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1. INTRODUCTION

A KNOWLEDGE of the quantity of water vapour present at any moment in different air layers of the atmosphere above a station is of fundamental importance to the meteorologist. The humidity records obtained from sounding-balloon meteorographs sent up in the atmosphere give some indication of the variation of humidity with height; but the use of the hair element for the measurement of humidity has not been found to be quite satisfactory. The problem of improving the method of recording humidity is engaging the attention of many workers.

The possibility of estimating the total precipitable water in the atmosphere by a spectroscopic method was first demonstrated by Fowle[1] by using his laboratory measurements of the absorption coefficients of water vapour in the bands in the near infra-red. The spectroscopic method does not indicate the distribution of water vapour with height, but does provide a rapid means of estimating the total water content of the atmosphere above a station whenever the sun is not obscured by clouds. The method has been used by a number of workers.[2,3,4,5] The necessary apparatus was set up at Poona towards the end of 1939, and some measurements recorded in 1940. During 1941 the measurements were made regularly and the data obtained are discussed here. A description of the experimental arrangement, the method of taking the records and some typical results are given in the following sections.

2. APPARATUS AND METHOD OF OBSERVATION

The apparatus (see Fig. 1) consists of:—

(i) a locally constructed spectrograph, L_1 and L_2 being the collimating and focussing lenses respectively and P a flint glass prism (an equilateral one) with base 7·8 cm. and hight 4 cm.;

(ii) an ordinary heliostat H with a front silvered mirror, to direct the sun's rays into the slit S of the spectroscope after being condensed by the lens L_3;

(iii) a Moll's micro-thermopile (with a glass window and a vertical slit) mounted on the carriage of a travelling microscope capable of horizontal movement along the focal plane RV of the spectroscope; and lastly

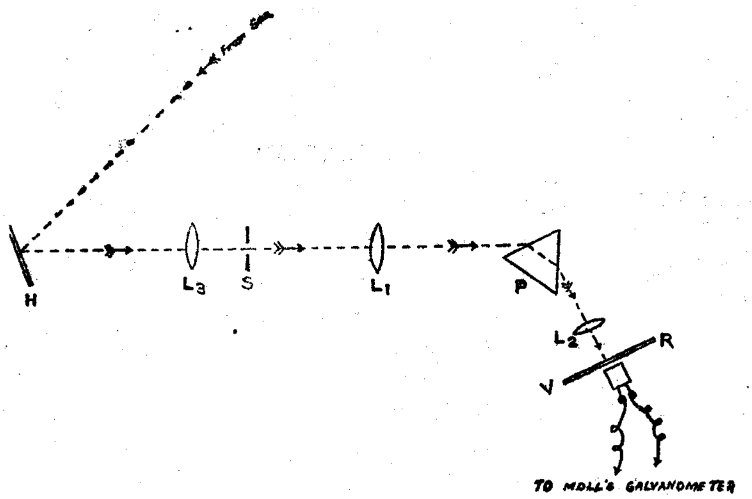

FIG. 1

(iv) a sensitive Moll galvanometer (period ½ second) (connected to the thermopile), with a lamp and scale arrangement for reading the deflections.

It may be pointed out that glass is sufficiently transparent in the near infra-red region of the spectrum in which we are interested and that the whole experimental set-up has, when sunlight is focussed on the spectrograph, a maximum sensitiveness in the wavelength interval $0 \cdot 75\,\mu$ to $1 \cdot 2\,\mu$, the deflection decreasing rapidly on either side, *i.e.*, when the thermopile is shifted towards the visible region or towards wavelengths greater than $1 \cdot 2\,\mu$.

Fig. 2 is a typical curve showing the deflections in cm. on the scale against the readings of the travelling microscope in cm. The positions of the various important absorption bands are indicated in the figure. It may be noticed that the chief water vapour absorption bands are

ψ' at $1 \cdot 47\,\mu$

ψ at $1 \cdot 42\,\mu$

ϕ at $1 \cdot 13\,\mu$

ρ at $0 \cdot 93\,\mu$

Fowle's absorption measurements in the laboratory with columns of moist air a few hundred metres long (using Nernst glowers as the source of radiation) were naturally confined to the intense absorption bands ϕ and ψ'. In these measurements Fowle reached values of water content up to 0·5 cm. of

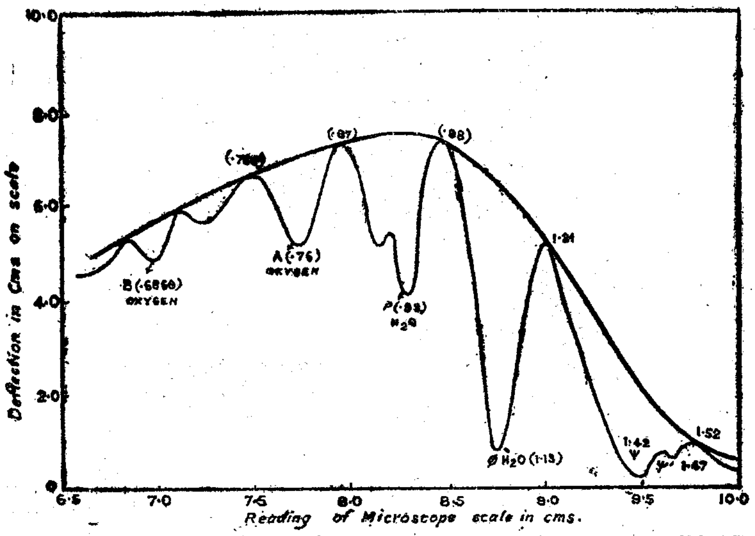

FIG. 2. ABSORPTION BANDS IN THE SPECTRUM OF SUNLIGHT IN THE NEAR INFRA-RED REGION (·7 TO 1·52 μ)

FIG. 2

precipitable water, W. He extended the measurements to larger values of W by working at Mount Wilson with the sun as the source and with air masses up to 3·5, *i.e.*, at different zenith distances of the sun. Fowle's transmissibility values for the bands ϕ and ψ' have been correlated with the transmissibility values at the relatively weaker band at ρ (0·93 μ) so that the transmission of radiation at the ρ band may be used for computing the values of W. Fig. 3 gives the transmissibility at ψ' plotted against that at ρ as given by Pierre Lejay[4] and Fig. 4 gives the transmissibility at ψ' against the values of W (precipitable water in cm.) as given by the same author. In our measurements we have recorded the transmission at ρ and used Figs. 3 and 4 for computing W. The advantage in using the ρ band is that the variations in the absorption at different times or dates are larger and are recorded more accurately as the deflections in this region are comparatively larger than at the other bands. The base line in Fig. 2 is obtained by screening the radiation from the instrument. The transmission at ρ is obtained as the ratio of CD to O'D in Fig. 5 where OX is the base line, A and B are the maximum readings on either side of the band giving O' as

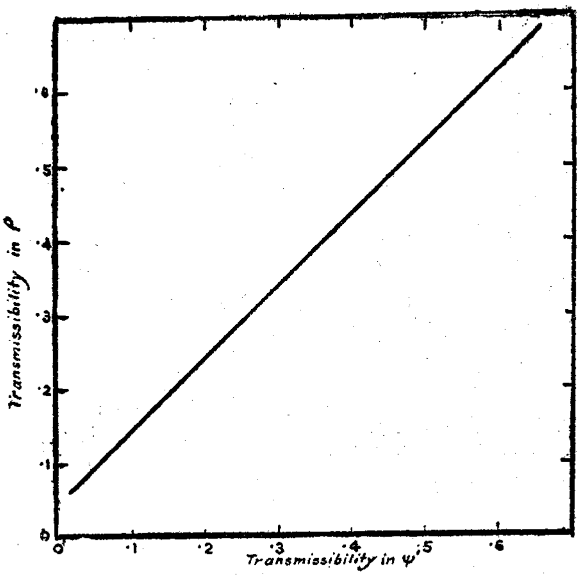

FIG. 3

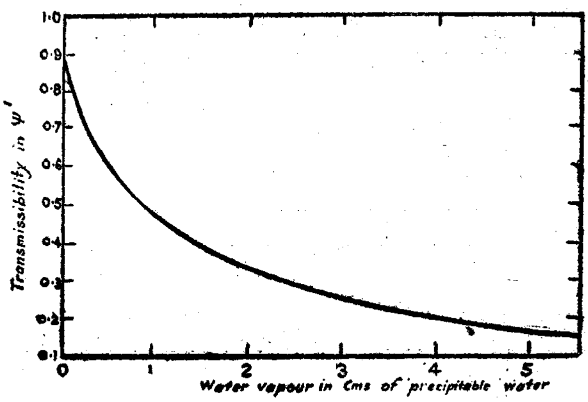

FIG. 4

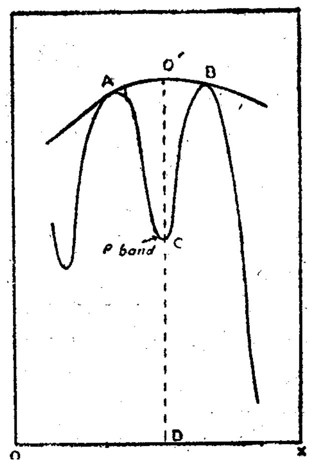

FIG. 5

the point for 100% transmission and C is the minimum deflection corresponding to the centre of the absorption band ρ.

3. DATA RECORDED AND A BRIEF DISCUSSION OF SOME OF THE MAIN RESULTS

The observations were recorded whenever sunshine unobscured by clouds could be focussed on the spectrograph. During clear weather the observations could proceed regularly at more or less fixed times; during cloudy weather one had to wait for openings in the clouds. On many or most of the days during the wet season no observations were possible. During the period September to June the records are available for some days; the number is large during the period November to April and small in September and October and June. During June to September, attempts were made to take observations during the rare occasions when the skies cleared temporarily.

Table I gives the observations recorded at different hours during the 17th February 1941. These illustrate the process of computing the values

TABLE I

Example giving observations recorded on the 17*th February* 1941 *and the method of computing W*

Hour.	θ	Sec. θ	D. B. / W. B.	V. P. / H%	Min. of ρ	Max. near ρ		Max. ρ	Tran. in ρ	Tran. in ψ'	W Sec θ	W	Whether Remarks
0820	75·5	4·000	20·2 / 15·8	11·3 / 64	0·30	2·00	2·30	2·20	·1363	·096	8·80	2·200	1 Ci
0855	67·5	2·613	21·7 / 16·5	11·5 / 59	0·52	2·00	2·30	2·20	·2363	·195	4·30	1·642	1 Ci
0930	60·0	2·000	24·2 / 18·0	12·4 / 55	0·50	1·85	2·00	1·95	·2564	·216	3·60	1·800	
205	34·0	1·206	31·0 / 18·8	10·2 / 30	0·85	2·25	2·30	2·29	·3698	·330	2·10	1·741	
235	32·5	1·186	32·2 / 18·0	8·4 / 23	0·90	2·51	2·65	2·61	·3443	·305	2·27	1·914	
1333	35·0	1·221	31·2 / 16·5	6·7 / 20	1·05	2·70	2·90	2·86	·3671	·327	2·13	1·745	
1430	42·0	1·346	33·2 / 17·5	7·1 / 19	1·00	2·50	2·70	2·63	·3802	·342	1·97	1·464	
600	60·0	2·000	33·5 / 18·0	7·7 / 20	0·65	2·50	2·69	2·60	·2500	·210	3·70	1·850	1 Cu
1653	70·5	3·000	34·0 / 18·5	8·2 / 21	0·45	2·00	2·25	2·16	·2083	·169	5·30	1·766	2 Cu
1720	75·5	4·000	33·0 / 18·0	8·0 / 21	0·30	1·60	1·80	1·71	·1754	·135	6·80	1·700	3 Cu

of W, the depth of the total precipitable water in centimetres, in a vertical column of the atmosphere 1 sq. cm. in cross-section extending up to the outer limit of the atmosphere. It will be noticed that when the sun is at a zenith distance θ, the value obtained is W sec. θ, and that W is obtained by dividing W sec. θ by the air mass sec. θ at the time of observation. The dry bulb and wet bulb temperatures D.B., W.B., were recorded with an Assmann Psychrometer near the instrument and the values of the vapour pressure and relative humidity are also given in the table.

(*a*) *Seasonal and diurnal variation of W.*—Table II gives the mean daily values of W in cm. in different months of the period February 1941 to

TABLE II

Mean value of W in cm. in different months during different hours of the day during the period February 1941 *to January* 1942

(*n*) *is the number of observations on which the means are based.*

Month		0800 to 0900 hrs.	0900 to 1000 hrs.	1000 to 1100 hrs.	1100 to 1200 hrs.	1200 to 1300 hrs.	1300 to 1400 hrs.	1400 to 1500 hrs.	1500 to 1600 hrs.	1600 to 1700 hrs.
February	W	1·66	1·74	2·10	1·70	1·77	1·76	1·75	1·75	1·84
1941	(*n*)	(37)	(25)	(4)	(6)	(23)	(23)	(19)	(12)	(22)
March	W	1·41	1·51	..	1·67	1·71	1·68	1·66	1·73	1·51
1941	(*n*)	(45)	(27)		(5)	(25)	(19)	(22)	(10)	(24)
April	W	1·64	1·75	1·72	1·77	1·84	2·03	1·83	1·88	1·45
1941	(*n*)	(39)	(10)	(19)	(11)	(25)	(19)	(21)	(4)	(23)
May	W	1·73	1·63	1·99	1·87	2·15	2·34	2·02	2·14	2·39
1941	(*n*)	(28)	(1)	(24)	(14)	(28)	(9)	(19)	(6)	(23)
June	W	2·68	2·09	2·89	3·15	2·89	2·72	2·94	2·92	2·43
1941	(*n*)	(6)	(6)	(6)	(5)	(6)	(7)	(6)	(7)	(12)
July	W	..	..	..	..	..	2·72	..	..	..
1941	(*n*)						(3)			
August	W	..	..	..	2·53	..	..	..	..	..
1941	(*n*)				(1)					
September	W	1·87	1·72	2·07	2·36	2·30	2·03	2·48	2·76	1·65
1941	(*n*)	(10)	(4)	(17)	(7)	(11)	(8)	(3)	(10)	(8)
October	W	1·39	1·45	1·89	1·56	1·93	1·91	1·96	1·71	1·64
1941	(*n*)	(19)	(11)	(24)	(8)	(16)	(13)	(17)	(10)	(16)
November	W	1·03	1·35	1·38	1·47	1·54	1·55	1·46	1·69	1·41
1941	(*n*)	(13)	(14)	(20)	(9)	(18)	(13)	(11)	(14)	(22)
December*	W	0·45	0·74	0·82	1·25	1·11	1·09	0·89	1·03	0·83
1941	(*n*)	(3)	(3)	(8)	(5)	(8)	(9)	(6)	(5)	(8)
January*	W	0·62	0·83	1·02	1·14	1·17	1·08	1·25	1·27	1·24
1942	(*n*)	(4)	(8)	(9)	(12)	(19)	(9)	(9)	(17)	(15)

* *N.B.*—The comparatively lower values of W in the morning hours of December 1941 and January 1942 are due to the number of observations available for these hours as well as the values of W recorded on the few occasions being rather small.

January 1942 (one year) at different hours of the day. The figures within brackets indicate the number of observations on which the means are based. The table based on observations so far recorded gives some idea of the diurnal variation of W in different months of the year. The values are comparatively small, generally < 2 cm. during the dry season October to April. After April there is a rapid increase towards June, when the south-west monsoon sets in. All the available observations from June to August indicate values higher than 2 cm.; they are higher than 2·5 cm. and often 3·0 cm. or more during wet spells (*i.e.*, individual occasions). Looking at the mean values of W at different hours, one finds that there is a tendency for the values of W to increase in the afternoon and in some months like March, April, June and September a tendency later towards the evening for W to decrease. On individual days the effect of sea-breeze is perceptible. A study of W in relation to the properties and sources of the air masses at different levels is being attempted.

(*b*) *Mid-day or noon values of W.*—The noon values of W are recorded when the incoming solar rays are normal or nearly normal to the atmosphere, *i.e.*, the air mass is nearly unity. The seasonal variation of W is brought out clearly in Fig. 6 where the noon values of W are plotted as dots against the dates for which the data are available during the period February 1941 to January 1942. The dots cluster about a mean value of W which is low in

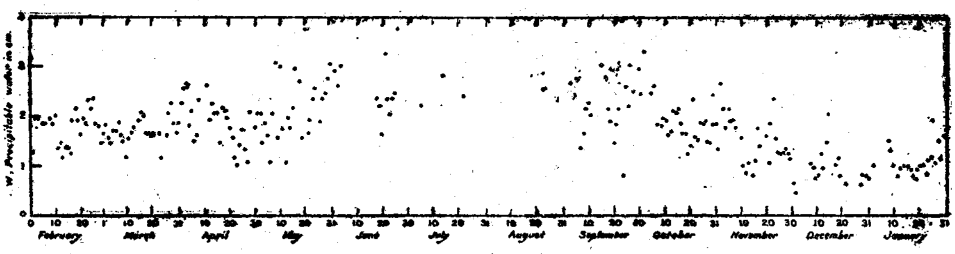

FIG. 6

winter (lowest values are recorded in December) as may be seen from the two ends of the diagram. The value of W increases in summer and attains a maximum value during the middle of the monsoon season (July–August). The lowest value of W so far recorded was 0·46 cm. on the 2nd December 1941 and the highest value was 3·97 cm. recorded on the 4th June 1941. During the monsoon months the number of occasions when observations could be recorded was small; the seasonal tendency is, however, shown even by the few dots plotted against these months. It should be pointed out that the values of W recorded during the short intervals of clear weather during the monsoon would be smaller than those during the rest of the season, so that they should be taken as the lower limit of W during the rainy season.

(*c*) *Mean daily values of W in different months of the year*; *a comparison of these with values of W estimated by other methods.*—Columns 2, 3 and 4 in Table III give the mean daily values of W during different months of the year as computed from the spectroscopic observations during the hours falling within the zenith distance of 60° of the sun before and after noon. The available data are given separately for the years 1940, 1941 and 1942. The figures inside brackets below the values of W indicate the number of observations on which the mean values are based. It may be noticed that the values

TABLE III

Month	Mean values of W in cm. based on						
	Spectroscopic measurements made in			Normals of sounding balloon data based on 10 years' records	Measurements of heat radiation from the night sky	Hann's formula W = 2·1 × *e*, using	
	1940	1941	1942			Data of *e* recorded in 1941–42	Normal values of *e* computed from 50 years' records
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
January ..			1·16 (71)	1·52	1·46	1·68	1·76
February ..	1·79 (16)	1·76 (111)		2·09	2·83	1·87	1·70
March ..	1·61 (51)	1·69 (128)		1·88	2·85	1·64	1·86
April ..	1·93 (47)	1·86 (125)		3·27	3·06	1·75	2·24
May ..		2·17 (125)		4·23	3·05	2·42	3·02
June ..		2·77 (34)		4·82	2·86	3·39	3·74
July ..		2·72 (3)		4·80	4·36	3·56	3·79
August ..		2·53 (1)		5·21	4·82	3·44	3·71
September ..		2·31 (68)		5·11	3·94	3·44	3·64
October ..	1·65 (24)	1·94 (102)		3·88	3·66	2·64	3·26
November ..	1·53 (61)	1·46 (87)		2·67	3·07	1·77	2·36
December ..	0·91 (16)	1·00 (53)		2·47	1·84	1·53	1·83

of W in February, March, April, October, November and December given for both 1940 and 1941 more or less agree with each other. The seasonal variation, as already pointed out, indicates a minimum in December and a maximum during the monsoon season (June-August). In the 5th column of Table III are given the values of W computed from the normal values of *e*, the vapour pressure in mm. of Hg and T the temperature in degrees absolute at different levels above ground based upon 10 years' sounding balloon records. These computations were made according to the formula:

$$\delta W = \delta h/T \times \cdot 622\, e/2\cdot 8703 \times 10^3 \text{ cm.},$$

where δW is the precipitable water in the height interval h_1 to h_2 or δh (cm.) at mean temperature of T° A and having a vapour tension *e* (expressed in millibars). W is obtained by adding up the values of δW for the different height intervals. The values of W are nearly of the same order of magnitude as the spectroscopic values only in the first three months of the year. During the rest of the year the values computed from the sounding balloon records are higher. This difference may partly be due to the fact that while the spectroscopic values refer only to spells of clear weather, the sounding balloon data are available for all types of weather.

The values of W given in columns 7 and 8 are based on Hann's[6] formula $W = 2 \cdot 1\ e$, where e is the vapour pressure at the surface in cm. of Hg. The values computed from (1) the data of e during the period 1941–42 and (2) the normal values of e based on past 50 years' records are more or less similar. They are not so high as those based on the sounding balloon records but are somewhat higher than the spectroscopic values.

Lastly, in column 6, we have given the estimates of W obtained from the measurements of the nocturnal heat radiation falling on unit area of a horizontal surface made with an Angstrom's Pyrgeometer at Poona during clear nights. It is well known[7,8] that the ratio of S, the heat radiation received from the night sky to the black-body radiation σT^4 emitted by the same surface at a temperature of T° A is given by

$$S/\sigma T^4 = A - B\ 10^{-kw}$$

where A, B and k are constants whose values are $0 \cdot 77$, $0 \cdot 28$ and $0 \cdot 33$ respectively and W is the precipitable water in the atmosphere (cm.). The values of W computed from the above formula, knowing all the factors except W, are slightly higher than the values given in columns 7 and 8, but smaller than those given in column 5. The estimates of W from the heat radiation data are not strictly comparable with the day estimates obtained spectroscopically. The comparative values of W given in Table III show that the spectroscopic values are smaller than the other estimates. It may be mentioned that during the month of November 1940 there were a number of days when sounding balloons had been let off at Poona and when the values of W had also been let off at Poona and when the values of W had also been determined by the spectroscopic method. The values of W obtained by the two methods are given in Table IV below in the order of increasing values of W.

The spectroscopic values are roughly half of the values obtained from the sounding balloon data. It is hoped that, with further improvements in these two methods of measurements, the real source of difference will be located. It is more than possible also that Fowle's original relation between W and the transmissibility of radiation at the ψ', and ϕ bands may require revision.

TABLE IV

Date	W in cm. Spectroscopic	W in cm. Computed from sounding balloon data
18-11-1940	0·67	1·43
22-11-1940	1·40	2·42
16-11-1940	1·47	2·90
6-11-1940	1·70	4·08
14-11-1940	2·30	3·29
5-11-1940	2·38	4·26
24-11-1940	2·96	4·88

The variations in W from day to day are, however indicated unmistakably by the spectroscopic measurements which have the great advantage that the results are available immediately to the weather forecaster. This aspect is dealt with in the next section.

4. W in Relation to Some Weather Phenomena

(*a*) *Effect of sea-breeze.*—On many days during the pre-monsoon months the sea-breeze with a westerly component replaces the air of land origin. On some of these occasions the marked contrast in the moisture contents of these air masses brings about an increase of W, after the sea-breeze sets in. An example is given in Table V; the data refer to the 3rd of April 1941.

TABLE V

Time	W in cm.	Remarks
Hrs. I.S.T.		
0905	1·97	
1045	2·16	
1130	2·29	
1305	2·25	2 Cu at 1315 hours
1408	2·15	5 Cu at 1400 hours
1640	2·39	Sea-breeze started at 1655 hrs.
1712	3·43	

(*b*) *Prior indications of wet weather as given by W.*—The use of W in the prediction of local weather at Poona and its neighbourhood was tried out during the current year. It was found by experience that on some days during the pre-monsoon months and on a few days in September of the year 1941, an increasing tendency in W did give an indication of the following wet weather. It appears that the measurements of W, whenever possible, would be of some aid in the prediction of local weather. For example, the first rainfall during the year 1941 occurred on the evening of the 1st April 1941, in association with a thunderstorm. The observations on this date showed a progressive increase in W. These are given in Table VI.

TABLE VI

Date	Time hrs. I.S.T.	W in cm.	Remarks
27-3-1941 ..	Means value for each date	1·92	2 As at 1000 hrs.
28-3-1941 ..		1·99	8 Cs at 0800 hrs. and 5 Cu at 1630 hrs.
29-3-1941 ..		1·57	1 Cs at 0740 and 2 Cu at 1710 hrs.
30-3-1941 ..		1·72	4 Cu at 1400 hrs. and onwards
31-3-1941 ..		1·57	1 Cs at 0735 hrs.
1-4-1941 ..	0744	1·71	
,, ..	0803	1·67	
,, ..	0853	2·18	
,, ..	1232	2·21	
,, ..	1346	2·29	
,, ..	1530	2·31	6 Cu at 1510 hrs. later culminating in thunderstorm beginning at 1715 hrs. and ending at 1815 hrs. 10 cents of rainfall
,, ..	1625	2·45	

Again, it may be remarked that the mean values of W day by day during the period 26th May to 26th June indicated the gradual onset of the monsoon on the 4th June, its weakening after the spell of rain up to the 9th June, the prevalence of a drought which persisted up to the 25th of June when the monsoon strengthened once again. The data during the above period are given in Table VII.

TABLE VII

Date	Mean W in cm.	Remarks
26-5-1941	2·61	
27-5-1941	2·76	
28-5-1941	2·10	
29-5-1941	2·15	
30-5-1941	2·75	
31-5-1941	2·92	7 Ci 1730 hrs. onwards
1-6-1941	2·82	4 Ci 0715, 4 Cu at 1330 hrs.
2-6-1941	2·92	7 Ci 1030 to 1300 hrs.
3-6-1941	2·75	7 Cu and Ci at 0700, 8 Cu at 1330 and slight rain at 2000 hrs.
4-6-1941	3·97	Rain at 1230 and 1430 hrs., start of monsoon
18-6-1941	1·89	
19-6-1941	1·98	
20-6-1941	1·64	6 Cu Ci at 0723 to 1230, 5 Cs at 1730 hrs.
21-6-1941	3·03	
22-6-1941	2·16	Veil-like cloud 1330 to 1700 hrs.
23-6-1941	1·86	
24-6-1941	2·51	
25-6-1941	3·37	Thick Ci veil at 0705 hrs.
26-6-1941	3·75	Monsoon re-established with slight rain on 26th and a heavy shower on 27th.

Conclusion

The investigation is being continued. A more detailed discussion of the various aspects of the subject has been given in a thesis submitted to the Bombay University.

The author wishes to thank Dr. L. A. Ramdas, for suggesting the problem and for guidance during the investigation and the Director-General of Observatories for permission to work in the Meteorological Office, Poona.

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