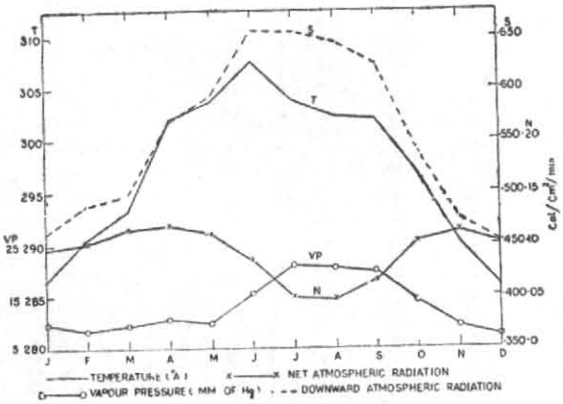

Fig. 1. Annual march of atmospheric radiation on all nights at New Delhi, 1958-62

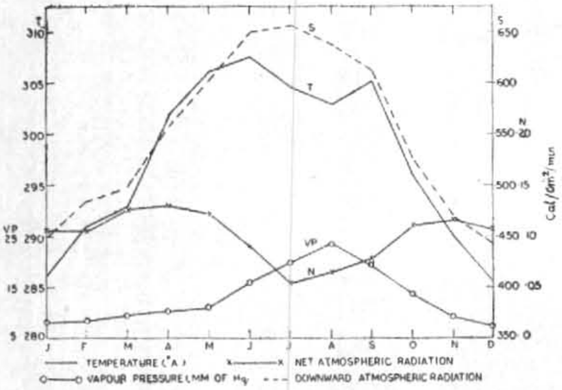

Fig. 2. Annual march of atmospheric radiation on clear nights at New Delhi, 1958-62

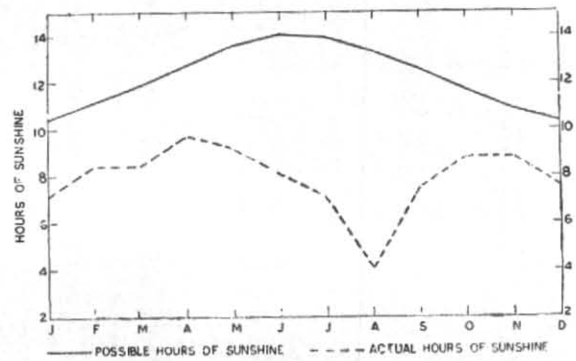

Fig. 3. Actual and possible hours of sunshine at New Delhi during 1961

disturbances from the west in this season. Downward atmospheric radiation accordingly shows an increase during January-February, despite the low temperatures and low humidities. On the whole, there is fairly close agreement between the downward atmospheric radiation, temperature and water vapour pressure curves in Fig. 1, all three showing high values from May to September and low values from November to March.

Clear nights — The agreement is better in Fig. 2, where the downward atmospheric radiation, vapour pressure and temperature are plotted for only clear nights. The curves are similar to those in Fig. 1 except that the maximum in S is reached in July and the maximum in vapour pressure in August, and there is a second rise in temperature in September. The fall in air temperature in August is compensated by the rise in water vapour pressure and the fall in S is, therefore, less marked. The mean annual value of downward atmospheric radiation for clear nights for all five years in $0 \cdot 549$ cal/cm^2/min, with mean seasonal values for the monsoon of $0 \cdot 645$ cal/cm^2/min and for the winter of $0 \cdot 465$ cal/cm^2/min. The highest maximum recorded is $0 \cdot 707$ cal/cm^2/min in June 1959 and the lowest in November 1960, $0 \cdot 363$ cal/cm^2/min.

The last column in Tables 1 and 2 gives the ratio of S/E. During the months July to September downward atmospheric radiation on all clear days reaches a value of $0 \cdot 91$ of the black body radiation at the surface temperature. The mean value for the year is $0 \cdot 85$ and the range $0 \cdot 80$ to $0 \cdot 92$.

3.2. *Net atmospheric radiation*

The net atmospheric radiation curve is almost a mirror image of the downward atmospheric radiation curve with a minimum during the cloudy monsoon season and a maximum during the remaining clear months. A secondary minimum occurs during December to February as a result of the clouding and slight increase in water vapour content, caused by the passage of western disturbances. The maximum in N is thus reached not in winter but in the clear summer months, April ($0 \cdot 118$ cal/cm^2/min). The minimum value is reached in July-August ($0 \cdot 047$ cal/cm^2/min).

The mean value of net atmospheric radiation for the whole year considering all nights is

TABLE 3

Mean values of atmospheric radiation on all nights at New Delhi

	Downward atmospheric radiation (S) (cal/cm²/min)						Net atmospheric radiation (N) (cal/cm²/min)					
	1958	1959	1960	1961	1962	Mean	1958	1959	1960	1961	1962	Mean
Jan	·522	·444	·448	·443	·441	·460	·055	·105	·100	·111	·074	·096
Feb	·529	·461	·485	·468	·486	·487	·059	·118	·111	·128	·100	·101
Mar	·521	·501	·492	·514	·404	·497	·111	·129	·099	·115	·120	·114
Apr	·570	·530	·559	·567	·589	·568	·117	·128	·118	·121	·110	·118
May	·586	·654	·615	·609	·638	·592	·124	·109	·110	·106	·100	·111
Jun	·646	·653	·660	·655	·664	·655	·098	·082	·084	·079	·070	·085
Jul	·645	·653	·657	·663	·658	·654	·052	·050	·045	·049	·050	·049
Aug	·619	·643	·643	·644	·607	·643	·069	·048	·041	·041	·052	·047
Sep	·616	·632	·622	·640	·601	·623	·059	·055	·075	·060	·070	·064
Oct	·521	·574	·528	·543	·523	·539	·106	·094	·108	·100	·108	·103
Nov	·450	·502	·457	·468	·485	·473	·129	·089	·122	·110	·111	·112
Dec	—	·482	·438	·430	·415	·452	—	·079	·113	·108	·096	·101
Annual	·567	·561	·550	·554	·546	·554	·089	·091	·094	·094	·090	·092

TABLE 4

Mean values of atmospheric radiation on clear nights at New Delhi

	Downward atmospheric radiation (S) (cal/cm²/min)						Net atmospheric radiation (N) (cal/cm²/min)					
	1958	1959	1960	1961	1962	Mean	1958	1959	1960	1961	1962	Mean
Jan	·511	·409	·441	·444	·437	·443	·061	·127	·107	·111	·110	·103
Feb	·524	·457	·478	·470	·475	·481	·061	·122	·114	·126	·109	·106
Mar	·517	·494	·502	·497	·543	·511	·128	·129	·121	·126	·123	·125
Apr	·557	·542	·549	·558	·586	·556	·127	·133	·128	·139	·116	·129
May	·581	·585	·606	·606	·619	·603	·129	·126	·117	·118	·117	·122
Jun	·642	·665	·656	·630	·651	·649	·109	·072	·092	·089	·084	·089
Jul	·655	·655	·655	·659	·653	·656	·062	·062	·047	·060	·057	·058
Aug	·595	·636	·644	·637	·637	·636	·092	·073	·050	·049	·062	·065
Sep	·599	·616	·627	·628	·587	·617	·080	·075	·079	·065	·082	·076
Oct	·505	·541	·525	·528	·521	·525	·119	·101	·110	·114	·110	·111
Nov	·450	·503	·457	·462	·403	·469	·129	·089	·122	·114	·114	·114
Dec	—	·464	·438	·421	·452	·442	—	·093	·113	·113	·099	·105
Annual	·558	·547	·547	·540	·558	·549	·100	·100	·100	·102	·099	·100

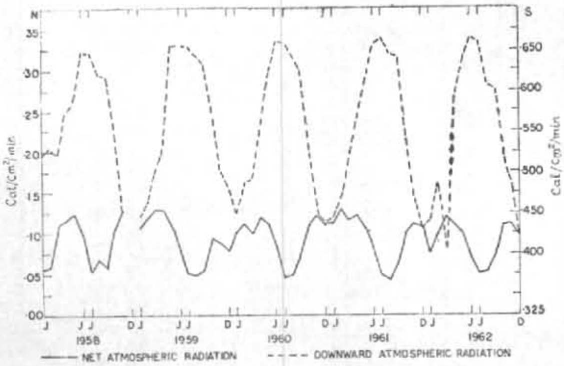

Fig. 4. Monthly distribution of atmospheric radiation on all nights at New Delhi (1958-62)

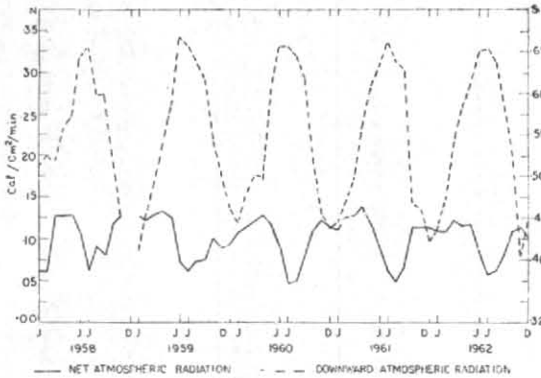

Fig. 5. Monthly distribution of atmospheric radiation on clear nights at New Delhi (1958-62)

0·092 cal/cm²/min. The mean seasonal value for the months October to February is 0·103 cal/cm²/min and for the dry summer months March to May 0·114 cal/cm²/min. The seasonal mean for the warm moist cloudy monsoon months July to September is only 0·053 cal/cm²/min.

Corresponding values for clear nights alone are naturally higher. The annual mean being 0·100 cal/cm²/min. It is as high as 0·125 cal/cm²/min in March to May. The mean for the months October to February is 0·108 cal/cm²/min. The highest maximum observed in five years is 0·192 cal/cm²/min in November 1960 and the lowest minimum 0·014 cal/cm²/min in July 1960. On an average about 0·11 cal/cm²/min is lost to the atmosphere from the earth's surface at New Delhi during the clear season. This falls to half this value during the warm moist monsoon months.

New Delhi lies in the semi-arid region in north India and has a continental climate with extreme summers and winters. The atmosphere is very dry except during the monsoon months. The summer months April to June are hot and dusty, with dust raising winds and duststorms. Winters are cold and dry and clear, except during the passage of western disturbances. The seasonal variations in S and N are correspondingly large, with large annual variations in temperature, clouding and water vapour content. The large values of net outgoing radiation during the clear seasons cause appreciable nocturnal cooling near the ground.

3.3. *Effect of dust*

An examination of the values of S from March to September (Fig. 2) shows that despite the comparatively low humidities in April to June, the downward atmospheric radiation even on clear nights is as high as that during the moist months August to October. The reason is to be found in the increased dust content during these months in the atmosphere over Delhi. The departure of observed values of downward atmospheric radiation from the computed values using Angstrom's formula is also to be ascribed to this important atmospheric radiator. Actual values of S/E are generally 0·9 while computed values are about 0·42. Atmospheric radiation on clear nights depends not only on temperature and moisture content, but on the dust content in the lower layers of the atmosphere.

3.4. *Year-to-year variations in S and N*

Tables 3 and 4 give the mean values of N and S for the individual years 1958, 1959, 1960, 1961 and 1962 for the different months, for all nights and for clear nights respectively. The annual march of S and N for the years 1958– 62, is shown in Figs. 4 and 5, for all nights and clear nights respectively. It will be seen that while the basic pattern of seasonal variations remains unchanged, significant year-to-year variations are present, during winter, closely associated with the passage of western disturbances, and during summer, as a consequence of the varying dust content in the atmosphere. The mean annual values of S and N in Tables 3 and 4 show no systematic changes.

4. Comparison of monthly mean values of atmospheric radiation with values over Madras

A comparison of atmospheric radiation values over Delhi and Madras (Fig. 6) shows that — (1) The downward radiation in any month at Madras is larger than at Delhi throughout the year, except during the hot monsoon months June to August. (2) The net atmospheric radiation in any month at Delhi is greater than at Madras except during the cloudy months July—August. The difference is large during the clear season. (3) There are large seasonal variations at Delhi, but

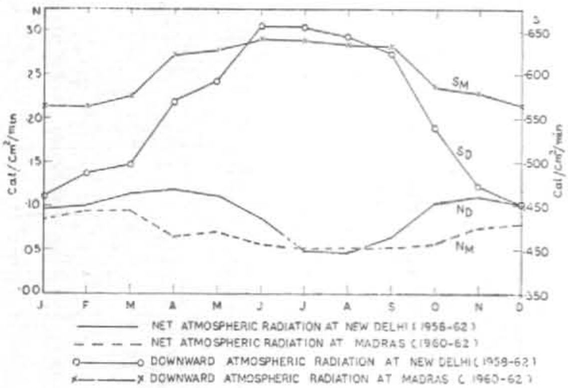

Fig. 6. Atmospheric radiation at New Delhi and Madras

little seasonal variation of S and N over Madras. The difference between atmospheric radiation values at Delhi and Madras are to be expected from the nature of the air supplies over the two regions. Over Madras, the supply in the lower levels is from the sea throughout the year and over Delhi it is land air from the west or northwest during the winter and summer and from the east or southeast during the monsoon.

5. Conclusion

The main results may be summarised as follows—

(1) Downward atmospheric radiation is a maximum during the cloudy monsoon months May to September and a minimum during the winter months, December—January. High values also occur in winter associated with western disturbances and in the summer due to increased dust content in the atmosphere.

(2) Net atmospheric radiation is a minimum during the cloudy monsoon months and a maximum during the cloud-free winter and summer months, with a slight fall in winter, associated with western disturbances.

(3) Due to the continental, semi-arid character of its climate and the extreme dryness of the atmosphere over Delhi, except during the monsoon months, the annual variations in both downward and net atmospheric radiation are very large, unlike those at Madras.

(4) Year-to-year variations are not significant except during the winter months, in association with the western disturbances and in summer due to varying values of turbidity in the atmosphere.

REFERENCES

Mani, A. and Chacko, O. 1963 *Indian J. Met. Geophys.*, **14**, p. 196.

Mani, A, Chacko, O. and Iyer, N.V. 1965 *Ibid.*, **16**, p. 445.