NOCTURNAL ATMOSPHERIC RADIATION AT POONA — A DISCUSSION OF MEASUREMENTS MADE DURING THE PERIOD JANUARY 1930 TO FEBRUARY 1931.

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(With 9 figures.)

Summary: Results of measurements of nocturnal radiation at Poona with an Ångström pyrgeometer extending over a year are analysed. The net radiation is maximum in February and March and minimum in the monsoon months July to September. Comparing the results with those obtained by W. H. & L. H. G. Dines in England, the net radiation in any particular month at Poona is greater than that at Benson. Comparing sky radiation, its value in winter at Poona is smaller than that at Benson in summer in spite of higher temperatures at Poona. This is probably due to the comparative dryness of the atmosphere over Poona. It is found that there is a general agreement between the observed values of sky-radiation and those calculated from Ångström's equation, although there are significant departures at high and low values of vapour-pressure. During the months May to October, the sky radiation on all clear days reaches a value about 0.75 of the black body radiation at the surface temperature — the maximum that may be expected if water-vapour is practically the sole radiating constituent. Tables are given showing the relation between night radiation and surface inversion at night. The marked influence of upper winds at Poona on sky radiation during winter months is pointed out.

Introduction.

The rapid drop in temperature at nightfall which is a characteristic feature of continental climates is very well-marked in North India during the months November to April and to a less degree in the Deccan. Actual measurements of sky-radiation in the tropics are, however, very rare and the measurements discussed in this paper were undertaken to provide some reliable data on the subject which will be of use in considering problems of radiation of the atmosphere.

The sky radiation was measured at night, generally between 20 and 22 hrs., with an Ångström's pyrgeometer. The instrument was obtained from Mr. G. Rose of Upsala. One of the two strips of constantan was coated with lamp-black and the other gilded. The instrument was

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exposed horizontally on the top of the tower of the Poona Meteorological Office. A calibrated Siemens and Halske milliammeter was used to measure the heating current and a mirror galvanometer to indicate the equality of temperatures of the thermo-couples soldered to the backs of the strips.

The pyrgeometer was tested in the following manner. A metal vessel was prepared with a hollow cylindrical dent at its bottom with a diameter of about 15 cm. The concave side of the cavity was coated with lamp-black. The vessel was filled with water at different temperatures below that of the room and supported over the pyrgeometer so that the instrument received radiation from the vessel over a solid angle 2π and the rate of loss of heat from the black strip was determined as usual from the heating current required to equalise the temperatures of the bright and black strips. The radiation loss was found to be practically proportional to $T^4 - T_1^4$ when T was the temperature of the strips and T_1 that of the water in the vessel.

If the black strip and the hollow radiator were assumed to be perfect absorbers for long-wave radiation and the bright strip to be perfectly reflecting, the mean value of STEFAN's constant came out to be $8.1 \cdot 10^{-11}$ in agreement with the accepted standard value $8.15 \cdot 10^{-11}$. The value obtained by calibration was used in all calculations. The vapour pressure of water at the time of measurement of night radiation was calculated from the readings of the wet and dry bulb thermometers exposed in a Stevenson Screen at the top of the tower. It was observed (as was noticed by ÅNGSTRÖM) that whenever the wind was markedly unsteady, the galvanometer did not have a steady zero. Movement of low or medium clouds, or change of their character caused fluctuations in the balancing current, which were largest when the clouds were overhead and least when they were near the horizon.

Results.

The daily values of radiation and weather elements at the time of observation together with relevant weather remarks will be published elsewhere.

In Table 1 are given the mean monthly values of air temperature and aqueous vapour pressure at the time of observation including both clear and cloudy days, black body radiation at the temperature of the instrument, net radiation and sky radiation as well as the number of observations on which the means are based.

Table 1.

Mean monthly values of night radiation (all days).

Month	No. of observations n	Air Temp. °A	Vapour pressure mm. of Hg	Black body radiation gcal/cm² min.	Net radiation gcal/cm² min.	Sky radiation gcal/cm² min.
Jan.	31	298	8.5	0.638	0.205	0.433
Febr.	34	297	8.1	.631	.215	.416
March	29	301	10.3	.670	.214	.456
April	27	302	11.6	.675	.194	.481
May	25	301	16.0	.669	.161	.508
June	20	300	17.3	.655	.114	.541
July	8	297	17.1	.633	.064	.569
August	17	297	16.4	.629	.115	.514
Sept.	8	298	18.1	.644	.097	.547
Oct.	17	300	15.9	.659	.117	.542
Nov.	26	298	11.6	.638	.176	.462
Dec.	28	298	9.9	.639	.184	.455

Table 2 contains the mean monthly values of the same quantities on clear days alone. The maximum and minimum net radiation from the instrument and of sky radiation on these days are also given in the Table. Days with high cloud or with medium or low cloud near horizon

Table 2.

Mean monthly values of radiation (clear days).

Month	No. of observations n	Air Temp. °A	Vapour Pressure mm. of Hg	Black body radiation cal/cm² min.	Net radiation gcal/cm² min.			Sky radiation gcal/cm² min.			(9) ÷ (5)
					Mean	Max.	Min.	Mean	Max.	Min.	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Jan.	30	297	8.5	0.637	0.207	0.238	0.186	0.430	0.457	0.392	0.68
Febr.	34	297	8.1	.631	.215	.257	.173	.416	.462	.335	.66
March	25	301	9.9	.669	.225	.257	.200	.444	.474	.382	.66
April	20	301	11.0	.672	.214	.249	.183	.458	.498	.413	.68
May	16	301	16.5	.664	.171	.203	.138	.493	.528	.456	.74
June	6	300	16.7	.661	.173	.196	.144	.488	.518	.467	.74
July	1	297	17.2	.633	.152	—	—	.481	—	—	.76
Aug.	1	298	16.8	.641	.152	—	—	.489	—	—	.76
Sept.	2	298	17.9	.644	.149	—	—	.495	—	—	.77
Oct.	5	301	12.7	.667	.165	.176	.149	.502	.519	.488	.76
Nov.	22	297	10.3	.636	.191	.227	.147	.445	.490	.406	.70
Dec.	23	298	8.8	.639	.197	.244	.147	.442	.502	.378	.69

and amount less than one have been taken as clear days; even if the sky was completely covered with light high cloud, the day has been taken as a clear day as it was found that the balancing current was little affected by the presence of such cloud. In the last column are given the ratios of the mean sky radiation to the black body radiation at the same temperature.

Monthly and seasonal variation of sky radiation and net radiation.

The mean monthly values of sky radiation and vapour pressure on all days (Table 1) and on clear days (Table 2) are plotted in figures 1 and 2 respectivley.

From figure 1 we find that the sky radiation gradually increased from February to July, decreased in August, slightly increased again from August to October and thereafter decreased till February, when

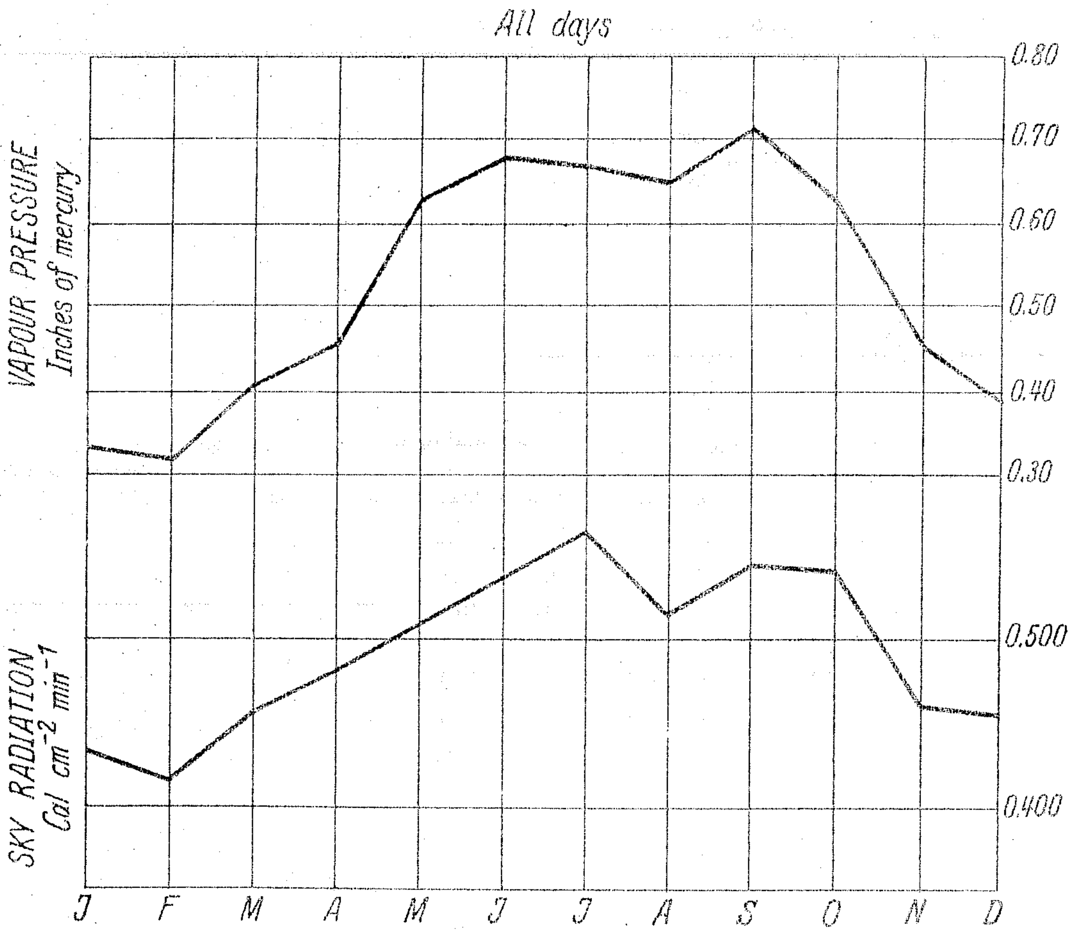

Fig. 1.

it was lowest. The vapour pressure curve also shows the same tendency. The number of observations in the months July and September are only 8 each, but on most of the other days in these months, it was either heavily clouded or was raining, so that their inclusion would only lead to an increase in the value of the sky radiation. One interesting feature of the curves is the smaller vapour pressure as well as sky radiation in

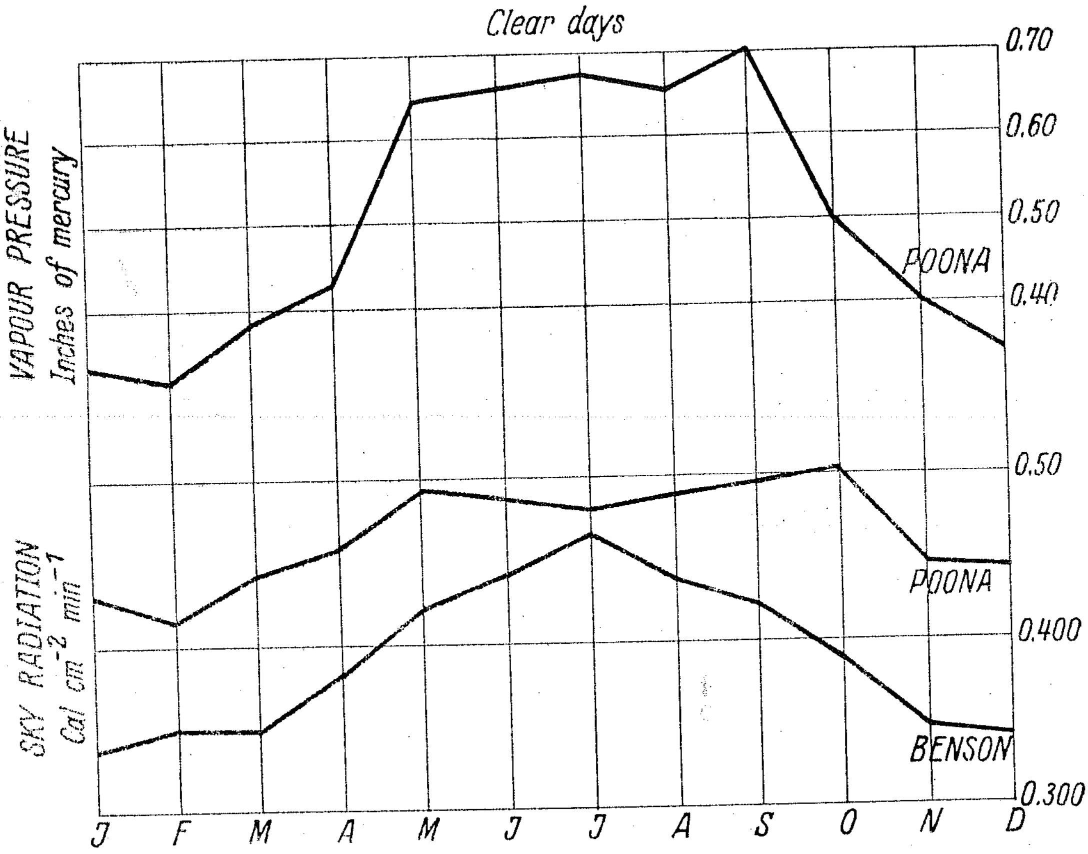

Fig. 2.

August than in July or September. This is connected with a break in the monsoon over the Indian Peninsula in August.

The only difference of figure 2 from figure 1 is that there is greater similarity between vapour pressure and sky radiation in figure 2 due to the elimination of the effect of clouds on atmospheric radiation. The number of observations on clear days in the months June to September are very few. The existing data, however, show that both sky radiation and vapour pressure vary little during these months when Southwesterly moist winds blow in the lower levels up to at least 2 km.

Comparison of monthly mean values of sky radiation with values over England.

In figure 2 is also given a curve showing mean monthly values of sky radiation on clear days at Benson (England) [1]) [2]). The following points are of interest:

1. The sky radiation at Poona in any month is larger than that at Benson in the same month.

2. The sky radiation at Poona in winter is smaller than that at Benson in summer in spite of the fact that temperatures over Poona are higher. This is due to the great dryness of the atmosphere over Poona during winter, a fact supported by results of sounding balloon ascents.

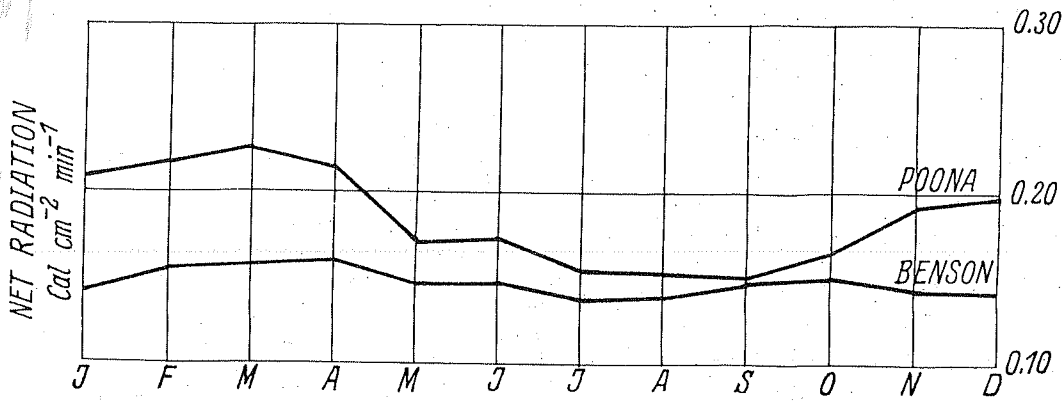

Fig. 3.

The monthly variation of net radiation at Poona and Benson is given in figure 3. The nocturnal radiation in any particular month at Poona is seen to be greater than that at Benson. This difference is large in winter and hot season. There is very little seasonal variation of net radiation over Benson. The difference in net radiation at Poona and Benson in different seasons is to be expected from the nature of the air supplies over the two places. The air supply of Poona during winter and hot season is land air from Northwest India, Baluchistan and Persia while from June to October, it is sea air from between south and west. The air supply over England is from the Atlantic throughout the year.

In his paper on "Further studies in Terrestrial Radiation", SIMPSON has calculated the limits of nocturnal radiation (maximum and minimum) for different temperatures from the absorption coefficients of water-vapour and carbon dioxide for different wave-lengths.

The values given in Table 5 of his paper have been plotted in figure 4 as thick curves. The curves have been extended to 305° A. The mean monthly and extreme values of net radiation on clear days in each month over Poona as given in Table 2 have been plotted in figure 4. The mean values are indicated by circles and the extreme values by dots. We find that all these values fall between the two extreme curves.

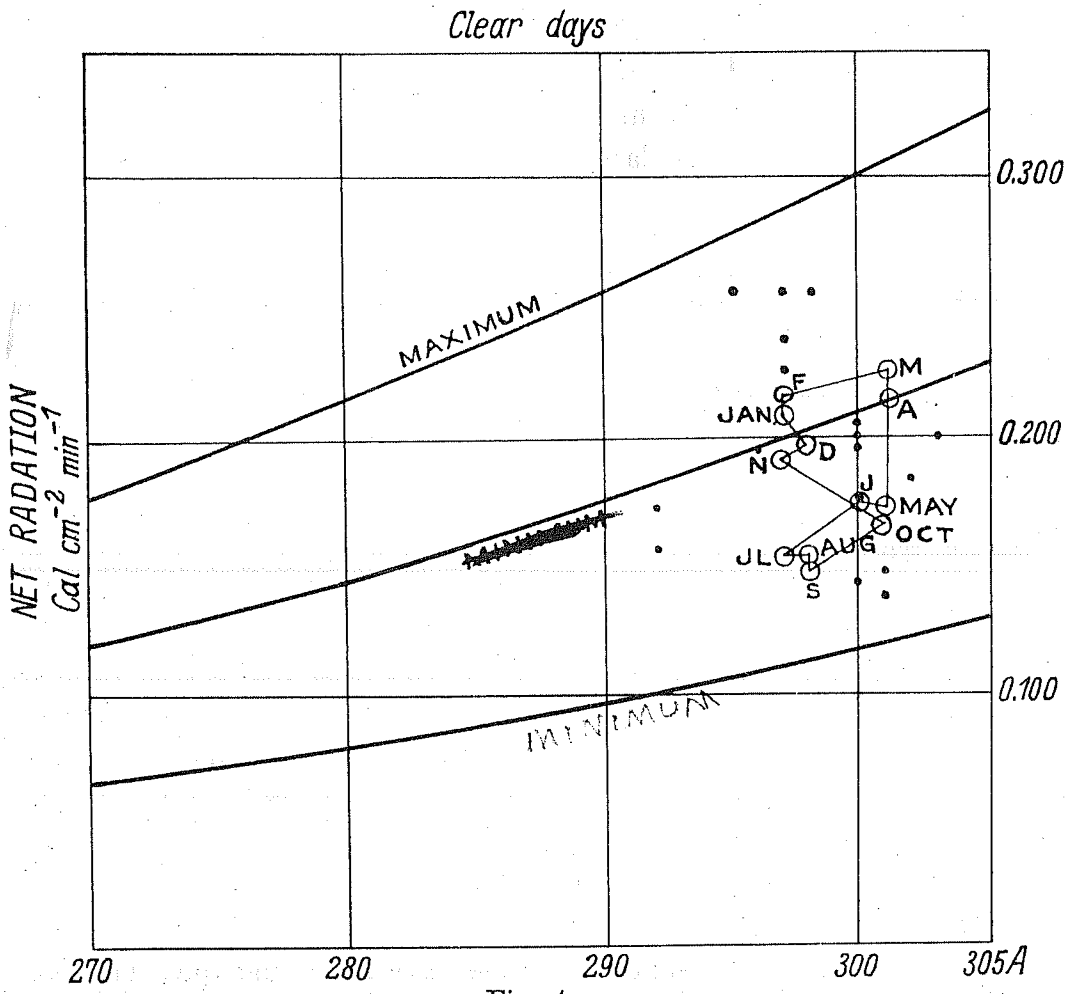

Fig. 4.

The net radiation in May is found to be less than that in March or April in spite of the fact that the air temperature in all the three months was the same. This is due to a gradual increase in water vapour content of the atmosphere from March to May. We also find that the drier the atmosphere, the higher the value of net radiation.

Relation between sky radiation, vapour pressure, and temperature.

From his studies of the radiation of the atmosphere, A. Ångström [3]) has deduced the following semi-empirical equation connecting sky radiation and the aqueous vapour pressure at the surface.

(1) $$E_a = S_t\,(0.75 - 0.32 \cdot 10^{-0.069p})$$

where E_a is the sky radiation and S is the black-body radiation at the temperature of the air at the surface and p the aqueous vapour pressure in millimetres of mercury. According to (1), the value of sky radiation from a clear sky will lie between 0.75 and 0.43 of that of a black body at the temperature of the atmosphere at the earth's surface. Table 3 compares the monthly means of the observed radiation on clear days with the values calculated according to (1).

Table 3.
Mean monthly values of sky radiation (clear days).

Month	Jan.	Febr.	Mar.	Apr.	May	Jun.	July	Aug.	Sept.	Oct.	Nov.	Dec.
E_a Calculated	0.425	.419	.453	.460	.486	.480	.463	.468	.468	.468	.431	.430
E_a Observed	0.430	.416	.444	.458	.493	.488	.481	.489	.495	.502	.445	.442

It is not quite correct to extrapolate the equation to zero value of humidity, but as has been explained by Simpson, owing to the very high absorptivity of water-vapour for some regions of long-wave radiation spectrum, the radiating power of the atmosphere is high even for exceedingly small quantities of moisture-content.

The daily values show that the limits of sky radiation on clear days at Poona lie between 0.77 and 0.58 of that of a black-body at the temperature of the atmosphere near the instrument and that the maximum value is reached on practically all clear days during the months May to October.

There is good agreement between the calculated and observed average monthly values in the drier part of the year. In the wet months July to October, the observed values are generally higher. This may be due either to the cloud haze that is often present in the atmosphere in these months or to the imperfect applicability of the formula when the vapour pressures are high. It should be remembered that the number of observations in these months is also small.

The individual values of sky radiation on clear days are plotted in figure 5 together with the curve of Ångström's equation [1]) given above. The black dots which represent the values in the months June

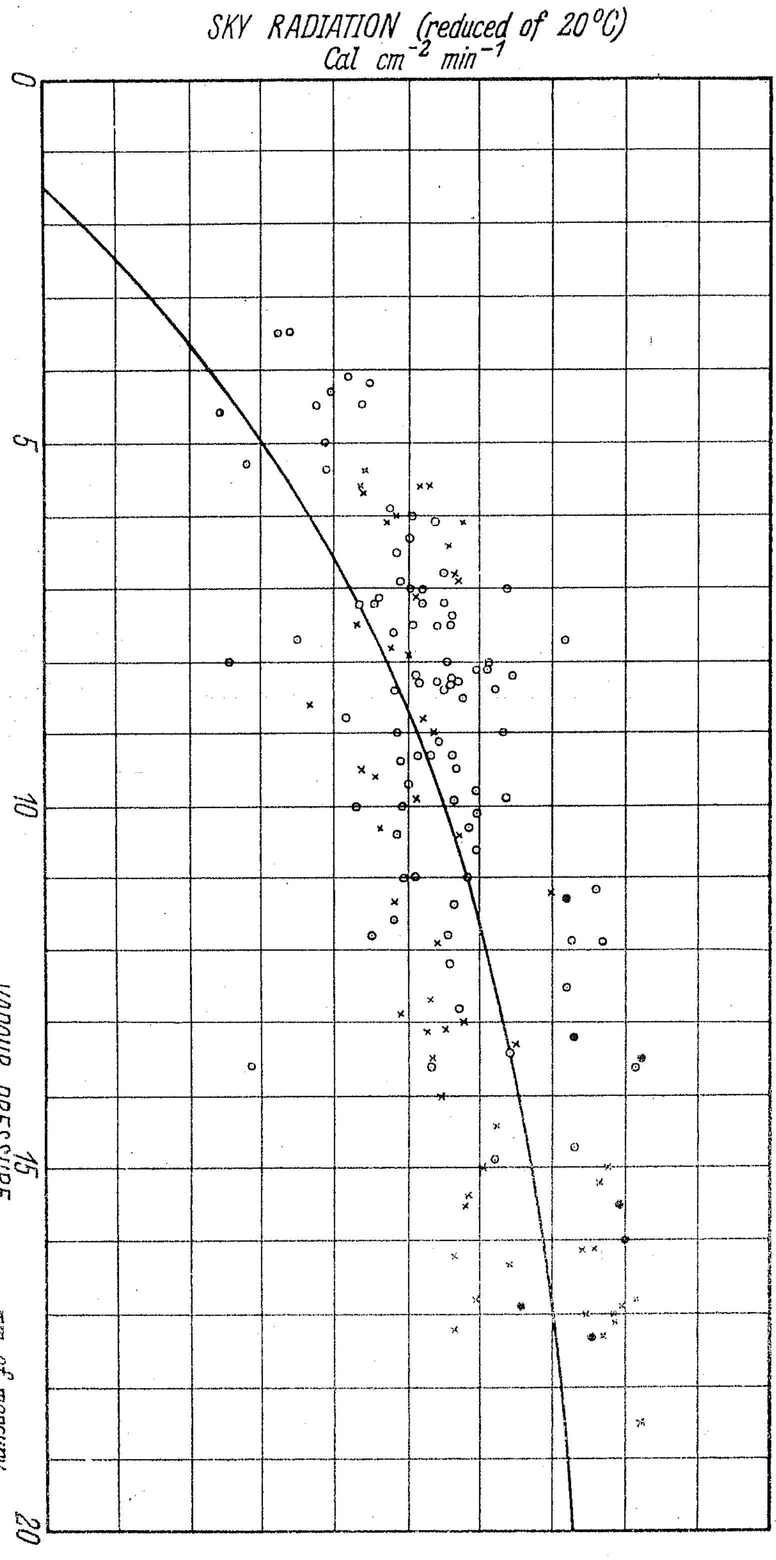
SKY RADIATION (reduced of 20°C)
Cal cm⁻² min⁻¹
0
5
10
15
20
VAPOUR PRESSURE
mm of mercury

Fig. 5.

to October are generally higher than those given by the curve. Also when the vapour pressure is below 7 mm. which usually occurs under anti-cyclonic condition in the months December—March, there is a tendency for the observed values to be higher than the calculated. This is not surprising as ANGSTRÖM's equation does not take into account variations of upper air temperatures and humidities.

Surface inversion and nocturnal radiation.

At the Poona Meteorological Office, thermographs are kept in Stevenson Screens supported on 4 ft. stands on the top of the tower and on the ground in the office compound. A grass minimum thermometer is also exposed near the ground Stevenson Screen. In Table 4 are given the number of occasions when the difference between the minimum temperatures recorded in the Stevenson Screen on the ground and by the grass minimum thermometer had various values ranging from 0° F to 12° F and the corresponding mean values of net radiation on the previous night.

Table 4.
Clear days.

Stevenson Screen minimum — grass minimum. $(S-G)$ °F.										
2	3	4	5	6	7	8	9	10	11	12
Number of occasions.										
2	3	9	18	22	20	22	27	25	8	1
Average net radiation gcal/cm² min.										
0.038	0.153	0.152	0.174	0.191	0.208	0.207	0.209	0.224	0.223	0.242

Only clear nights or nights on which there was no appreciable alteration of high cloud amount (with no middle or low clouds) have been considered for the purpose of this table. In figure 6 are plotted the individual values of net radiation against the difference between the 4 ft. screen minimum and grass minimum. The mean values of net radiation for definite values of difference between the screen and grass minimum are also plotted as circles. It will be seen that the strength of the inversion grows at increasing rates as the net radiation increases. Radiation tends to produce stratification while turbulence tends to destroy it. For any value of eddy diffusivity there will be a definite value of radiation required to set up stratification; with increase of radiation in excess of this value, the stratification will increase in intensity.

In Table 5 are given the number of clear days on which the difference between the minimum temperatures recorded in the Stevenson Screens

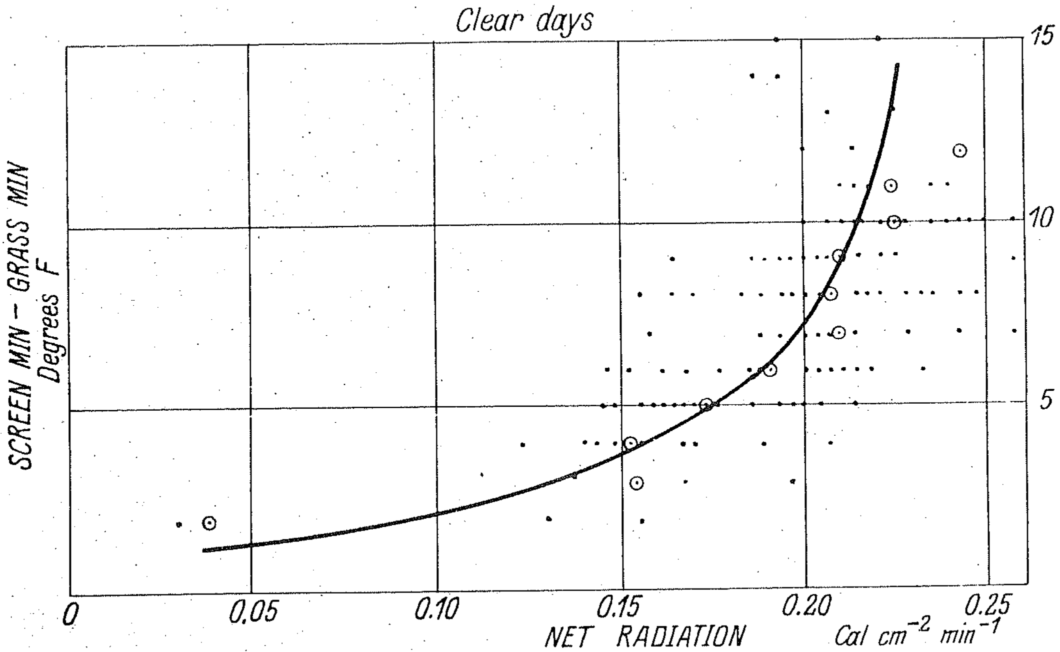

Fig. 6.

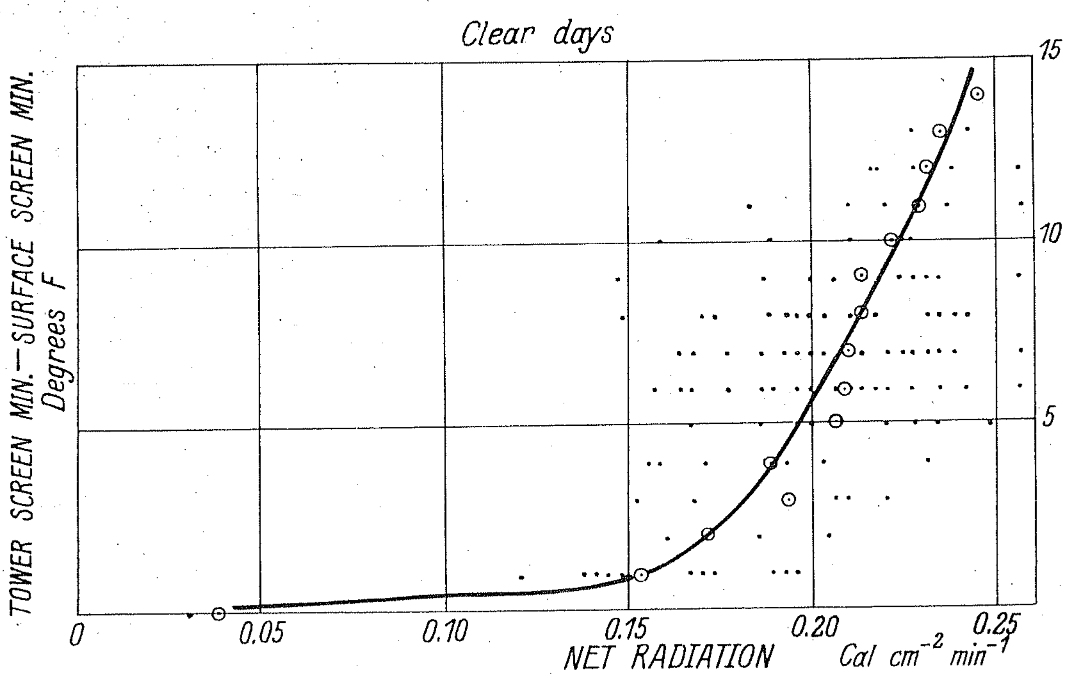

Fig. 7.

at a height of 4 ft. above ground (S) and on the top of the Tower (T) had values ranging from 0° to 14° F and the corresponding mean values of net radiation. The individual and mean values are plotted in figure 7.

Table 5.
Clear days.

Tower S. S. Min. — Surface S. S. Min. ($T-S$) °F.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Average net radiation gcal/cm² min.	0.038	.153	.172	.194	.189	.207	.209	.210	.213	.213	.222	.229	.231	.235	.245
Number of occasions.	2	13	3	5	3	9	28	33	24	12	4	5	5	2	2

The inversion extends appreciably above 4 ft. only when the net radiation exceeds 0.150 gcal/cm² min.

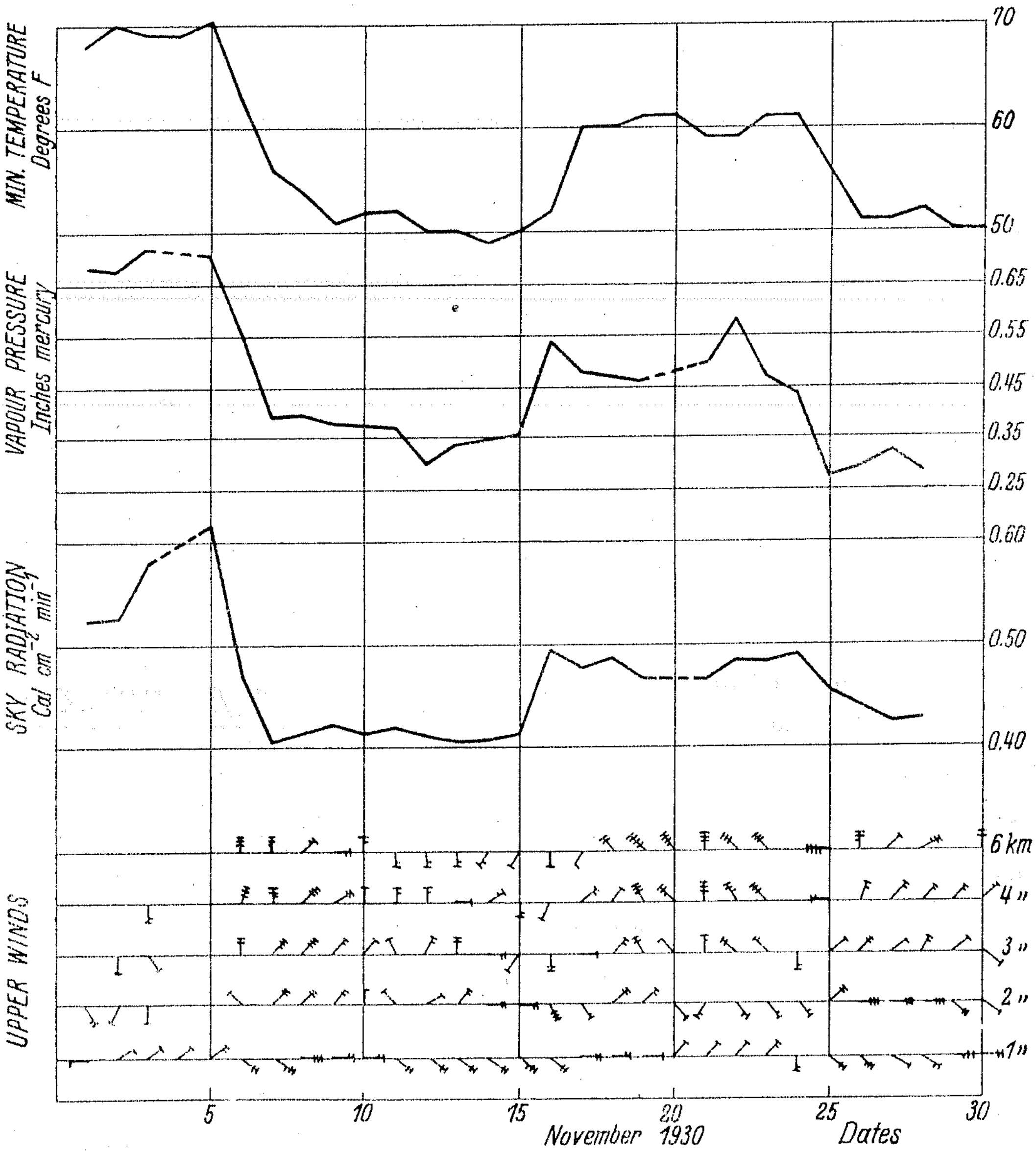

Fig. 8.

Sky radiation and upper winds.

As the intensity of the sky radiation is intimately connected with the moisture content of the atmosphere, it may be excepted that the source of supply of air in the upper atmosphere and hence the direction of upper wind will influence the sky radiation, especially in those seasons and days when the moisture near the surface is small.

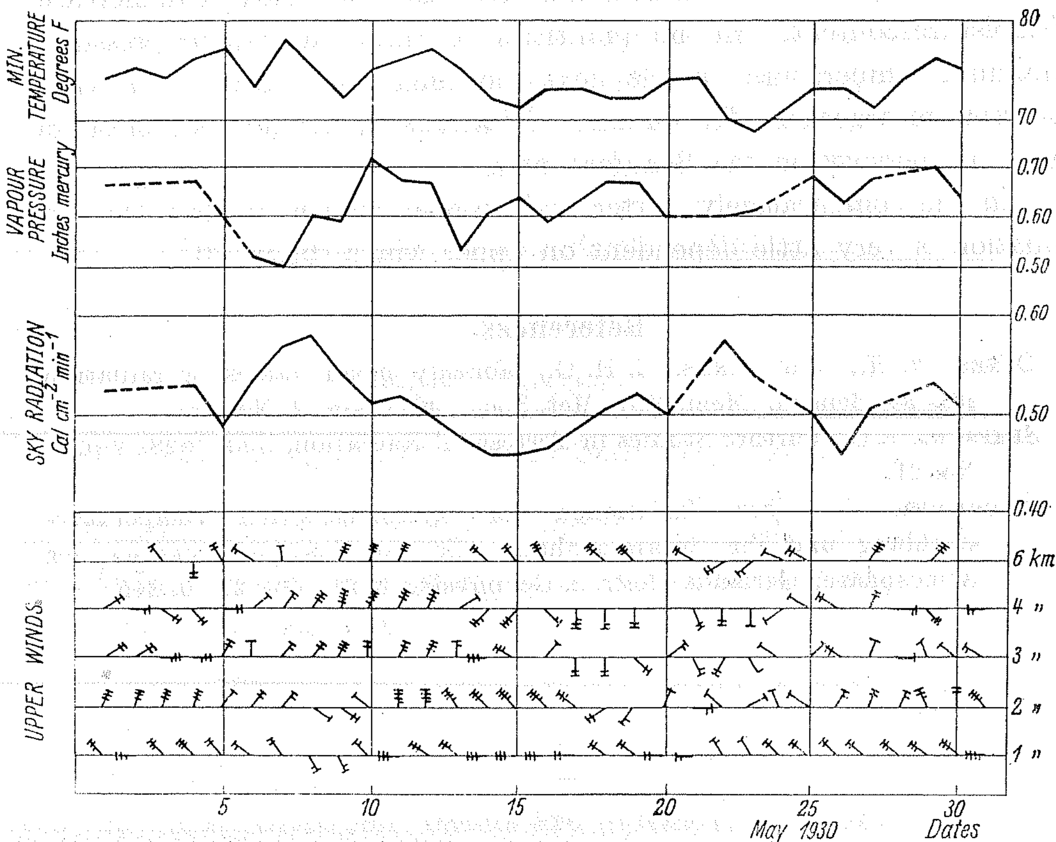

Fig. 9.

In figure 8 are plotted the daily values (in November 1930) of morning upper winds at 1, 2, 3, 4 and 6 kms., and the values of sky radiation measured on the night of the same day. The vapour pressure near the pyrgeometer at the time of measurement of the sky radiation and the minimum temperature recorded next morning near the ground are also plotted for comparison. It will be seen that winds with southerly components at 2 to 4 km. were generally accompanied by high values of sky radiation, and when the winds were northerly to easterly at these levels, the sky radiation was generally small. It will also be noticed that northerly to northeasterly winds are accompanied by smaller values of sky radiation than northwesterly winds. This is due to the fact that in the former case, Poona is situated to the southwest of the seasonal anticyclone which extends up to about 3 km. while northwesterly winds at 2 and 3 km. over Poona occur in the immediate rear of western disturbances moving eastward across N.India. The winds and radiation on the 8^{th} to 15^{th} show that the direction of wind at 6 km. and above has little influence on the radiation. A Southeasterly wind at 1 km. alone does not appear to be markedly different from an easterly at the same level. The wind at 2 km. gives the best index of an increase of moisture content. All the quantities skyradiation, vapour pressure, minimum temperature on the next morning, and direction of wind at 2 km. go together. The number of feathers in the arrows represents the wind velocity on the Beaufort Scale.

In the comparatively hotter and moister month of May the sky radiation is very little dependent on upper winds (figure 9).

References.

1. Dines, W. H., and Dines, L. H. G., Monthly mean values of radiation etc. at Benson. Mem. Roy. Met. Soc. 1927, Vol. 2, No. 11.
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3. Ångström, A., Über Variationen der atmosphärischen Temperaturstrahlung und ihr Zusammenhang mit der Zusammensetzung der Atmosphäre. Gerlands Beitr. z. Geophysik, 1929, Vol. 21, p. 145.