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Studies of raindrop size characteristics in different types of tropical rain using a simple raindrop recorder*

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ABSTRACT. The paper describes an easily constructed raindrop recorder for obtaining a continuous record of the time of occurrence, duration and range of raindrop sizes of all types of rain (thunderstorm, showers, and continuous type of rain). The important meteorological parameters such as liquid water content W, intensity of rainfall R', size distribution of raindrops for all types of rain N_D, radar reflectivity Z can all be obtained from the raindrop recorder. Regression equations connecting the intensity of rainfall with the various rainfall parameters have been developed and compared with the findings of other investigators all over the world. A brief description of a suitable rain receiver, tilting bucket raingauge is also given for determining the intensity of rainfall at minute intervals for various types of rain from a continuous photographic record. It is shown, in agreement with results obtained by Blanchard (1953) and Atlas and Chmela (1957) that the rain intensity corresponding to most size spectra can be represented by a uniform collection of drops with size equal to the median volume diameter D_0. The study clearly shows that any two of the four raindrop size parameters R', Z, W, D_0 fix the other two. The physical basis for the Z-R' correlation for different types of rainfall are explained using Bartnoff and Atlas's equation (1951). The presence or absence of appreciable electric charge in rain helps to find out whether the rain is from freezing or non-freezing clouds.

1. Introduction

The study of size distribution of raindrops in different types of precipitation has attracted the attention of many Meteorologists and Cloud Physicists in recent years. The size distribution of raindrops is an important factor in determining and interpreting the radar echoes from various types of precipitation, with a view to understand the mechanism by which precipitation develops. Attempts have been made to develop empirical relation between the size of raindrops and rain intensity by numerous workers (Laws and Parson 1943, Marshall and Palmer 1948, Spilhaus 1948, Best 1950, Bowen and Davidson 1951, Blanchard 1953, 1957, Mason and Ramanadham 1953, Atlas and Chmela 1957, Mason and Andrews 1960). The data collected by most of these workers have been *averaged* to derive relations between drop size distributions and rate of rainfall and relates to precipitation in temperate latitudes and in situations where the intensity of rainfall is mostly limited below 20 mm/hr.

In India, observations of the drop size distribution have been made by Kelkar (1945, 1959), Ramanadham and Vidyavathi (1957), Roy and Srivastava (1958), Ramana Murty and Gupta (1959) using the well known filter paper technique. Unfortunately most of the available data refer to *intermittent* samples taken on the ground, so that we know very little about how the concentration and size distribution of raindrops varies in space and time *during an entire storm.* The size distribution of raindrops varies considerably with the character of the rain (*e.g.*, thunderstorm, showers, continuous steady rain, orographic), with the type of the cloud from which they fall, and also with the rainfall intensity.

In this paper, therefore a description of a simple raindrop recorder, rain receiver, and tilting bucket raingauge is given to *record continuously* the size distribution of raindrops and intensity of rainfall in different types of rain to understand the mechanism of precipitation in tropical rain. The recorded data is carefully matched to that obtained with a 10-cm radar, with a view to correlate any distinctive features with the rainfall types, release mechanism and other characteristics of the rain as revealed by the structure and

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*Paper was also presented at the symposium on "Physics of Cloud and Rain in the Tropics" held during 29 October to 1 November 1960 at the Meteorological Office, Poona evolution of the radar echoes. The drop recorder is a simple instrument which records the imprints of the raindrops on the moving paper tape coated previously with Rhodamine dye thereby obtaining a *continuous record* of the time of occurrence, duration of different types of rain and the range of raindrop sizes. It resembles the one constructed by Blanchard (1953) for obtaining the predominant sizes of rain on the windward and leeward sides of the island of Oahy, Hawaii, but it differs from his recorder in driving the tape at constant speed. The speed of the tape can be altered to three different speeds by suitable adjustment of the gear assembly, for use with different types of rain having variable intensities.

2. Description of the recorder

The recorder consists of an induction type motor (1/30 H.P.), having a speed of 1500 RPM which is reduced by suitable gears to a speed such that 60 cm of paper tape are pulled per minute. The paper tape, which is previously dusted with Rhodamine dye is 6 cm wide and two reels are used to take up the paper tape. The rain falls on the paper tape through a 15×30 mm opening in a rectangular metal box (B) shown in Fig. 1, giving an effective area of 15×3 sq. cm (45 sq. cm) for 15 seconds. As this recorder is designed for Poona rains, which are composed mainly of drops less than three mm in diameter, the 45 sq. cm area for 15 seconds exposure is found to be adequate. Calibration of the tape showed that a three mm diameter drop at terminal velocity produced a splash diameter of 15 mm for smooth paper. If the paper tape is made of Whatman No. 1 filter paper a three mm diameter drop produced a splash diameter of 18 mm (see Fig. 3). In areas where heavy thunderstorms and storms are common, one has to use a tape of sufficient width to handle raindrops in excess of four mm. It may also be necessary to increase the speed of the tape by changing the gears suitably. The optimum values of tape width and speed will depend on the general drop size distribution in the particular region where the recorder is used.

The time marking arrangement consists of a worm and gear assembly coupled to the tape pulling shaft of the motor. The shaft (Fig. 1) in the gear train makes one revolution in about one minute and carries a wheel (Fig. 1) with four teeth, one of which is double pronged; by the use of a micro-switch (Fig. 1) the time marking pen, a sharp pencil lead, will move every 15 seconds, but one out of every four will be double to count the full minutes conveniently. A sample time mark every fifteen seconds can be seen at Section A of the record (Fig. 5).

The paper tape from its spool after exposure to the rain through the opening of the box passes over two 25-watt cylindrical lamps, for quick drying of the tape, even in the heaviest rain, so that no smearing of the drop record takes place before the tape is taken by the take-up reel. The time of start of the recorder is noted so that from the subsequent time marks given by the pencil lead on the top of the tape, the time of occurrence and duration of the raindrop recorder can be known correctly.

3. Description of the rain receiver, tilting bucket raingauge used for continuous recording of intensity of rainfall at minute intervals for different types of rain

Fig. 2 gives a diagram of the rain receiver and tilting bucket raingauge used for the measurement of electricity carried by precipitation described in detail elsewhere (1957, 1959). The rain receiver consists of an insulated copper funnel which is shielded from the earth's surfce by a conical shield having an opening of 8″ (20·3 cm) above the funnel, giving an area of 324 sq. cm for the mouth of the cone. For measuring the amount of rain caught by the funnel, a gauge carries a mercury switch which at each tilt of the bucket turns on a light source to the photographic paper used for recording the electrometer deflections when charged rain is falling on the insulated funnel, thereby giving a vertical line of the record for every cent of rain collected by the apparatus amounting to 8 c.c. The time interval between the tilts of the bucket could be measured and the rate of rainfall R' can be determined accurately

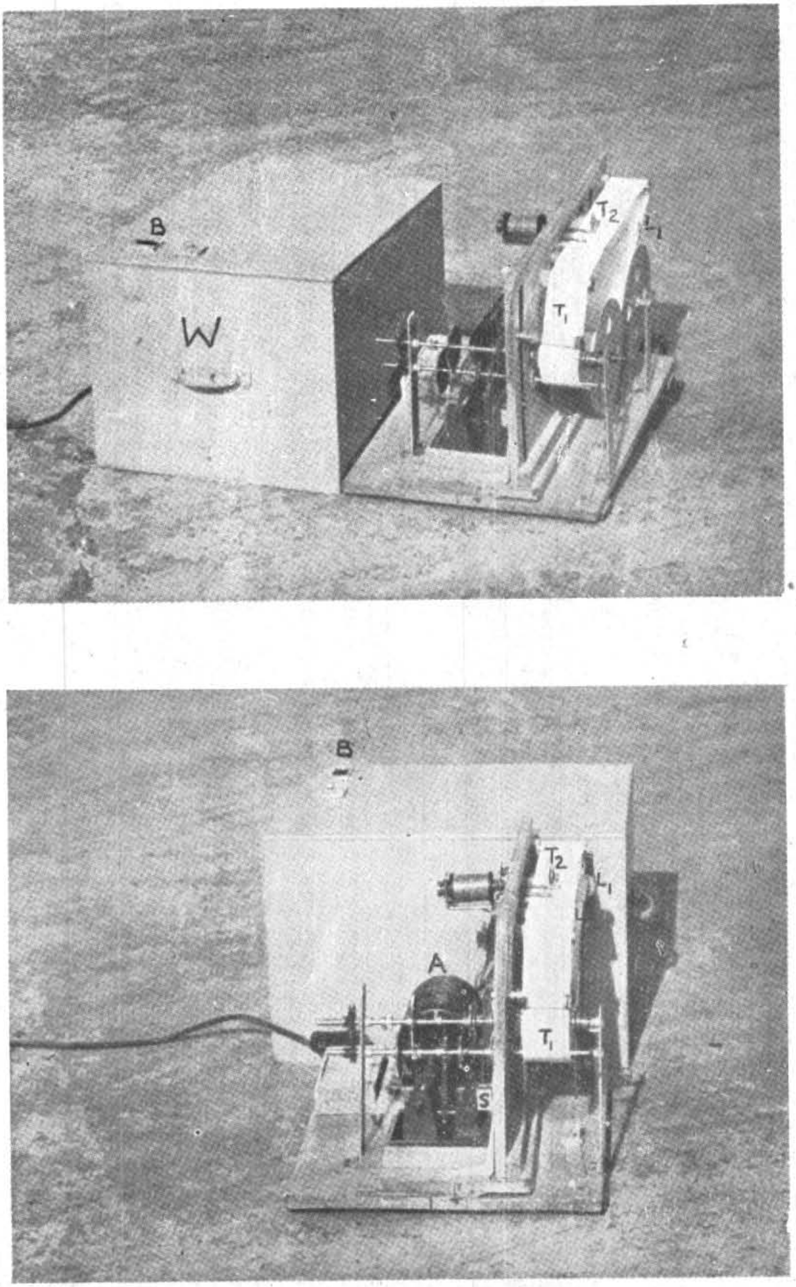
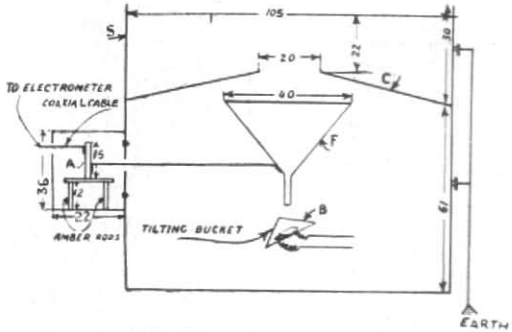


Fig. 1

The raindrop recorder consisting of : A—Induction motor 1/30 H.P., 1500 R.P.M.; B—Aperture 15 × 30 mm in box; W—Worm and gear assembly; S—Time marking microswitch; T_1—Dyed tape-width 6 cm (Whatman filter paper); T_2—Time marking lead pencil; L_1L_2—25 watts cylindrical lamps



(All dimensions are in cm)

Fig. 2

A view of the rain receiver and tilting bucket raingauge with mercury switch which at each tilt of the bucket turns on a light source to the photographic paper used for recording the electrometer deflections when charged rain is falling on the insulated funnel, thereby giving a vertical line of the record for every cent of rain amounting to 8 cc. The time intervals between tilts of bucket being known, the rate of rainfall (R') can be determined at *minute intervals*.

A—Insulated stand supporting funnel
B—Tilting bucket raingauge
C—Conical shield
F—Insulated funnel
S—Outer cylindrical shield

at minute intervals. Having known R' it is easy to calculate the *mean mass* of the raindrop from an empirical relation given by Best (1947) and modified by Browne, Palmer and Wormell (1954)—

$$\overline{m}\,(\mu_g) = 180\,R'^{\,0.75} \qquad (1)$$

where $\overline{m}$ = mean mass of raindrop in microgramme and R' = intensity of rainfall in mm/hr.

From equation (1), we easily have

$$D_v = 0{\cdot}70\ R'^{\,0.25} \qquad (2)$$

where D_v = mean volume diameter in mm.

Fig. 12 gives values of $\overline{m}$ (μ_g) for various rates of rainfall R'.

It is not always convenient to compare two sets of rain measurements by comparing their drop size distribution. The liquid water content W (mg/m^3) and R' for a particular type of rain can be used as a measure of drop size distribution, which can graphically be represented by a single point. In the present series of measurements, about '2000' minutes of disturbed weather consisting of different types of rain (thunderstorm, showers, and continuous type of monsoon rain) have been studied at Poona during the years 1955-58. The rate of rainfall R' and liquid water content W at minute intervals are obtained from *continuous* photographic record using the rain receiver, tilting bucket, and photographic rain electrograph. A sample record taken with the above arrangement is given in Fig. 4.

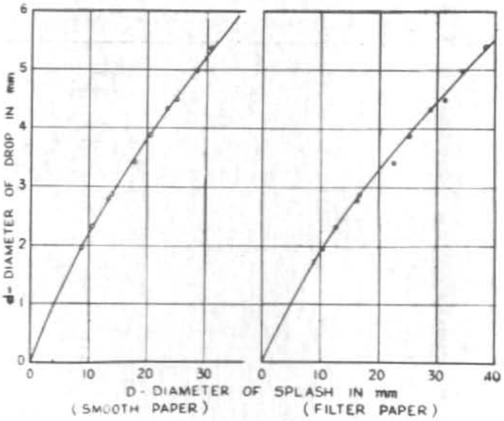


Fig. 3. Calibration curve showing the relation between splash diameter and raindrop diameter

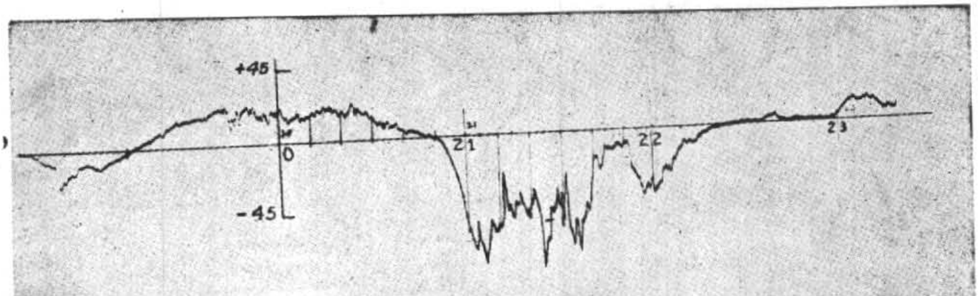
4. Typical records and results obtained using the raindrop recorder, rain receiver, and tilting bucket raingauge

Figs. 5 to 9 give sections of the raindrop record with corresponding self recording syphon raingauge and Bibby type intensity raingauge records during a few thunderstorms, showers, and continuous type of rain showing radar melting band phenomena and rain from non-freezing clouds. The criterion used for determining non-freezing rain is (1) from the estimated cloud height from Poona tephigrams wherever possible, (2) by visual observation of the top of clouds and (3) by the absence of electric charge carried by such rain.

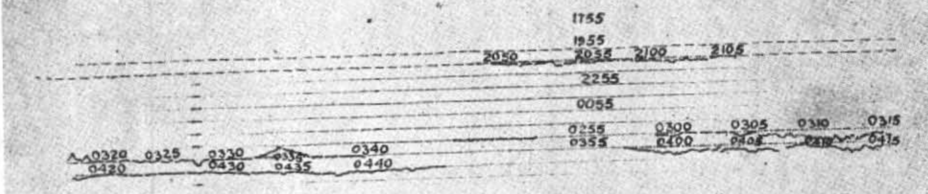
Knowing the effective area of the tape, *i.e.*, 45 sq. cm for 15 seconds exposure, Table 1 for calculating

(1) The number of drops per cubic metre N_D,

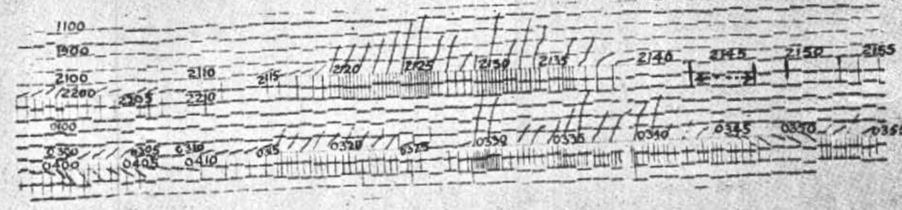
(2) The liquid water content W (mg/m^3),



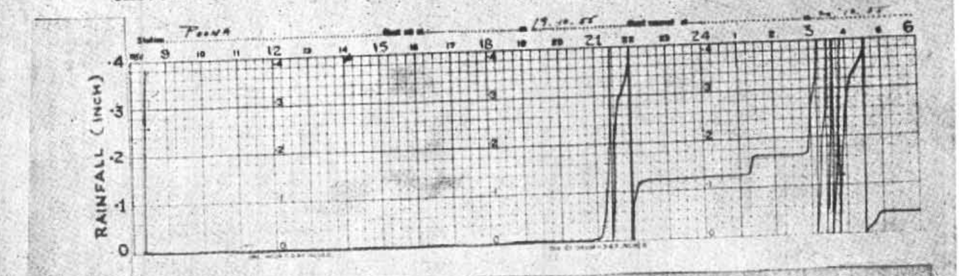
A— PORTION OF ELECTROGRAPH RECORD DURING A THUNDERSTORM AT POONA 19-20 OCT 1955



B— PORTION OF THE POINT DISCHARGE RECORD CORRESPONDING TO — A. SCALE ↕ = MICROAMPERE ↑ POSITIVE



C— PORTION OF RAIN ELECTROGRAPH RECORD CORRESPONDING TO — A AND B, ↑ POSITIVE



D - NATURAL SYPHON RAINGAUGE RECORD CORRESPONDING TO FIG. 'C'

Fig. 4

Portions of potential gradient, point discharge, rain electrograph and natural syphon raingauge records during a thunderstorm on 19-20 October 1955. The time intervals between vertical lines in the rain electrograph record gives a measure of the progressive development in the intensity of rainfall (R') at *minute intervals* for the *entire period of storm*

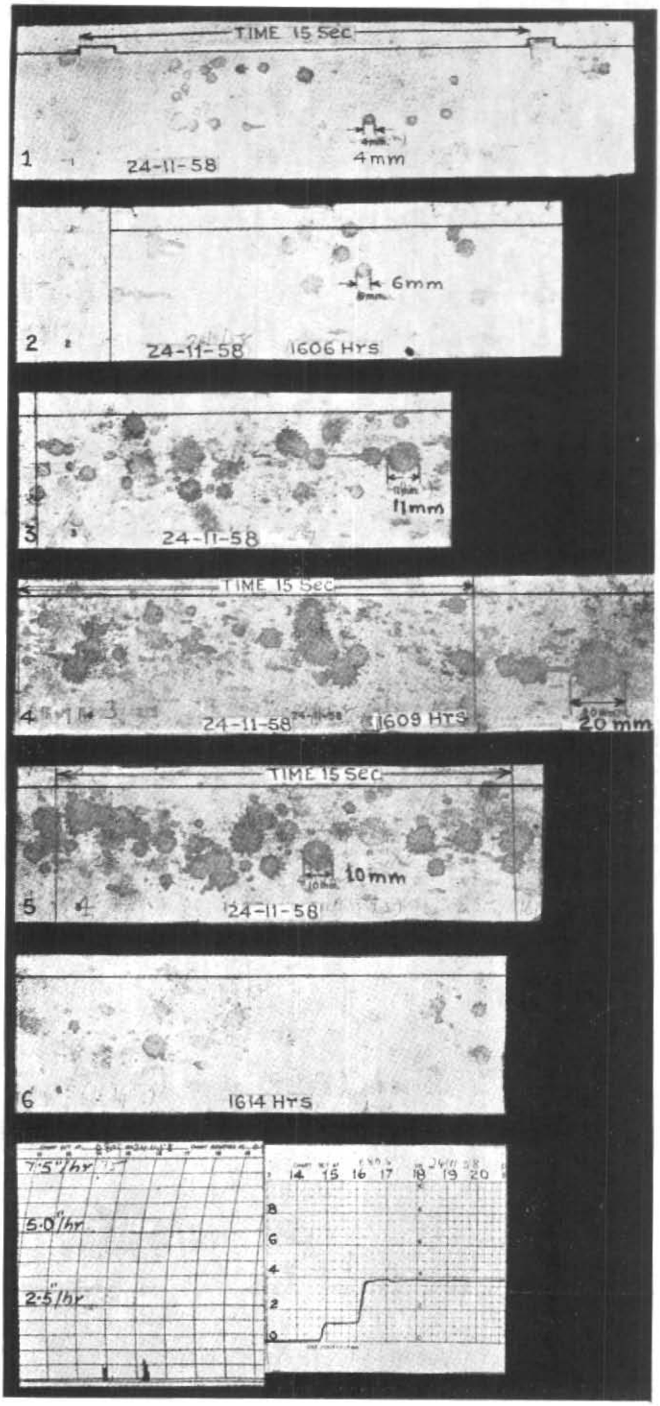
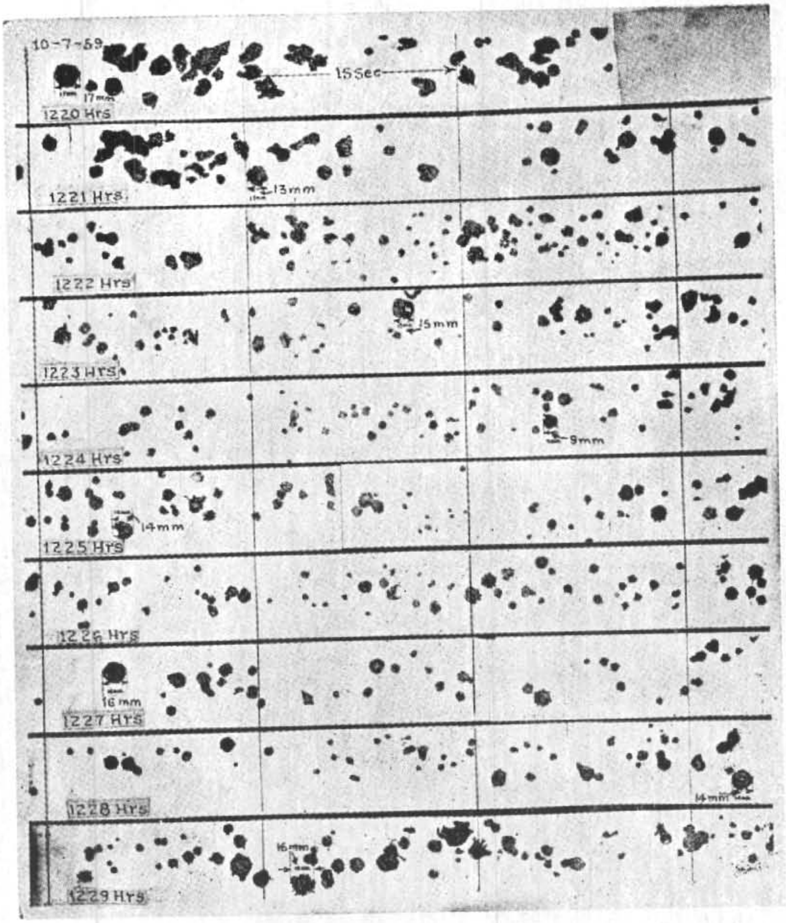
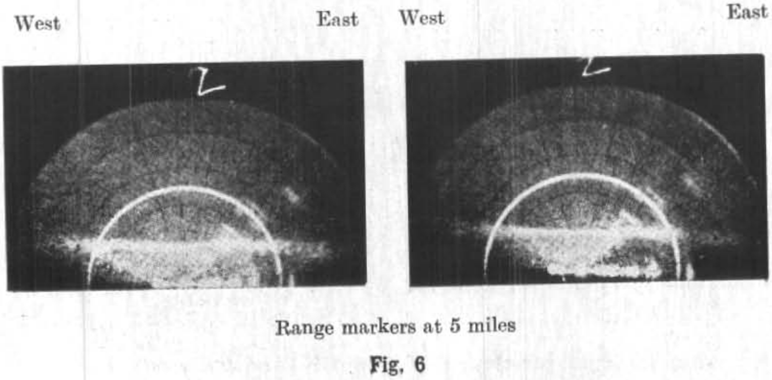


Fig. 5

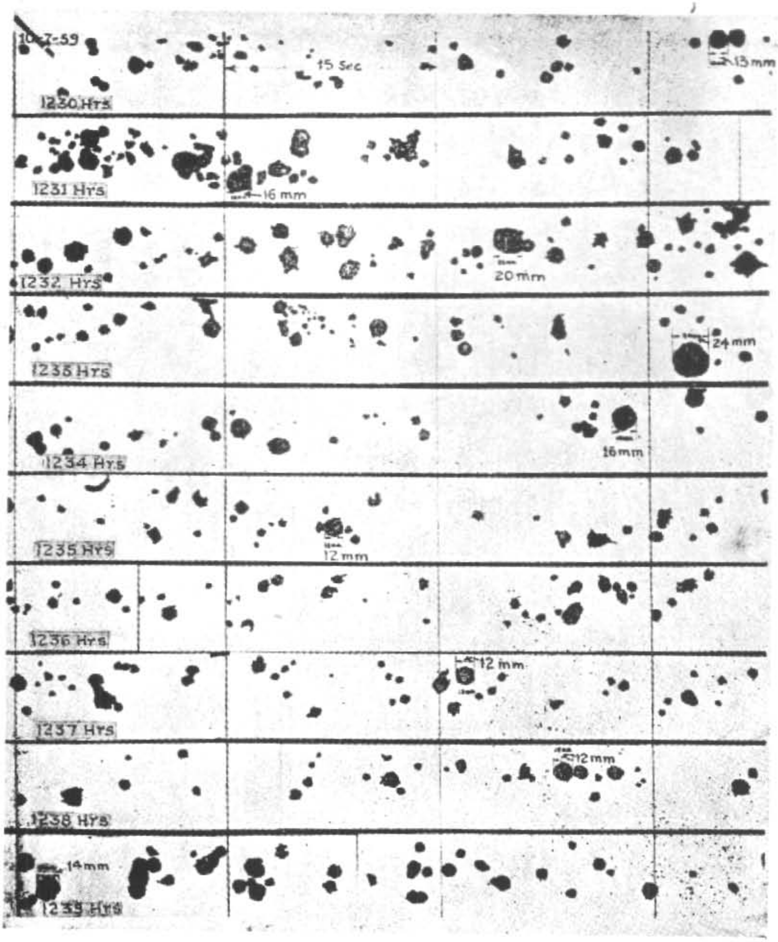
Portions of the raindrop records taken with the drop recorder during a sharp thundershower on 24-11-1958 from 1604 to 1614 hours with intensity of rainfall record using a Bibby type impulse recorder and natural syphon raingauge record





Range markers at 5 miles

Fig. 6



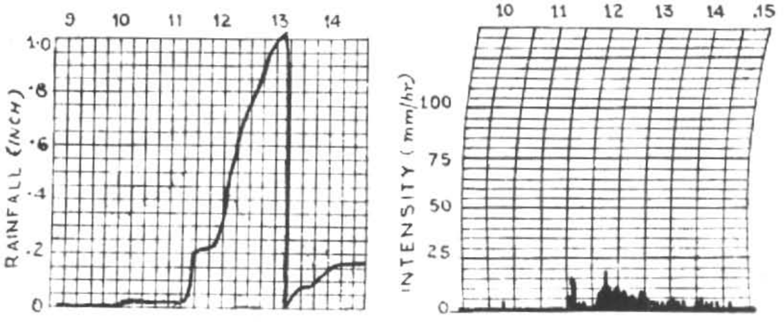


Fig. 7

Figs. 6-7. Portions of the raindrop records taken on 10-7-1959 during continuous monsoon rain showing *10-cm radar melting band phenomena* from 1220 to 1240 hours, with natural syphon raingauge record and intensity of rainfall record using a Bibby type impulse recorder

TABLE 1

For calculating the number of drops per cubic metre N_D, the liquid water content W (mg/m^3), the intensity of rainfall R' (mm/hr), and radar reflectivity Z (mm^6/m^3) from the rainfall recorder using Whatman No. 1 filter paper

Splash diameter (mm)	Rain-drop (mm)	Drop diameter limits (mm)	Group	N_D	W (mg/m^3)	R' (mm/hr)	Z (mm^6/m^3)
1	0·2	0—·25 (0·125)	1	548·1	·548	·001	—
2	0·35	·25—·50 (0·375)	2	91·4	2·54	·015	·274
3	0·55	·50—·75 (0·625)	3	59·9	7·68	·068	3·595
4	0·75						
5	0·95	·75—1·00 (0·875)	4	40·3	14·19	·188	18·106
6	1·1	1·00—1·25 (1·125)	5	34·4	25·73	·399	69·873
7	1·3	1·25—1·50 (1·375)	6	28·5	38·85	·728	192·39
8	1·5						
9	1·7	1·50—1·75 (1·625)	7	26·2	59·0	1·201	481·9
10	1·85	1·75—2·00 (1·875)	8	23·1	80·0	1·848	1005·9
11	2·05	2·00—2·25 (2·125)	9	22·4	112·9	2·688	2064·9
12	2·2						
13	2·4	2·25—2·50 (2·375)	10	20·9	146·6	3·752	3742·6
14	2·5						
15	2·65	2·50—2·75 (2·625)	11	19·5	184·8	5·065	6370·6
16	2·8	2·75—3·00 (2·875)	12	19·0	236·7	6·653	10720
17	2·9						
18	3·05	3·00—3·25 (3·125)	13	18·3	292·8	8·544	17010
19	3·15						
20	3·3	3·25—3·50 (3·375)	14	17·6	355·2	10·752	26041
21	3·4						
22	3·55	3·50—3·75 (3·625)	15	17·2	430·0	13·320	39040
23	3·65						
24	3·75						

NOTE—Calculation is for a single drop of each size, values for more drops being obtained by simple multiplication

(3) The intensity of rainfall R' (mm/hr) assuming the terminal velocities determined by Gunn and Kinzer (1949), and

(4) The radar reflectivity Z ($\mathrm{mm}^6/\mathrm{m}^3$) for a single raindrop of each size has been constructed, values for more drops being obtained by simple multiplication.

Table 2 gives values of

(1) Sampling period,

(2) The number of drops sampled,

(3) The spatial drop density N_D/m^3

(4) The liquid water content $W = \frac{1}{6}\pi\, \Sigma N_D D^3$ ($\mathrm{mg/m}^3$),

where $N_D =$ Number of drops between diameter limits per unit volume of air, D=Drop diameter,

(5) The intensity of rainfall R' in mm/hr $= \frac{1}{6}\pi\, \Sigma\, N_D\, D^3 \times V$, where V=Terminal velocity of drop size D,

(6) The radar reflectivity $Z = \Sigma N_D D^6\, \delta D$

(7) The reflectivity coefficient $G(n) = D_0^{-3}\, \Sigma N_D D^6 / \Sigma N_D D^3$, a quantity dependent on spectrum breadth, the median volume diameter D_0 (mm), *i.e.*, the diameter at which the liquid water content is divided equally, and

(8) The median diameter D_0 and maximum diameter $D_{\mathrm{max.}}$

By the method of least squares, the relation between intensity of rainfall and (1) The median volume diameter D_0 ,(2) The liquid water content W, and (3) The radar reflectivity Z has been determined separately for (*a*) thunderstorm rain, (*b*) rain showing radar melting band from stratified clouds, and (*c*) non-freezing rain from stratified clouds. These observations are compared with previously estimated empirical relations between R' and the various rainfall parameters by different investigators all over the world and given in Table 3.

5. Analysis of results

5·1. *Relation of intensity of rainfall R′ with distribution of raindrops* N_D *for different types of rain at Poona*—Figs. 10 and 11 show the raindrop distribution (*a*) during two thunderstorms on 3 July and 16 April, (*b*) during rain showing radar melting band phenomena on 10 July 1959, (*c*) during non-freezing rain on 15 and 20 July 1959 along with the distribution proposed by Marshall and Palmer (1948) for different intensities of rain. The striking features shown by all the above types of rain are—

(1) For very low intensity, namely, less than 5 mm/hr the curve is more or less a straight line in general agreement with that given by the empirical relationship given by Marshall and Palmer (1948).

(2) As the rainfall rate increases, the curve instead of being a straight line consists of a number of peaks and troughs as noticed by previous investigators (Mason 1953, Ramana Murty and Gupta 1959, Mason and Andrews 1960). In agreement with Ramana Murty and Gupta (1959) we may say that a marked discontinuity in the updraft rate, with maximum occurring at a certain level at a given time especially during thunderstorms may be an important factor to account for a distinctly larger number of drops of a certain size compared with drops of sizes next below or above. This level, by acting as a sort of barrier to falling raindrops below a certain size, will cause a maximum concentration of raindrops belonging to a particular size group.

(3) The drop size spectra obtained for thunderstorm rain, for rain from stratified clouds showing 10-cm radar melting band phenomena and for non-freezing rain show distinct features.

The size of raindrops falling from thunderstorm has a broad spectra, the heaviest rain (sample No. 44) containing drops up to 4·95 mm diameter and large concentration of small drops less than 0·25 mm in diameter. There are usually considerably higher concentration of both the very small and the very large drops than would be predicted by Marshall and Palmer distribution. This has been observed by Mason and Andrews (1960) also in their study of drop size distribution from various types of rain in England.

Raindrop samples taken on 10 July 1959 showing 10-cm radar well marked melting band echoes from stratified clouds indicating that the rain is from the melting of snow flakes, show that the rainfall is far from steady with peaks and troughs like thunderstorm rain samples.

The drop size spectra (Samples 40-57) associated with non-freezing clouds show a distinct feature from other types of rain. The maximum diameter of raindrop obtained is generally found to be less than 2 mm probably due to the restricted depth of cloud, updraught velocity and the water content.

(4) Samples 11, 12, 14, 16, 18, 29, 33, 36, 39, 40, 42, 47, 54, 56 show a decrease in the number of drops N_D with increasing size.

(5) Samples 3, 5, 7, 20, 30, 34, 43, 48, 55 show an increase in the number of drops N_D with increasing size.

(6) Samples 1, 2, 4, 8, 9, 10, 13, 15, 17, 19, 21-28, 31, 32, 35, 37, 38, 41, 44-46, 50-53, 57 show the combined characteristics of both (4) and (5).

5·2. *The relation of intensity of rainfall R' with liquid water content W in different types of rain*—By the method of least squares, the following relations between W and R' have been obtained for different types of rain—

(1) $W = 86{\cdot}4\, R'^{0.177}$ (for radar melting band rain from stratified clouds) (correlation coefficient between W and $R' = {\cdot}977$)

(2) $W = 70\ R'^{0.83}$ (for thunderstorm rain) (correlation coefficient between W and $R' = 0{\cdot}727$)

(3) $W = 101\ R'^{0.69}$ (non-freezing rain) (correlation coefficient between W and $R' = 0{\cdot}971$)

Fig. 12 shows the values of W for various values of R' for different types of rain as compared with the empirical relation found by Best (1950) in England for rain in general $W = 67\ R'^{0.846}$ (Best has not mentioned the type of rain, for which the above relation holds).

While the general features of the curves appear to be similar, a closer examination shows that the liquid water content W values for thunderstorm rain and rain showing radar melting band are found to be higher than that for non-freezing rain at Poona.

It is possible to calculate the liquid water content W at minute intervals from a knowledge of the rate of rainfall R' and the terminal velocity of the average drop size, V (preferably for the median volume diameter), as explained below, using the relation $R' = V \times W$ where R', V and W are expressed in proper units. From the continuous records obtained from the rain receiver, tilting bucket raingauge and photographic rain electrograph, it is possible to calculate W at minute intervals from a knowledge of R' and V. The terminal velocity values used here are for the median drop diameter taken from the experimental values of Gunn and Kinzer (1949) and plotted in Fig. 12 in relation to rate of rainfall and mean mass of raindrop.

5·3. *The relation of intensity of rainfall R' with median volume diameter D_0 in different types of rain*—Median volume diameter D_0 is defined as that value of drop diameter which divides the drop distribution into two parts such that each represents half of the liquid water content W. It is obtained by plotting a cumulative per cent curve of liquid water content. The drop diameter at the 50 per cent ordinate is the median drop diamter D_0.

By the method of least squares, the following relations between D_0 and R' have been obtained for different types of rain—

(1) $D_0 = 0{\cdot}82\ R'^{0.29}$ (Thunderstorm rain) (correlation coefficient between D_0 and $R' = {\cdot}706$)

TABLE

Summary of rain samples taken with the raindrop recorder during

Serial No.	Date	Time (IST)	R' (mm/hr)	W (mg/m^3)	Z (mm^6/m^3)	$D_{\circ}$ (mm)	Reflectivity coefficient $G(n)$	Dmax
1	24 Nov 1958	1606	5·1	325·9	932·6	1·0	1·5	1·3
2	,,	1608	20·3	801·6	15326·3	1·85	1·6	2·50
3	,,	1609	20·7	959·1	13298·6	1·85	1·2	2·05
4	,,	1610	23·0	894·0	41297·0	1·85	3·8	3·6
5	,,	1611	43·7	1837·1	38438·8	2·0	1·4	2·5
6	,,	1612	3·6	226·0	739·3	1·0	1·7	1·3
7	3 July 1959	1600—01 (0—15″)	15·2	620·5	12656·2	2·0	1·3	2·4
8	,,	1600—01 (15—30″)	14·9	575·1	28363·1	2·7	1·3	3·3
9	,,	1600—01 (30—45″)	8·3	342·8	8490·1	2·4	0·9	2·5
10	,,	1600—01 (45—60″)	1·6	129·9	774·8	0·75	1·7	1·1
11	,,	1601—02 (0—15″)	5·2	227·7	4246·1	2·0	1·2	2·4
12	,,	1601—02 (15—30″)	1·2	77·3	266·4	1·12	1·3	1·3
13	,,	1601—02 (30—45″)	2·4	134·0	1053·3	1·35	1·7	1·85
14	,,	1601—02 (45—60″)	4·4	234·0	2373·9	1·25	2·7	2·2
15	,,	1602—03	1·0	71·0	124·5	0·8	1·8	1·1
16	,,	1603—04	1·0	89·8	118·1	0·75	1·6	1·1
17	,,	1604—05 (0—15″)	6·9	349·2	4392·3	1·1	4·9	2·4
18	,,	1604—05 (45—60″)	5·4	232·3	2845·5	1·5	1·9	2·05
19	,,	1605—06	12·9	632·0	6477·9	1·75	1·0	2·05
20	,,	1608—09	13·1	657·7	5560·5	1·5	1·3	2·05
21	,,	1609—10 (15—30″)	9·2	526·2	3524·6	1·5	1·0	1·85
22	,,	1609—10 (30—45″)	11·6	651·7	3620·2	1·25	1·5	1·85
23	,,	1610—11	19·5	895·9	9607·2	1·5	1·7	2·20
24	10 July 1959	1220—21 (0—15″)	10·7	517·3	7083·9	1·5	2·1	2·4
25	,,	1220—21 (45—60″)	23·1	1021·2	18088·4	2·0	1·2	2·65
26	,,	1221—22 (0—15″)	7·9	438·6	3274·8	1·125	2·7	2·50
27	,,	1221—22 (45—60″)	6·5	312·2	4400·7	1·25	3·8	2·4
28	,,	1222—23 (0—15″)	7·1	416·1	2891·6	1·25	1·9	2·05
29	,,	1222—23 (45—60″)	9·1	493·2	4177·3	1·375	2·9	2·2

2

thunderstorms, showers and continuous type of rain at Poona

No. of drops per cubic metre with 0·25 mm size interval centred about indicated size (mm)													Drops sampled	$\frac{\overline{V}}{V_0}$
0·125	0·375	0·625	0·875	1·125	1·375	1·625	1·875	2·125	2·375	2·625	3·375	3·625		
	152·4		33·6	373·3	23·7								16	1·11
		246·9	370·0	57·4	23·7	43·3	57·9		34·8	16·3			23	1·13
	381·1	99·9	168·2	57·4	95·0	21·9		130·9					22	0·96
	457·3		100·9	28·7	47·5			56·1	17·4			14·4	17	1·14
	152·4		168·2		118·7	43·7	77·2		156·5	16·3			25	1·02
		49·9	179·0	86·1	71·2								9	1·13
		59·9	80·7				23·1	44·9	41·7				7	1·05
	91·4	179·8	121·0		28·5			22·4			17·6		10	0·93
	91·4		121·0					22·4		19·5			6	0·90
	91·4	239·7	201·6	34·4									11	1·14
		59·9	40·3			26·2			20·9				4	0·98
	182·7	59·9		34·4	28·5								5	1·05
	91·4	179·8	80·7				23·1						7	1·03
	182·7	179·8	80·7	34·4	28·5			22·4					10	1·13
	91·4		121·0	34·4									5	1·22
	456·8	179·8	80·7	34·4									11	1·00
	182·7	299·6	121·0		85·4				20·9				14	1·34
	91·4		80·7	34·4	28·5	26·2		22·4					7	1·22
1096·3	365·4	359·5	80·7		56·9	51·9	69·4	22·4					22	0·98
	456·8	359·5		34·4	142·3	26·2	92·5						22	1·04
	456·8	599·2	121·0	206·5			69·4						27	0·91
	182·7	119·8	403·3	103·3	113·8	78·6	23·1						25	1·07
	548·2	239·7	201·6	68·8	113·8	78·6	69·4	44·9					29	1·14
	91·4	359·5	80·7	34·4	28·5	51·9		22·4	20·9				15	1·08
		299·6	80·7	68·8	113·8		23·1	67·2	20·9	19·5			19	0·97
	91·4	599·2	40·3		170·7			22·4					19	0·52
548·1	274·0	119·8		34·4	85·4				20·9				11	0·89
	91·4	599·2	161·3	68·8	85·4			22·4					21	1·37
	913·6	239·7	161·3	68·8	56·9	26·2	23·1	22·4					25	1·01

TABLE

Serial No.	Date	Time (IST)	R' (mm/hr)	W (mg/m^3)	Z (mm^6/m^3)	D_0 (mm)	Reflectivity coefficient $G(n)$	$D_{\text{max.}}$
30	10 July 1959	1223—24 (0—15″)	6·3	391·9	1464·9	1·25	1·0	1·5
31	,,	1223—24 (45—60″)	7·9	449·5	3131·5	1·375	1·4	1·85
32	,,	1224—25 (0—15″)	15·3	719·6	13558·1	1·5	2·9	2·9
33	,,	1224—25 (45—60″)	5·6	314·8	3141·8	1·0	5·2	2·05
34	,,	1225—26 (0—15″)	7·4	324·1	4449·7	1·75	1·3	2·20
35	,,	1225—26 (45—60″)	7·9	446·1	2957·8	1·25	1·8	1·85
36	,,	1226—27 (0—15″)	18·9	747·6	41844·9	2·2	2·7	3·65
37	,,	1226—27 (45—60″)	5·8	354·2	1479·2	1·25	1·1	1·70
38	16 April 1959	1407—08 (0—15″)	10·8	485·3	6717·7	1·75	1·3	2·05
39	,,	1408—09 (0—15″)	12·3	498·3	27140·2	2·1	3·1	3·35
40	,,	1412—13 (15—30″)	3·1	180·4	1232·9	1·12	2·5	1·85
41	,,	1412—13 (45—60″)	33·3	1182·9	68997·3	3·0	1·1	3·75
42	,,	1413—14 (15—30″)	13·4	530·5	16539·8	1·75	3·0	2·9
43	,,	1414—15 (45—60″)	9·3	430·3	5703·2	1·5	2·0	2·05
44	,,	1415—16 (30—45″)	92·8	3324·6	21830·0	3·25	1·0	4·95
45	,,	1415—16 (45—60″)	13·1	660·4	3368·0	1·25	1·4	2·4
46	15 July 1959	1025—26 (0—15″)	2·25	216·04	196·2	0·5	3·8	1·30
47	,,	1025—26 (45—60″)	3·52	268·6	462·5	0·5	7·2	1·30
48	,,	1026—27 (0—15″)	2·36	202·5	284·5	0·75	1·7	1·10
49	,,	1026—27 (45—60″)	0·33	52·9	8·98	0·25	5·7	0·55
50	20 July 1959	1525—26 (0—15″)	2·18	131·4	372·9	0·9	2·0	1·50
51	,,	1525—26 (45—60″)	4·08	277·9	839·0	1·0	1·6	1·30
52	,,	1526—27 (0—15″)	10·41	518·0	6702·0	1·63	1·6	2·4
53	,,	1526—27 (45—60″)	2·93	204·5	466·4	1·0	1·6	1·5
54	,,	1527—28 (0—15″)	4·57	266·3	1553·4	1·25	1·2	1·85
55	,,	1527—28 (45—60″)	2·44	159·9	500·0	1·0	1·6	1·3
56	,,	1528—29 (0—15″)	2·01	155·7	322·3	0·75	2·6	1·5
57	,,	1528—29 (45—60″)	2·82	197·5	457·5	1·0	1·2	1·5

Date	Type of rain
24 Nov 1958 16 Apr 1959 3 Jul 1959	Samples of thunderstorm rain
10 Jul 1959	Samples of melting band rain from stratiform clouds
15 Jul 1959 20 Jul 1959	Samples of non-freezing rain of stratiform clouds

2 (*contd*)

No. of drops per cubic metre with 0·25 mm size interval centred about indicated size (mm)														Drops sampled	$\frac{\overline{V}}{V_o}$
0·125	0·375	0·625	0·875	1·125	1·375	1·625	1·875	2·125	2·375	2·875	3·125	3·375	3·625		
548·1	639·5	479·4	40·3	34·4	199·5									25	0·97
3836·7	639·5	651·1	121·0	34·4		51·9	46·3							33	0·96
2740·5	639·5	119·8	161·3	103·3	85·4	52·4	23·1			18·9				28	1·11
2740·5	1371·0	539·4	40·3				23·1	22·4						32	1·27
4385·2	639·5	119·8		34·4	28·5			44·8						21	1·09
6029·1	1371·0	299·6		68·8	113·8		46·3							39	1·07
2740·5	1461·7	179·8	121·0		28·5	26·2		22·4					17·2	31	0·99
2740·5	1096·2	239·7		103·2	113·8	26·2								29	0·99
1096·2			40·3	34·4		26·2	46·2	44·8						9	1·07
548·1	548·4	59·9	40·3	34·4			23·1					17·6		12	1·05
2740·5	548·4	239·6	40·3		28·5		23·1							18	1·16
	457·0	59·9	40·3		28·5		46·2			19·0	18·3		17·2	13	0·99
2192·4	365·6	179·7						22·4	20·9	19·0				14	1·21
2740·5	274·0	239·6		34·4		26·2	23·1	44·8						17	1·13
1644·3	731·2	359·4	59·9	137·6	57·0		46·2	89·6	20·9	19·0	18·3	17·6	17·2	36	0·87
7125·3	822·6	479·2	120·9	172·0	142·5	52·4			20·9					46	1·20
5929·0	822·6	838·6	161·2	34·4										39	1·11
4932·9	1005·4	599·0	201·5	68·8	28·5									37	1·40
4384·8	639·8	599·0	80·6	103·2										30	1·08
3836·7	1553·8	59·9												25	0·87
548·1	365·6	359·4	40·3	68·8	28·5									15	1·25
3288·6	274·2	239·6	80·6	103·2	85·5									21	1·05
4932·9	365·6	119·8	120·9	172·0		26·2		22·4	20·9					26	1·01
4384·8	457·0	359·4	40·3	68·8	57·0									24	1·02
1644·3	365·6	359·4		68·8	57·0		23·1							18	1·03
4932·9	365·6	119·8	80·6	34·4	57·0									20	1·08
2740·5	548·4	359·4	80·6	34·4	28·5									21	1·16
6029·0	1005·4	179·7	40·3	68·8	57·7									30	1·02

No. of drops against S. No. 44 and under 3·875 mm is 16·3

Sample 1–6 taken with dyed *smooth paper tape*; Sample 7–57 taken *with dyed* Whatman No. 1 filter paper tape

R = Rate of rainfall (mm/hr)

D_0 = Median volume diameter

W = Liquid water content (mgm/m^3)

Dmax = Maximum diameter

Z = Radar reflectivity (mm^6/m^3)

V_0 = Fall velocity of median volume size

$G(n)$ = Reflectivity coefficient

$\overline{V}$ = Weighted fall velocity given by equation (5)

TABLE 3

Median volume diameter D_0, liquid water content W, radar echo intensity Z as a function of rain intensity computed from various sources

Serial No.	Source	D_0 (mm)	W (mgm/m^3)	Z $(\Sigma N_D D^6 \delta D = CR'^n)$
1	Ynyslas (Best 1950)	$1\cdot20R'^{0\cdot20}$	$74\ R'^{0\cdot85}$	$224\ R'^{1\cdot54}$
2	Shoeburyness (Best 1950)	$1\cdot32\ R'^{0\cdot21}$	$59\ R'^{0\cdot82}$	$630\ R'^{1\cdot45}$
3	Lenard	$1\cdot23\ R'^{0\cdot27}$	$61\ R'^{0\cdot84}$	$360\ R'^{1\cdot66}$
4	Laws and Parson (1943) (U. S.)	$1\cdot06\ R'^{0\cdot20}$	$72\ R'^{0\cdot87}$	$220\ R'^{1\cdot44}$
5	Marshall and Palmer (1948) (as reported by Atlas) (mostly stratiform, Ottawa)	$0\cdot91\ R'^{0\cdot21}$	$72\ R'^{0\cdot88}$	$296\ R'^{1\cdot47}$
6	Marshall and Palmer (1948) (as reported by Best)	$0\cdot82\ R'^{0\cdot24}$	$72\ R'^{0\cdot88}$	$220\ R'^{1\cdot6}$
7	East Hill (R. F. Jones)	$1\cdot14\ R'^{0\cdot27}$	$65\ R'^{0\cdot83}$	$295\ R'^{1\cdot53}$
8	Hilo (Hawaii) (Possibly non-orographic) (Anderson)	$0\cdot81\ R'^{0\cdot28}$	$82\ R'^{0\cdot84}$	$208\ R'^{1\cdot53}$
9	Blanchard (1953) Warm orographic rain			
	(*a*) within clouds	$0\cdot30\ R'^{0\cdot40}$	$235\ R'^{0\cdot58}$	$16\cdot6\ R'^{1\cdot55}$
	(*b*) at cloud base	$0\cdot40\ R'^{0\cdot37}$	$150\ R'^{0\cdot70}$	$31\ R'^{1\cdot71}$
	(*c*) non-orographic (Hawaii)	$1\cdot18\ R'^{0\cdot19}$	$61\ R'^{0\cdot89}$	$290\ R'^{1\cdot41}$
10	Jones (1956) (Heavy rain showers, Illinois)	$1\cdot48\ R'^{0\cdot05}$	$52\ R'^{0\cdot97}$	$358\ R'^{1\cdot36}$
11	Atlas and Chmela (1957) (Stratiform rain showing melting band during April 1954 at Lexington Mass)—			
		(1) $0\cdot95\ R'^{0\cdot29}$	$80\ R'^{0\cdot88}$	$162\ R'^{1\cdot16}$
		(2) $1\cdot13\ R'^{0\cdot17}$	$64\ R'^{0\cdot88}$	$215\ R'^{1\cdot34}$
		(3) $1\cdot38\ R'^{0\cdot19}$	$62\ R'^{0\cdot94}$	$350\ R'^{1\cdot42}$
		(4) $1\cdot22\ R'^{0\cdot20}$	$63\ R'^{0\cdot87}$	$310\ R'^{1\cdot34}$
12	Ramana Murty and Gupta (1959)			
	(*a*) Orographic monsoon rain at Khandala, India		$76\ R'^{0\cdot84}$	$109\ R'^{1\cdot64}$
	(*b*) Non-orographic monsoon rain at New Delhi, India		$62\ R'^{0\cdot895}$	$242\ R'^{1\cdot42}$
13	Sivaramakrishnan (1959)			
	(*a*) Thunderstorm rain	$0\cdot82\ R'^{0\cdot29}$	$70\ R'^{0\cdot83}$	$219\ R'^{1\cdot41}$
	(*b*) Stratiform rain showing melting band	$0\cdot71\ R'^{0\cdot29}$	$86\cdot4\ R'^{0\cdot77}$	$67\cdot6\ R'^{1\cdot94}$
	(*c*) Non-freezing stratiform rain at Poona (1959)	$0\cdot49\ R'^{0\cdot5}$	$101\ R'^{0\cdot69}$	$66\cdot5\ R'^{1\cdot92}$
14	Ramana Murty and Gupta (1959)		$R'=1/67\times W\,D_0^{0\cdot6}$	(1) Khandala (2) New Delhi
15	Sivaramakrishnan (1959) (Poona)		$R'=1/63\times W\times D_0^{0\cdot5}$ (Poona) (for Bergeron type of rainfall)	

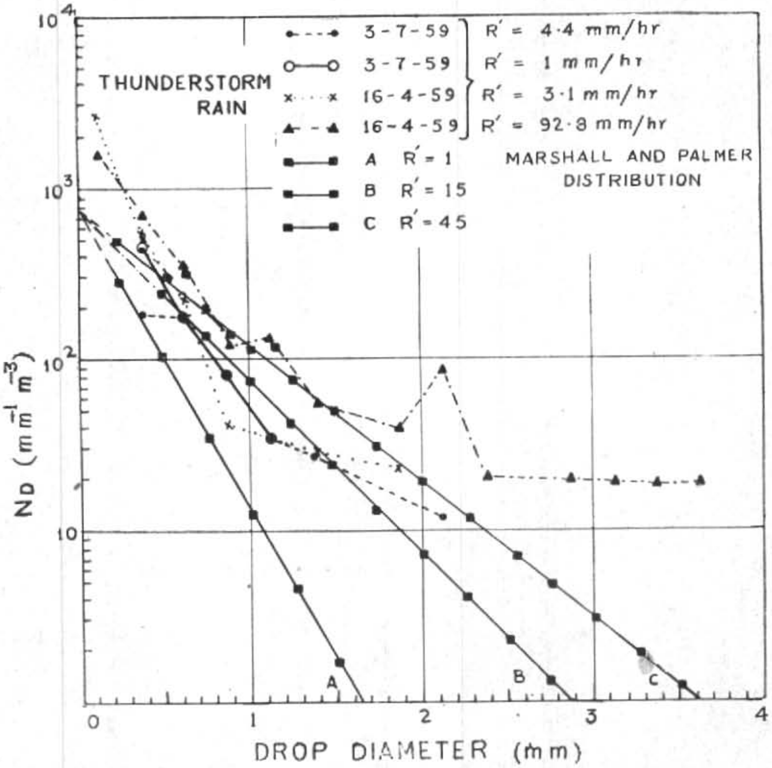


Fig. 10. Raindrop distribution of thunderstorm rain at Poona

(2) $D_0 = 0\cdot71\, R'^{0.29}$
(Rain showing radar melting band)
(Correlation coefficient$=\cdot833$)
(Stratified rain)

(3) $D_0 = 0\cdot49\, R'^{0.5}$
(Non-freezing rain)
(Correlation coefficient$=\cdot822$).

Values of D_0 corresponding to different types of rain samples with rate of rainfall have been plotted in Fig. 13 along with the data obtained by Laws and Parson (1943) and Best (1950) for comparison.

(1) The values of D_0 are in general found to be below the values obtained by Laws and Parson and Best. From Fig. 13 it is seen that the values of D_0 obtained for thunderstorm rain (curve 1) are greater than that for melting band rain (curve 4), though both involve the ice-crystal mechanism for initiation of rainfall. The values of D_0 for non-freezing rain (curve 5) is found to be *lower than* that for melting band rain and thunderstorm rain for rainfall intensities less than 10 mm/hr but *greater than* for values of R' greater than 10 mm/hr. This may be due to the curve of best fit being calculated for observations of intensities of rainfall below 10 mm/hr. As such the curve of best fit by the method of least squares should be used only for R' less than 10 mm/hr and not for R' greater than 10 mm/hr. It is proposed to continue these observations during monsoon season for non-freezing rain with intensities greater than 10 mm/hr as and when observed at Poona.

(2) It is also noticed from Table 2, that for the same intensity R' and same type of rain, the values of D_0 are widely different. But there is a unique relation for the same value

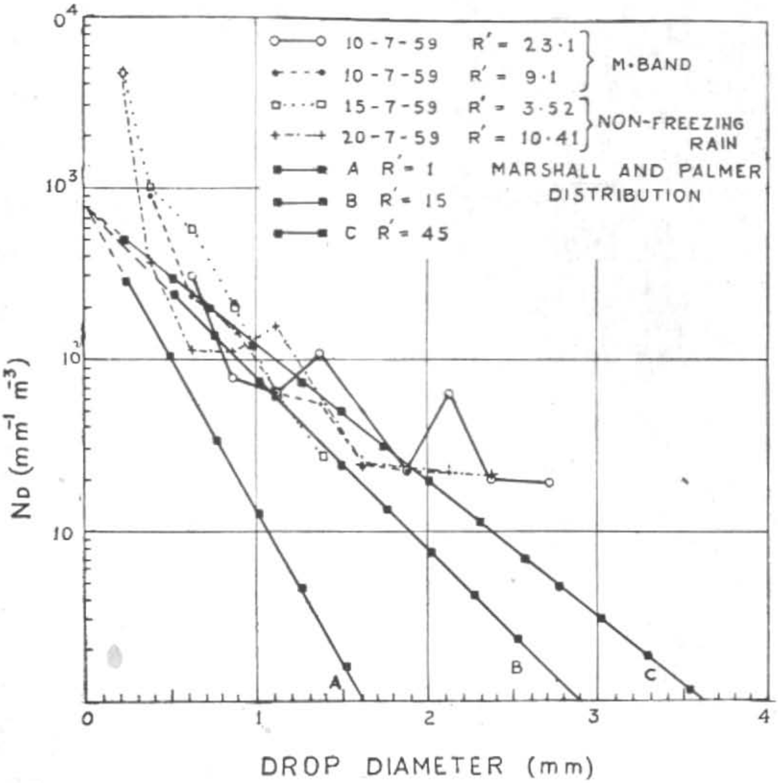


Fig. 11. Raindrop distribution of melting band and non-freezing rain at Poona

of D_0, W and R', given by $R'=KWD_0^n$ where $KD_0^n=V$ (Spilhaus 1948) (Terminal velocity of drop diameter D) and K and N are constants; when we plot log R'/W against D_0, the points form a straight line with the value of constant $K=\cdot016$ for thunderstorm rain and melting band rain, $K=\cdot014$ for non-freezing rain and slope $n=0\cdot5$ thereby giving

$$R' = \frac{1}{63} \times W \times D_0^{0.5} \qquad (3)$$

as against

$$R' = \frac{1}{67} \times W \times D_0^{0.6}$$

found by Ramana Murty and Gupta (1959) from their study of drop size distribution at Khandala and Delhi.

This relation helps as to determine any one of the rain parameter D_0, R' and W when any two of the other quantities are known.

5·4. *Radar reflectivity and intensity of rainfall*—The power received at a radar from a rain target is proportional to the radar reflectivity $Z = \Sigma N_D\ D^6.\ \delta D$, where N is the number of drops per cubic metre of diameter D on the size interval δD.

Values of $Z = \Sigma N_D\ D^6.\ \delta D$ have been obtained for the different types of rain and tabulated in Table 4. By the method of least squares, the following relations between radar reflectivity Z and R' have been determined for the different types of rain and plotted in Fig. 14.

(1) $Z = 219\ R'^{1.41}$ (Thunderstorm rain) (correlation coefficient between Z and $R' = \cdot549$)

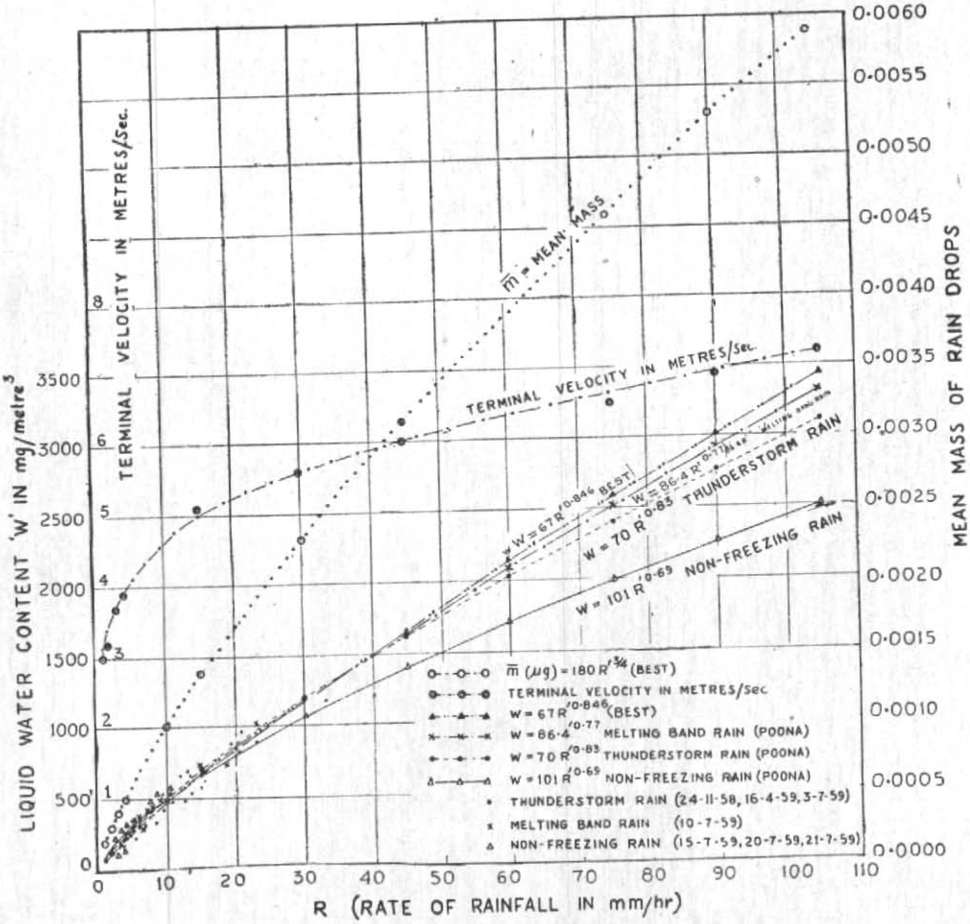


Fig. 12. Curves showing relation of liquid water content (W), mean mass of raindrops ($\overline{m}$), terminal velocity of raindrops with rate of rainfall (R')

(2) $Z = 67\cdot6\, R'^{1.94}$ (Radar melting band rain from stratified clouds) (correlation coefficient $= \cdot8025$)

(3) $Z = 66\cdot5\, R'^{1.92}$ (Non-freezing rain) (correlation coefficient $= \cdot964$)

As the sixth power of the diameter factor allows the relatively few large drops greatly to influence the radar reflectivity Z, although the intensity of rainfall may not be affected appreciably, any empirical relation between Z and R' may not satisfy the actual conditions in all instances and hence the measurement of R' by radar is found to be not correct always (Twomey 1953). Nevertheless Atlas and Chmela (1957) have attempted to give physical basis for Z—R' correlation to detect the Z—R' variations in practice.

Bartnoff and Atlas (1951) have given a basic equation for Z, the radar reflectivity factor as follows—

$$Z = \frac{6}{\pi}\, G(n).\; D_0\, \frac{W}{\rho} \quad \text{mm}^6/\text{m}^3 \quad (4)$$

where D_0 = median volume diameter in mm

W = liquid water content in mgm/m^3

ρ = particle density in gm/cc

$G(n)$ = Reflectivity coefficient

$= D_0^{-3}\cdot\Sigma N_D D^6/\Sigma N_D D^3$, a quantity dependent on spectrum breadth.

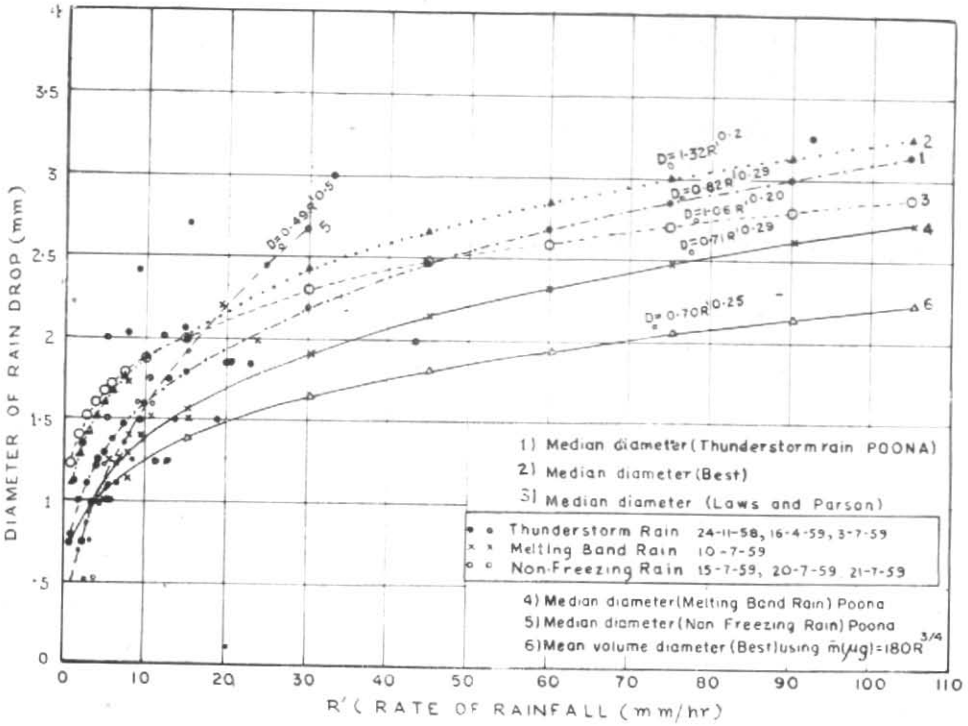


Fig. 13. Curves showing relation of average size of raindrop with rate of rainfall

It has been observed by Atlas (1953) as well as from Table 4 for Poona rains the value of $G(n)$ lies between 1 and 2 generally. According to Atlas this is nature's preference for a particular type of drop size distribution.

Atlas (1957) has also shown that

$$R' = \cdot 0036 \times V_0 \left(\frac{\overline{V}}{V_0} \right) \times W \qquad (5)$$

where V_0=Fall velocity of *median volume size*

$\frac{\overline{V}}{V_0}$ = Weighted fall velocity defined by equation (5) itself.

He has found that for most raindrop spectra

$$\frac{\overline{V}}{V_0} = \text{falls very close to one.}$$

For Poona rains also, from Tables 2 and 4, the ratio $\overline{V}/V_0$ has been calculated and found to be very close to *one* in agreement with Atlas, thereby proving Blanchard's remark that "in general, a drop distribution can be represented by a uniform collection of drops with size equal to the median volume diameter (D_0)".

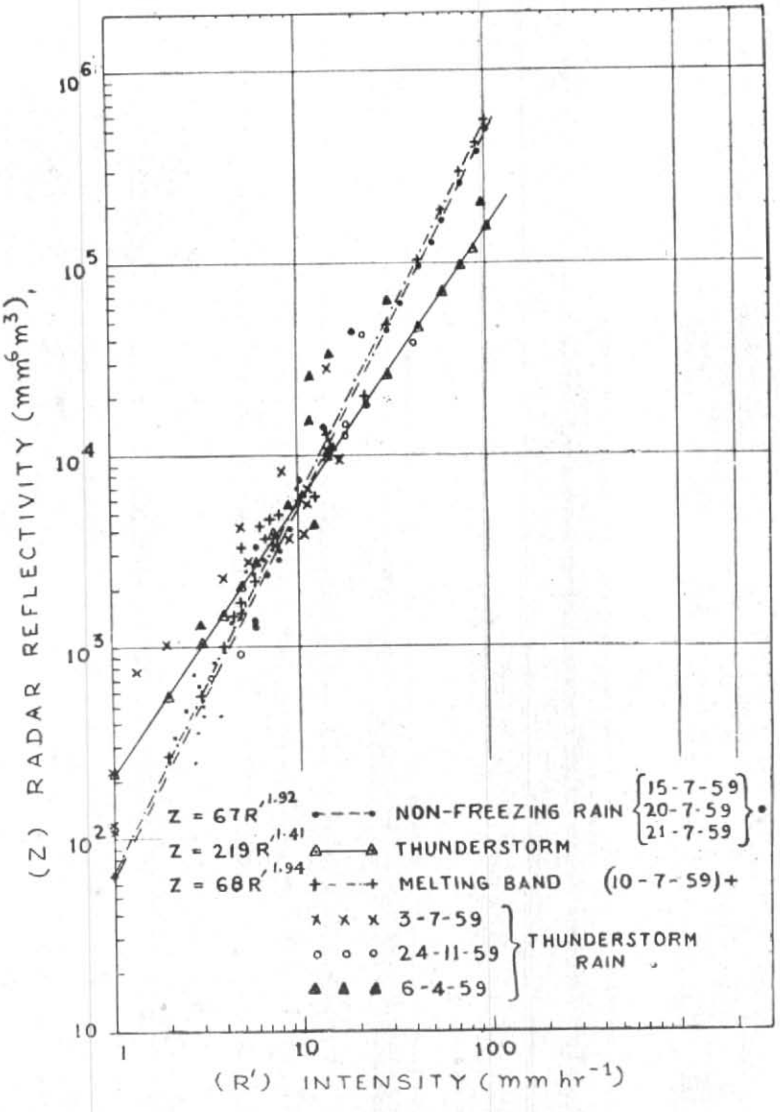


Fig. 14. Radar reflectivity as function of rain intensity observed at Poona

TABLE 4

Regression equations and rainfall parameters for different types of rain at Poona

(SUMMARY)

Date	Type of rain	D_0—R'	W—R'	Z—R'	$\frac{\overline{V}}{V_0}$	$G(n)$	Corr. coefficient D_0-R'	Corr. coefficient W-R'	Corr coefficient Z-R'
24-11-58 16-4-59 3-7-59	Thunderstorm rain	$D_0=\cdot 8R'^{0\cdot 29}$	$W=70R'^{0\cdot 83}$	$Z=218\cdot 5R'^{1\cdot 4}$	1·0	2·4	·7	·7	·55
10-7-59	Melting band rain from stratiform clouds	$D_0=\cdot 7R'^{0\cdot 29}$	$W=86\cdot 4R'^{\cdot 77}$	$Z=67\cdot 6R'^{1\cdot 9}$	1·0	1·9	·83	·97	·80
15-7-59 20-7-59 21-7-59	Non-freezing rain	$D_0=\cdot 49R'^{0\cdot 5}$	$W=101R'^{\cdot 69}$	$Z=66\cdot 5R'^{1\cdot 9}$	1·0	1·9	·82	·97	·96

6. Progressive development in the variation of rainfall rate at minute intervals using the rain receiver and tilting bucket raingauge

Figs. 15 and 16 give histograms showing variation of rainfall intensity at minute intervals for a few thunderstorms on 28 September 1955, and 18-19 October 1955. It is seen that superposed in a general trend of progressive increase in rainfall rate until the peak intensity is reached, fluctuations in intensity also occur. On the top of each histogram, '+', '—', '0' markings are given to indicate the nature of electric charge of the raindrop during that minute interval. They show that all the raindrops during the entire period of rainfall are not charged. It is possible that the origin of drops having electrical charge and drops having no electrical charge may be at different levels, one above the freezing level and the other below the freezing level depending upon the intensity of rainfall and consequent change in the drop size and terminal velocity. The author has proved earlier (1959) that for rain to have appreciable charge, the rain must have started as ice or at least in the form of ice for some part of its history. Non-freezing rain is found to have less or no electrical charge (Fig. 9). In this connection Simpson (1949) in a study of rain electricity lists a number of occasions of fairly heavy rain at Kew (England) without pronounced electrical effects. Smith (1951) reports that the estimated height of the cloud top on most of the occasions was below 0°C level. This affords a method of identifying occasions of rain from non-freezing clouds. It is possible that in some thunderstorms both Bergeron process and the coalescence process may work together as raindrops formed by coalescence *below the freezing level are not appreciably charged.*

Again in Fig. 17 radar melting band is seen during monsoon rain at Poona on 2 August 1955 from 1030 to 1230 hrs but all raindrops during the entire period of rainfall are not charged. This may be due to either that some of the charged raindrops discharging before reaching the ground or their origin may be below the freezing level.

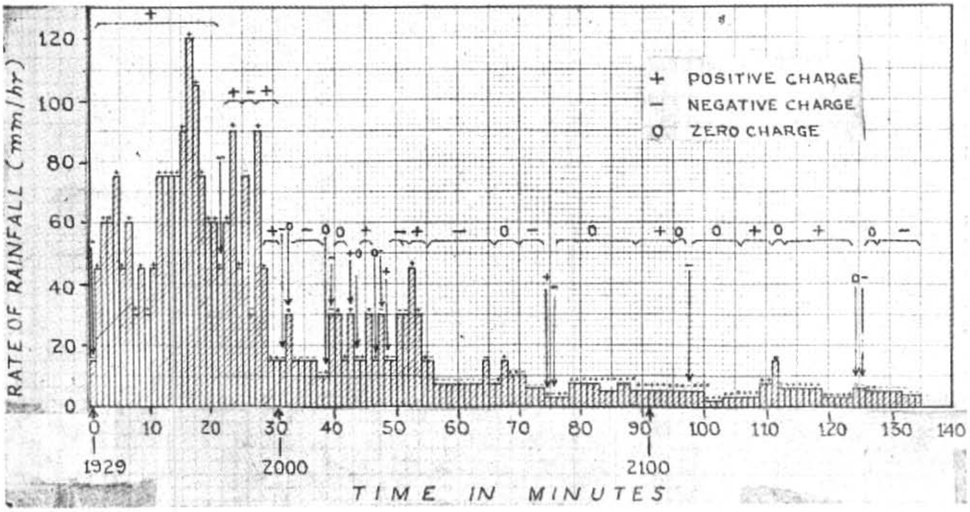


Fig. 15. Severe thunderstorm at Poona on 28 September 1955

The diagram shows that all the raindrops during the entire period of rainfall are not electrically charged; the peak intensity of 120 mm/hr is reached 15 minutes after the start of the storm

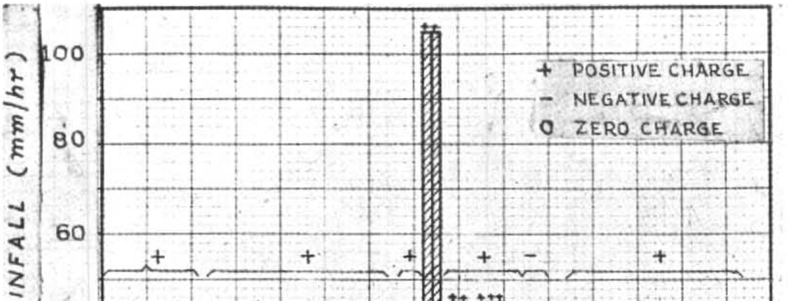
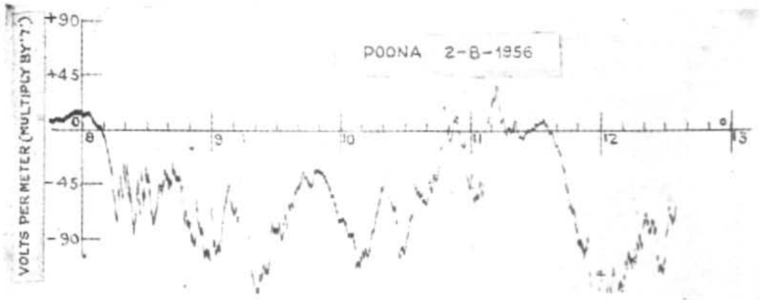


Fig. 16. Thunderstorm at Poona on 18—19 October 1955

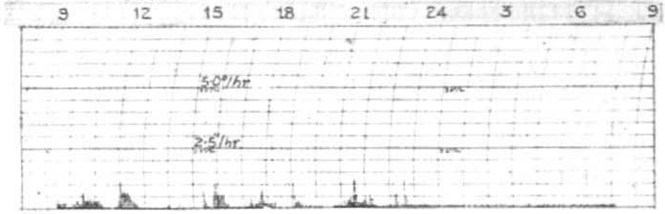
The peak intensity of 105 mm/hr is reached 36 minutes after the start of the storm

Figs. 15 and 16. Progressive development in rainfall rates and electric charge on raindrops at minute intervals

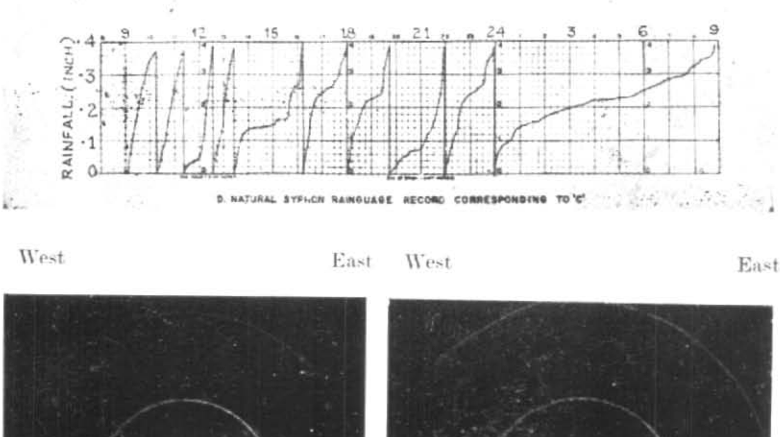


A PORTION OF ELECTROGRAPH RECORD DURING CONTINUOUS RAIN ON 2nd AUGUST 1956

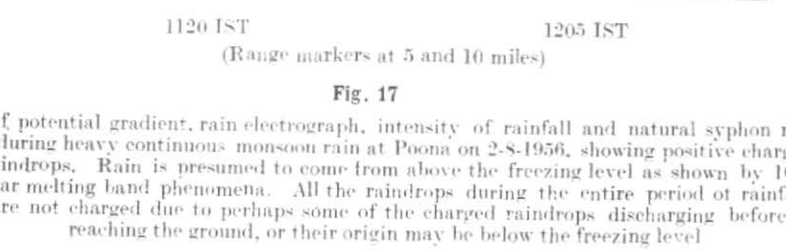
B PORTION OF RAIN ELECTROGRAPH RECORD CORRESPONDING TO 'A' POSITIVE



C-INTENSITY OF RAINFALL RECORD USING A BIBBY TYPE RECORDER ON 2nd-3rd AUGUST 1956



D. NATURAL SYPHON RAINGUAGE RECORD CORRESPONDING TO 'C'



1120 IST 1205 IST

(Range markers at 5 and 10 miles)

Fig. 17

Portions of potential gradient, rain electrograph, intensity of rainfall and natural syphon raingauge records during heavy continuous monsoon rain at Poona on 2-8-1956, showing positive charge only on raindrops. Rain is presumed to come from above the freezing level as shown by 10-cm radar melting band phenomena. All the raindrops during the entire period of rainfall are not charged due to perhaps some of the charged raindrops discharging before reaching the ground, or their origin may be below the freezing level

7. Conclusion

1. From the study of the size distribution of raindrops, it is shown that the relation of intensity of rainfall with

(1) Number of drops per cubic metre N_D

(2) Median volume diameter D_0

(3) Liquid water content W

(4) Radar reflectivity Z (mm^6/m^3)

is found to be different for different types of rain (thunderstorm, melting band rain and non-freezing rain) (see Table 3).

2. It is shown that the rain intensity corresponding to most size spectra can be represented by a uniform collection of drops with size equal to the median volume diameter D_0 in agreement with the results obtained by Blanchard (1953) and Atlas and Chmela (1957).

3. The study clearly shows that any two of the four raindrop size parameter, R' (rainfall intensity), Z (reflectivity factor), W (liquid water content), D_0 (median volume diameter) fix the other two.

4. The physical basis for the Z—R' correlation for different types of rainfall are explained using Bartnoff and Atlas equation (1951).

5. The progressive development of raindrop sizes using the raindrop recorder and intensity of rainfall at minutes intervals using the rain receiver, tilting bucket raingauge and photographic rain electrograph during *the entire period of a storm* helps to know in general, how the concentration and size distribution of raindrops varies in space and time, how the drops grow, coalesce and break up during their fall to the ground, which will not be possible if *intermittent samples* are taken for study especially during thunderstorms.

6. Although mean distribution curves obtained by averaging a large number of samples of the same intensity show smooth variation, curves relating to individual samples even in the so called steady rain show peaks and troughs in drop size distribution (Figs. 10, 11). This may be due to possible irregularities in the distribution of original precipitation elements or discontinuities in the rate of updraft within the cloud.

7. A knowledge of the electric charge carried by rain during the entire period of storm shows whether the rain mechanism process is ice-crystal process or coalescence process or both.

8. The presence or absence of appreciable electric charge in rain helps us to find out whether the rain is from freezing or non-freezing clouds.

9. The drop recorder described in this paper is thus useful to get a continuous record of the size distribution of raindrops for various types of rain. The important meteorological rain parameters such as liquid water content W, intensity of rainfall R', the size distribution of raindrops for various types of rainfall, the radar reflectivity $Z = \Sigma N_D D^6 \times \delta D$, the median drop diameter D_0 can all be obtained from this simple raindrop recorder.

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