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Size distribution of Raindrops — Part V

V. N. KELKAR

Department of Physics, Nowrosjee Wadia College, Poona

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ABSTRACT. Results of measurements of the size distribution of raindrops for thunderstorm rain recorded at Poona during August, September and October 1956 are described and compared with those for monsoon rain. The basic data are given in the form of a table showing the number of raindrops received per square metre per second, (grouped at intervals of 0·25 mm in diameter) for various intensities of precipitation. The total momentum and kinetic energy of raindrops per square metre per sec have been determined as a function of the intensity of precipitation. The concentration of raindrops and liquid water per cubic metre of air and their distribution in different diameter groups is discussed. The radar reflectivity factor for individual rain periods has been calculated for monsoon as well as thunderstorm rain. Evidence for the breaking up of large raindrops is presented in the paper.

1. Introduction

In the earlier parts of this series of investigations, we have dealt with the size distribution of raindrops in monsoon rain at Poona. In this paper we propose to present the results for thunderstorm rain at Poona.

Four periods of rainfall have been recorded, one in August, two in September and one in October 1956. The size of raindrops was determined by measuring the size of their impact on a collecting surface. Sheets of smooth paper (21 cm by 33 cm) were used. In all 169 papers were exposed. The total number of drops actually measured was 55,684. The exposure varied from 1 sec to 49 sec depending on the rate of rainfall. In our experiments the rate of rainfall varied from 0·17 to 71·2 mm/hr. The results are presented in the same form as was done for monsoon rain to facilitate comparison.

The basic data are given in Appendix I. Instead of arranging the results in the order of increasing magnitude of the intensity of precipitation, they are given in the time sequence in which the records were made. The origin of time is in all cases within a minute of the actual commencement of the rain. Complete showers have been recorded, except for 31 August 1956, when on account of the high intensity of rain and strong winds further observations were not possible. The reason for giving the results in the form of the time sequence in which the records were made is that the diameter spectrum of raindrops for identical intensity of precipitation, is strongly dependent upon the phase of the shower. The values of the total number of raindrops per m^2 per sec and the total number of raindrops per cubic metre of air are indicated in separate columns.

2. Results

Ground distribution

The variation of N, the total number of raindrops per m^2 per sec with intensity of precipitation I (mm/hr) was plotted on semi-logarithmic paper. This is shown in Fig. 1. Average values are shown by open circles and the individual values by dots. The relation between N and I was found to be

$$N = 562\, I^{0.52} \text{ per m}^2 \text{ per sec.} \qquad (2\cdot1)$$

The corresponding relation for monsoon rain was

$$N = 710\, I^{0.47} \text{ per m}^2 \text{ per sec.} \qquad (2\cdot2)$$

For thunderstorm rain the number of drops falling on unit area per sec was less than the corresponding number for monsoon rain, within the range of intensities observed. Unlike monsoon rain, however, in about 20 per cent of the cases, the frequency of drops was abnormally low in thunderstorm rain. The corresponding point form a separate branch of the scatter diagram and the mean values are shown approximately by the dotted curve in Fig. 1. These low values have reduced the average value of N, the main branch of the scatter diagram following a higher curve than the average.

The total momentum of raindrops was also calculated. The relation between M and I was found to be—

$$M = 112\, I^{1.136} \text{ c.g.s. units per m}^2 \text{ per sec.} \qquad (2\cdot3)$$

The ratio (M/I) varies from 104 for low values of the rate of rainfall to 200 towards the higher values. The corresponding relation for monsoon rain was —

$$M/I = 165 \qquad (2\cdot4)$$

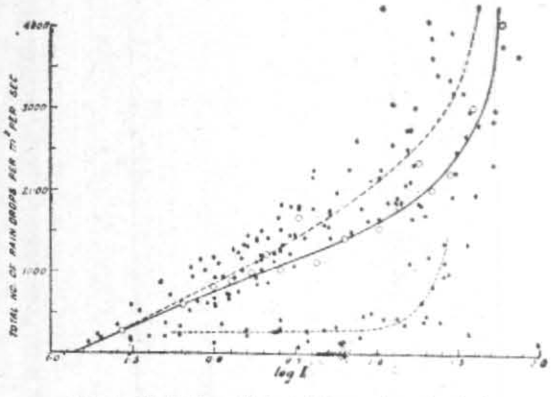

Fig. 1. Variation of the total number of raindrops per m² per sec with intensity of precipitation

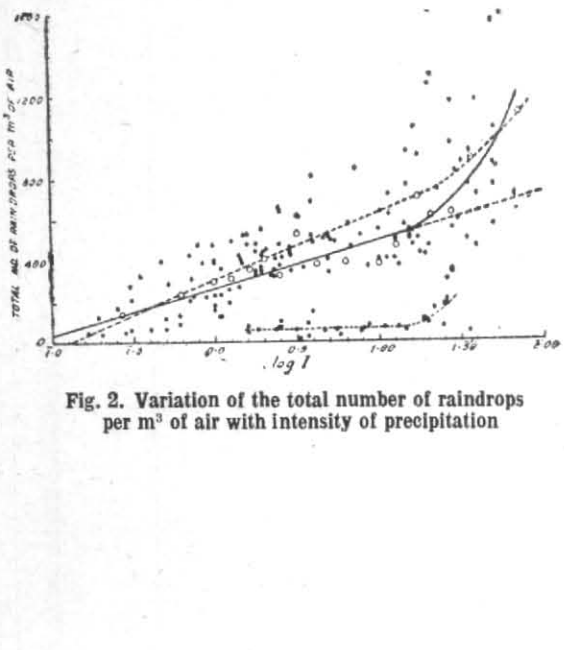

Fig. 2. Variation of the total number of raindrops per m³ of air with intensity of precipitation

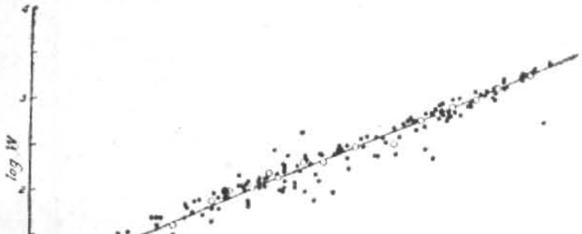

Fig. 3. Variation of total liquid water per m³ of air with intensity of precipitation

The ralation between the total kinetic energy E (in joules) and the intensity of precipitation (in mm/hr) was

$$E = 2\cdot82 \times 10^{-3} \times I^{1\cdot26} \qquad (2\cdot5)$$

The corresponding relation for monsoon rain was

$$E = 2\cdot80 \times 10^{-3} \times I^{1\cdot18} \qquad (2\cdot6)$$

The kinetic energy of raindrops for thunderstorm rain is slightly greater than that for monsoon rain at corresponding intensities.

In monsoon rain there was a progressive advance of the modal diameter with increase in the intensity of precipitation. No such regularity was observed in thunderstorm rain. The distribution curves are more frequently multimodal with a dominant mode in the region of small diameters less than one mm. Though the contribution of small drops to the total precipitation is insignificant, the number of the small drops far exceeds that of the larger ones. A part, at least, of the smaller drops seem to be of secondary origin, being produced by the breaking up of larger drops for which evidence has been obtained.

3. Space distribution

The variation of n, the total number of raindrops per cubic metre of air with intensity of precipitation is shown in Fig. 2. The abnormally low-values of the number of drops again form a seprate branch of the scatter diagram shown by dotted curve. The average graph is approximately a straight line upto an intensity of 15 mm/hr and curves upwards for higher intensities. The relation between n and I over the straight part is—

$$n = 265 + 227 \log_{10} I \qquad (3\cdot1)$$

The corresponding graph for monsoon rain was a straight line of the form—

$$n = 282 + 202 \log_{10} I \qquad (3\cdot2)$$

The concentration of drops in a unit volume of air is less for thunderstorm rain than for monsoon rain upto an intensity of 4·8 mm/hr.

The total amount of liquid water (W) as a function of the intensity of precipitaion I is shown on a logarithmic scale in Fig. 3. The relation between W snd I is found to be —

$$W = 70\ I^{0\cdot88}\ \mathrm{mm^3/m^3} \qquad (3\cdot3)$$

which is almost identical with the relation

$$W = 72\ I^{0\cdot88}\ \mathrm{mm^3/m^3} \qquad (3\cdot4)$$

obtained for monsoon rain.

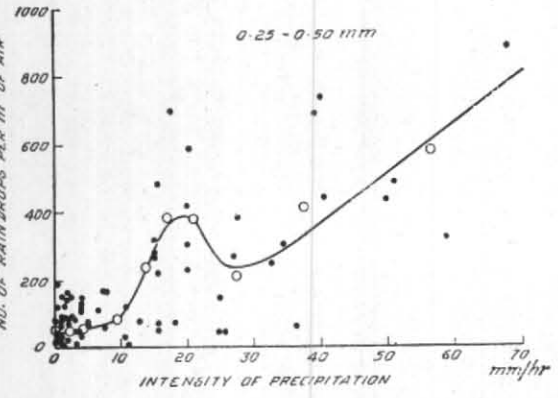

Fig. 4(a)

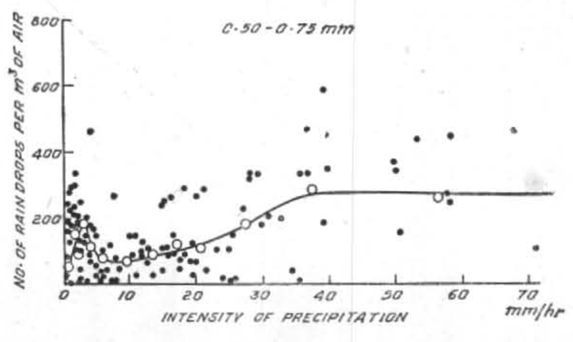

Fig. 4(b)

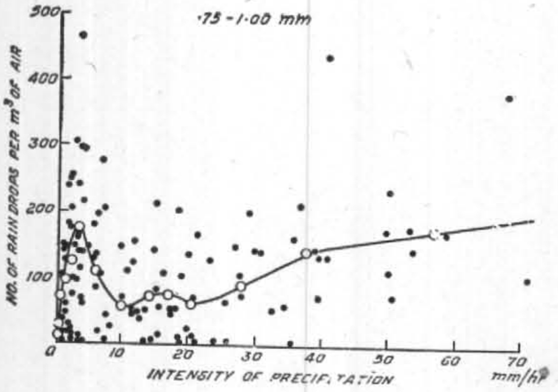

Fig. 4(c)

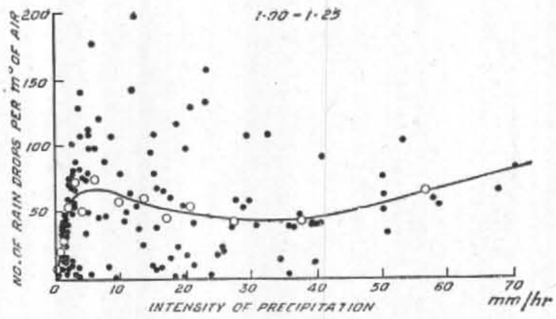

Fig. 4(d)

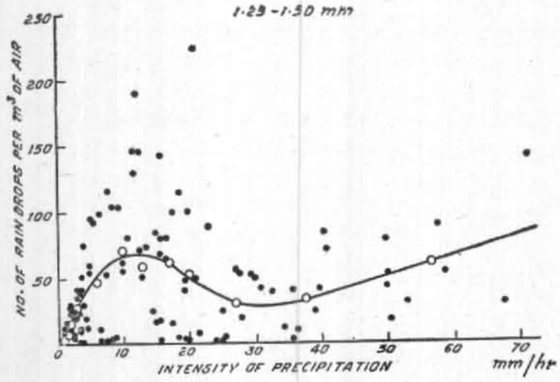

Fig. 4(e)

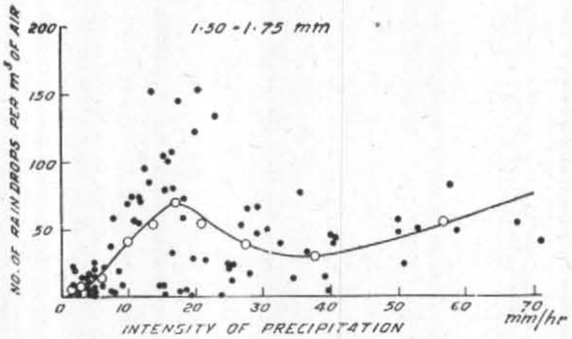

Fig. 4(f)

Figs. 4(a)—4(f). Variation of the number of drops of particular diameter groups per m³ of air with intensity of precipitation

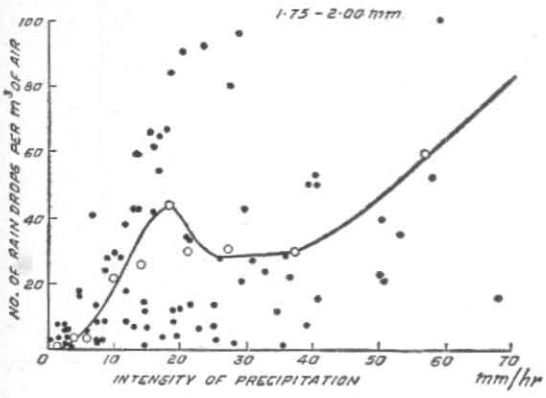

Fig. 4(g)

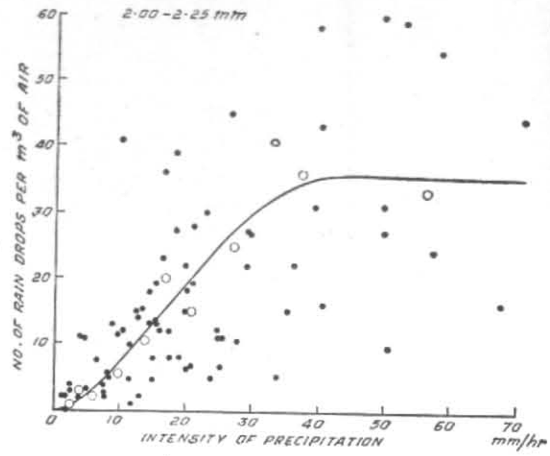

Fig. 4(h)

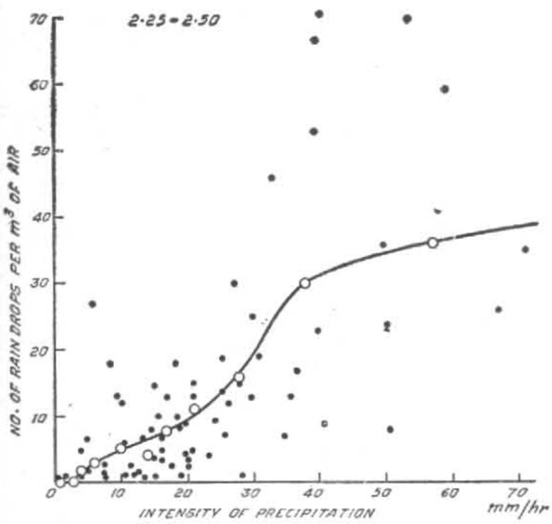

Fig. 4(i)

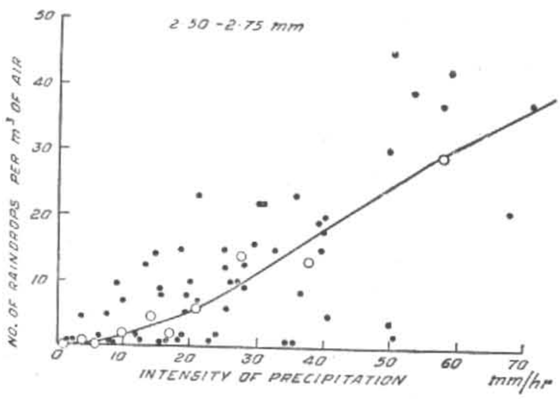

Fig. 4(j)

Figs. 4(g)—4(j). Variation of the number of drops of particular diameter groups per m³ of air with intensity of precipitation

The variation of the number of drops per m³ of air of particular diameter groups with intensity of precipitation is shown in Fig. 4 for ten different ranges of the diameter between 0·25 mm to 2·75 mm. Upto 2 mm diameter, the general feature common to all the diameter groups is that there is a maximum in the region of lower intensities and beyond the subsequent minimum steady rise towards larger intensities. For the range 0·75 to 1·00 mm, there are two maxima. The first maximum is strong and the second one is weak. For monsoon rain there is a well-developed maximum at about 4 mm/hr intensity for this diameter range. For thunderstorm rain the first pronounced maximum occurs at about 4 mm/hr and the second weak maximum at about 16 mm/hr. Beyond 2 mm diameter the number of drops steadily increases towards larger intensities.

Two samples of the normal and the abnormal distributions for identical or nearly indentical intensities of precipitations are shown in Fig. 5. The upper two histograms correspond to the abnormally low number of drops. The two lower histograms correspond to the normal distribution.

To examine the phase of the shower at which the number of drops is abnormally low, intensity-time curves have been plotted for individual rain periods shown by full lines in Fig. 6 [(a), (b), (c) and (d)]. The corresponding average volume of drop is shown by pecked lines in the same diagrams in each case. The average volume generally follows the fluctuations in intensity and is, as a rule, in phase with it. When the number of drops is small, the average volume of a drop increases above the normal, and the corresponding points (as indicated by the records) are shown by open circles. It is seen that these cases of small number of drops occur generally at the beginning—Figs. 6(a), (b), (c), at the end of the shower—Fig. 6(d) and also just before the intensity suddenly rises during the course of the shower after a comparative

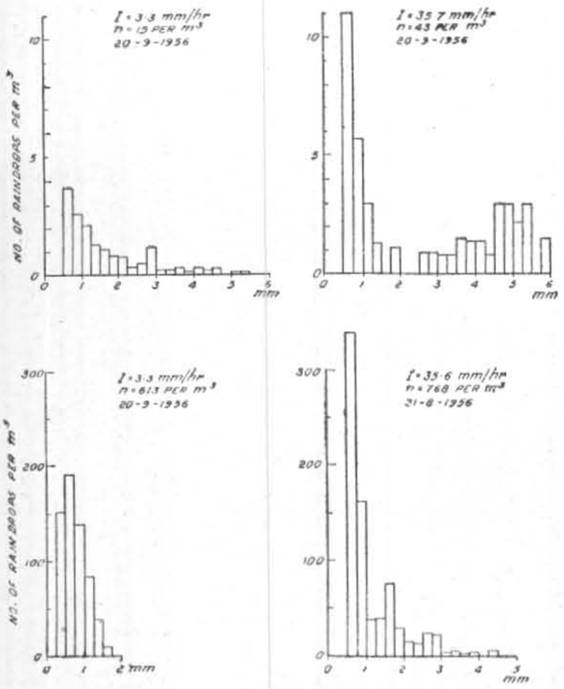

Fig. 5. Diameter spectra for nearly the same intensity of precipitation with abnormally low and the normal number of raindrops

lull—Fig. 6(b). Examination of the actual records gives the impression of a greater uniformity in the drop size, which may be large, medium or small. The large and medium size drops always precede a sudden outburst of intensity. The reason for this seems to be the time lag between the arrival of large and small drops, which can be considerable, of the order of several minutes, depending on the height of the cloud. The smaller drops get temporarily filtered out. Towards the end of the shower the elimination of smaller drops is almost certainly due to evaporation and the record again shows a more or less uniform drop size, though small in absolute value.

4. Radar Reflectivity

The radar reflectivity factor $Z = \Sigma x^6$ is plotted logarithmically against I, the intensity of precipitation in Fig. 7. The average relation between Z and I is found to be

$$Z = 216\ I^{1.56}\ \text{mm}^6/\text{m}^3. \qquad (4\cdot1)$$

The corresponding relation for monsoon rain was—

$$Z = 189\ I^{1.35}\ \text{mm}^6/\text{m}^3. \qquad (4\cdot2)$$

The radar reflectivity factor is, therefore, greater for thunderstorm rain than for monsoon rain.

Let us examine to what extent the Z-I relationship varies from shower to shower. With this in view, the logarithms of Z and I have been plotted for individual rain periods, four for monsoon rains and four for thunderstorm rains in

TABLE 1

Radar reflectivity (Z) for different rain periods

Date (1956)	Type of rain	Z (mm^6/m^3)
3 Aug	Monsoon	$120\ I^{1.46}$
30 Aug	,,	$133\ I^{1.49}$
19 Sep	,,	$263\ I^{1.50}$
8 Oct	,,	$105\ I^{1.49}$
31 Aug	Thunderstorm	$479\ I^{1.51}$
20 Sep	,,	$251\ I^{1.63}$
27 Sep	,,	$159\ I^{1.68}$
8 Oct	,,	$191\ I^{1.41}$

Figs. 8(a) and 8 (b). For convenience the abscissa has been shifted by 1·5 units to the right for each successive plot. The different Z-I relations are given in Table 1.

It is seen that the coefficient changes to a marked extent from shower to shower by a factor of 2·5 for monsoon rain and by a factor of 3 for thunderstorm rain. This increase in the coefficient seems to be due to an overall increase in the drop size. The variation in the exponent is small for monsoon rain and is a little greater for thunderstorm rain.

5. Further comparison with monsoon rain

For further comparison of the results for thunderstorm rain with those of monsoon rain, the number of raindrops of different diameter groups are added, irrespective of the intensity of precipitation and percentages calculated. The whole available data is regarded as a sample of the raindrop population of rain of each category. The number of raindrops actually measured in each case is nearly the same and the statistical weights of the two samples are nearly equal. The diameter spectra of the number of drops for the ground as well as the space distribution and the liquid water per m³ of air are shown in Fig. 9 for the two kinds of rain. As is to be expected all the three spectra are extended towards larger diameters for thunderstorm rain. For the ground distribution, the descending part of the curve beyond the maximum is initially convex for monsoon rain showing that the rate of fall in the number of drops with diameter is slow. For thunderstorm rain on the other hand, the corresponding part is concave and indicates a rapid fall. For the space distribution the curves are nearly similar but the value of the maximum and the subsequent rate of fall are higher for thunderstorm rain. The liquid water distribution curve is nearly symmetrical about the modal diameter of 1·5 mm for monsoon rain. For thunderstorm rain, the curve has two maxima, a small one in the range 0·75-1·00 mm and the other at 1·75 mm. Beyond this the curve shows some fluctuations but these can be attributed to statistical fluctuations due to the small number of observations involving large drops.

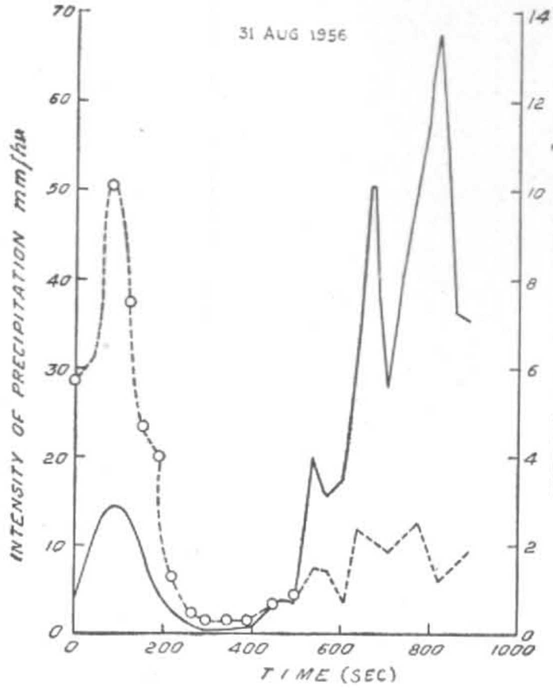

Fig. 6(a)

Fig. 6(b)

Fig. 6(c)

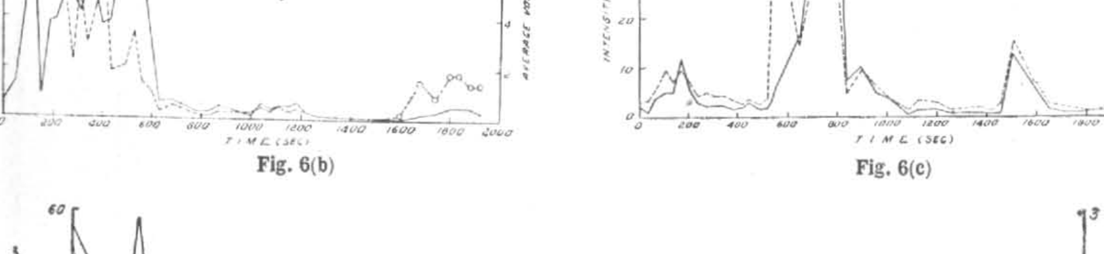

Fig. 6(d)

Fig. 6. Intensity—time curve as well as average volume of raindrop—time curve for four rain periods

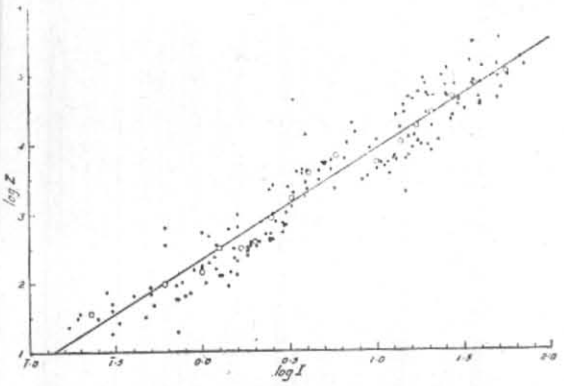

Fig. 7. Radar reflectivity factor as a function of the thunderstorms

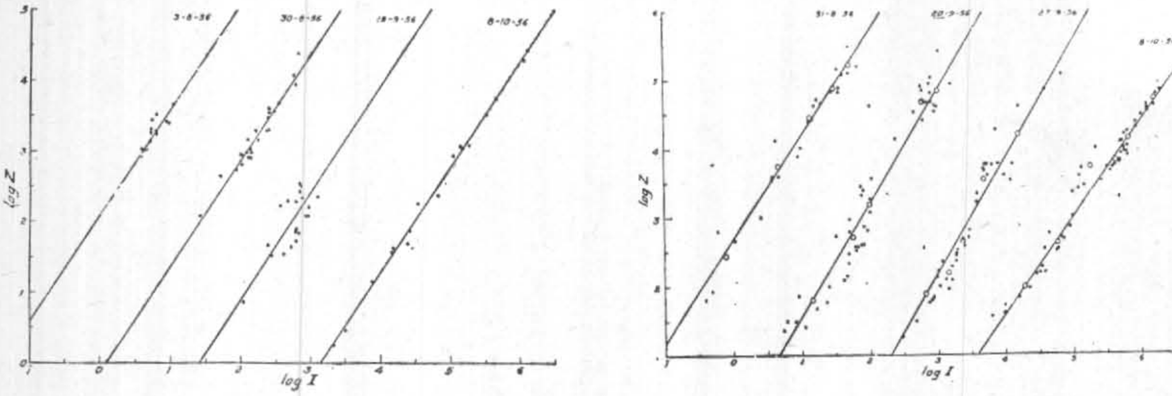

Fig. 8(a). Monsoon rains

Fig. 8(b). Thunderstorm rains

Fig. 8. Radar reflectivity factor as a function of the intensity of precipitation for individual rain periods

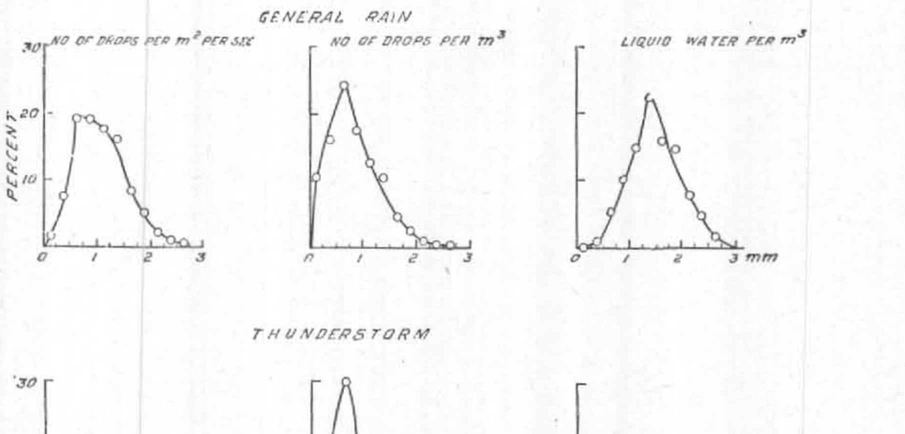

Fig. 9. Diameter spectra of the number of drops per m² per sec, number of drops per m³ of air and liquid water per m³ of air for general rains and for thunderstorm rains

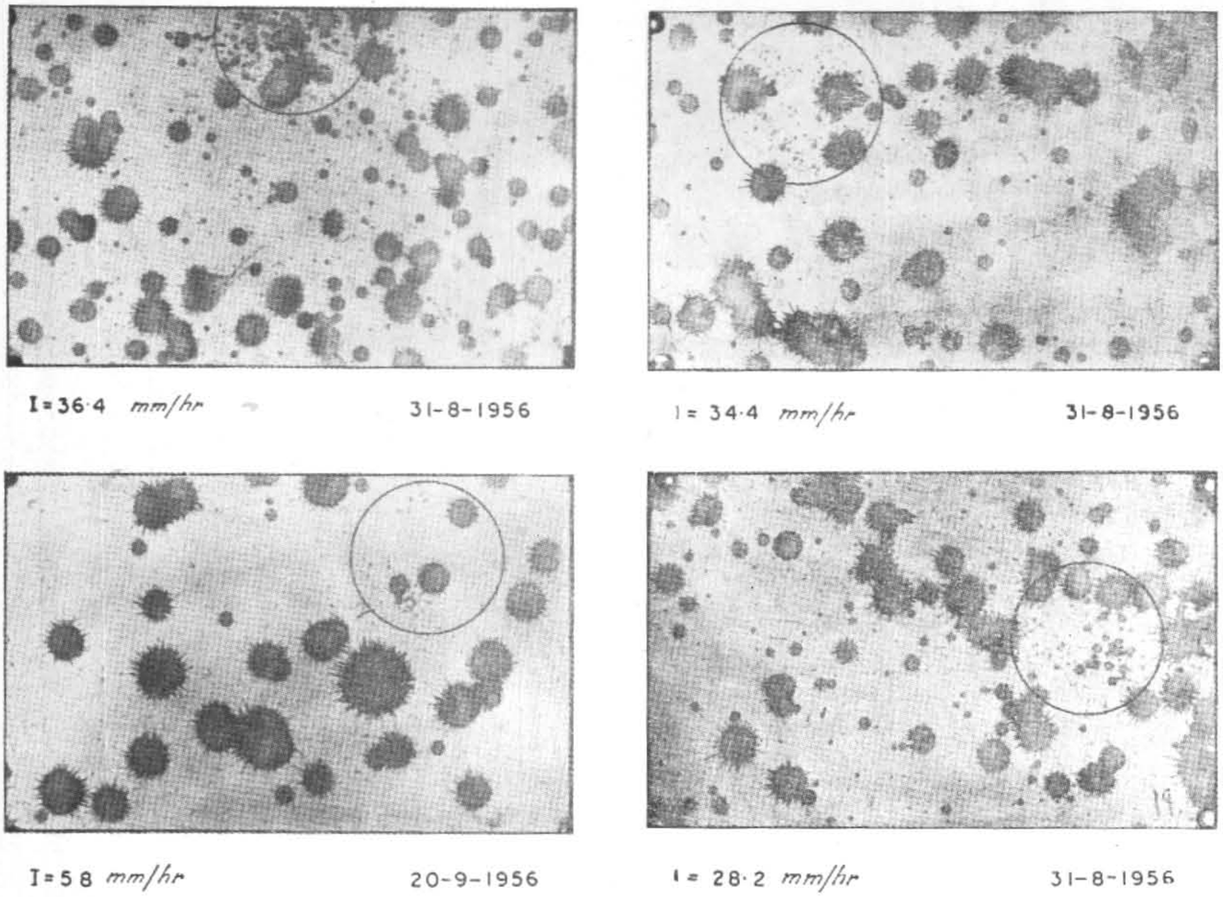

Fig. 10. Reduced photographs of four sample records showing that breaking up of a drop into small fragments (encircled)

6. Summary and Conclusions

We may summaries our main findings as follows —

(a) Very small drops less than 0·25 mm do not occure in thunderstorm rain. Even in monsoon rain the occurrence of these small drops was sporadic. At intensities higher than 5 mm/hr drops within the range 0·25—0·50 mm are not observed in 50 per cent of the cases recorded for thunderstorm rain.

(b) The maximum drop diameter observed is within the range 5·75—6·00 for thunderstorm rain. The corresponding diameter was within the range 3·75—4·00 mm for monsoon rain.

(c) In thunderstorm rain 55 per cent of the cases recorded correspond to intensities less than 5 mm/hr. For monsoon rain the corresponding percentage is 67.

(d) In thunderstorm rain the drop spectra frequently show gaps which sometimes persist even in the subsequent records. These gaps, if real, indicate a tendency to form certain preferred diameter groups, perhaps as a result of a coalescence.

(e) In five out of the 169 samples recorded for thunderstorm rain, there appears a close cluster of smaller droplets, quite inconsistent with the general run of drops recorded on the same paper. The nature of splashes indicates that these small droplets had hit the paper before attaining their terminal velocities. This means that these drops must have been formed within one or two metres above the recording paper. This seems to indicate the breaking up of a large raindrop into a number of fragments near the ground level. Fig. 10 shows these close clusters of small droplets (encircled) for four sample records reduced to about one half linear dimensions.

REFERENCES

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1960 *Ibid.*, **11**, 4, p. 323.
1961 *Ibid.*, **12**, 4, p. 553.

APPENDIX I

Time (sec)	I (mm/hr)	N (M^{-2} sec^{-1})	n (m^{-3})	W (mm^3 m^{-3})
31 AUGUST 1956				
0	3·7	164	26	149
35	10·1	445	67	414
83	14·6	365	54	547
119	13·2	451	67	502
152	9·1	512	81	380
190	4·7	299	49	201
225	2·5	413	101	128
262	1·1	365	138	61
300	0·4	219	79	24
348	0·5	213	78	27
395	0·6	236	109	32
449	3·7	269	107	78
494	3·9	339	147	132
538	20·1	1211	471	731
572	15·4	1116	515	748
605	17·5	1858	904	683
639	34·4	1366	501	1184
674	50·8	2334	876	1863
706	28·2	1951	555	1055
737	40·7	2805	714	1564
768	50·0	2997	765	1955
817	67·4	5669	2039	2531
857	36·4	3142	930	1351
890	35·6	2987	768	1464
20 SEPTEMBER 1956				
0	3·3	81	15	104
50	7·6	206	43	264
90	24·0	408	71	725
123	35·7	257	43	1123
155	5·8	123	33	181
192	19·0	404	104	628
223	19·7	484	93	699
252	25·2	956	183	915
280	25·0	1364	399	919
310	21·4	847	162	798
342	25·6	1139	300	905
373	25·8	999	204	941
403	18·7	541	106	746
435	19·4	1793	429	812
465	29·7	2717	629	1264
500	30·7	2486	597	1267
530	50·0	2871	573	1953
560	29·4	3201	835	1253
597	14·5	2093	572	652
630	3·3	1785	612	223
685	3·5	1410	365	212
747	2·1	1408	479	155
785	1·3	1292	499	111
828	1·5	1354	527	118
870	2·4	1692	643	170
20 SEPTEMBER 1956 (*contd*)				
907	1·9	1043	372	124
945	1·47	1022	390	106
988	0·75	650	237	59
1040	2·93	1802	460	196
1077	1·95	1352	446	145
1112	2·60	1355	417	175
1152	2·50	1519	484	177
1187	3·25	1810	615	259
1223	1·44	1180	406	114
1263	0·73	949	317	66
1302	0·53	724	287	50
1346	0·35	544	336	35
1392	0·25	367	163	24
1450	0·19	245	123	16
1523	0·28	152	61	18
1595	0·17	121	45	11
1678	1·01	141	31	46
1738	1·60	296	79	67
1793	2·50	310	69	109
1832	2·33	266	61	102
1880	2·40	287	71	101
1923	1·60	235	55	76
27 SEPTEMBER 1956				
0	2·47	1830	640	193
37	1·18	731	237	84
72	4·0	1778	488	265
108	5·0	1447	341	324
140	4·9	1566	405	285
174	11·9	3060	720	673
213	5·5	1987	493	341
242	3·0	1462	436	202
274	2·3	1132	320	155
314	2·3	1232	357	160
344	2·47	1275	378	168
379	1·80	1140	349	132
422	1·82	1413	485	141
454	2·90	1465	441	162
488	1·90	1515	555	146
522	1·90	1219	356	141
553	5·5	328	57	235
585	8·2	478	82	253
655	16·1	1666	478	699
724	39·5	1920	469	1479
785	71·2	3679	719	2831
840	7·2	2620	844	422
900	9·9	2165	548	520
957	5·1	1730	500	300
1012	3·9	2167	687	269
1084	0·71	1068	437	71

APPENDIX I (*contd*)

Time (sec)	I (mm/hr)	N (M^{-2} sec^{-1})	n (m^{-3})	W (mm^3 m^{-3})
27 SEPTEMBER (*contd*)				
1130	1·26	937	294	98
1196	1·60	1432	444	131
1260	0·79	1168	481	77
1316	0·96	1194	479	87
1377	0·85	1038	390	79
1420	0·47	890	399	50
1475	0·60	346	136	41
1528	12·6	1866	405	619
1586	6·6	2267	578	399
1647	1·82	1400	448	143
1708	1·05	1115	409	93
1770	1·00	944	395	67
1827	1·60	1321	534	73
1892	1·40	1253	427	116
1990	0·30	594	259	33
8 OCTOBER 1956				
0	57·5	3782	848	2288
40	53·0	4256	1044	2174
85	40·2	5375	1686	1698
120	21·1	3644	1303	980
160	39·7	4253	1179	1557
205	58·4	5308	1588	2435
250	39·0	4924	1725	1688
300	4·7	1576	517	265
345	6·7	1508	465	342
385	18·1	1824	436	813
435	3·1	4574	1589	458
485	4·0	2255	813	269
530	4·9	1757	516	290
565	14·9	2537	935	302
620	20·7	3873	1593	1066
660	7·7	1797	522	411
700	10·8	2264	634	274
745	15·6	2754	546	750
785	18·2	5085	1966	949
840	19·9	4089	1258	1020
8 OCTOBER 1956 (*contd*)				
885	14·9	2774	759	736
925	16·5	3017	1043	816
970	27·7	3944	1173	1371
1010	32·5	3210	882	1390
1055	26·9	3354	966	1199
1105	49·7	5548	1554	2195
1150	23·0	3420	745	1129
1205	11·8	2579	619	625
1265	13·3	1878	375	663
1320	17·3	2412	504	935
1380	15·6	2103	511	740
1440	12·8	1924	493	625
1500	10·4	1645	404	510
1560	16·3	2328	538	790
1620	11·3	1880	404	576
1680	8·5	1633	371	418
1740	3·0	1087	347	177
1800	3·9	1755	522	253
1860	1·2	742	259	82
1920	1·4	761	276	156
1980	1·8	864	327	112
2040	1·8	864	325	119
2100	2·2	875	327	279
2160	1·9	1154	431	128
2220	2·9	1228	450	111
2280	2·3	1232	406	157
2340	1·1	955	365	88
2400	0·9	634	224	55
2460	0·7	549	211	50
2520	1·0	694	230	75
2590	1·0	619	161	71
2665	1·2	683	198	85
2735	1·0	595	175	74
2800	0·5	380	122	41
2870	0·3	191	59	22
2945	0·2	100	51	16
3025	0·3	188	208	19