Size distribution of Raindrops — Part V

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(Received 28 April 1967)

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 second 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 breakup 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 m² 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 m² 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

\[
N = 562 I^{0.52} \text{ per m}^2 \text{ per sec.} \quad (2.1)
\]

The corresponding relation for monsoon rain was

\[
N = 710 I^{0.47} \text{ per m}^2 \text{ per sec.} \quad (2.2)
\]

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 —

\[
M = 112 I^{1.16} \text{ c.g.s. units per m}^2 \text{ per sec.} \quad (2.3)
\]

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 —

\[
M/I = 165 \quad (2.4)
\]
The relation between the total kinetic energy $E$ (in joules) and the intensity of precipitation (in mm/hr) was

$$E = 2.82 \times 10^{-3} \times I^{1.26} \quad (2.5)$$

The corresponding relation for monsoon rain was

$$E = 2.80 \times 10^{-3} \times I^{1.18} \quad (2.6)$$

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 separate branch of the scatter diagram shown by dotted curve. The average graph is approximately a straight line up to an intensity of 15 mm/hr and curves upwards for higher intensities. The relation between $n$ and $I$ over the straight part is—

$$n = 265 + 227 \log_{10} I \quad (3.1)$$

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

$$n = 282 + 202 \log_{10} I \quad (3.2)$$

The concentration of drops in a unit volume of air is less for thunderstorm rain than for monsoon rain up to an intensity of 4.8 mm/hr.

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

$$W = 70 I^{0.88} \text{ mm}^3/\text{m}^3 \quad (3.3)$$

which is almost identical with the relation

$$W = 72 I^{0.88} \text{ mm}^3/\text{m}^3 \quad (3.4)$$

obtained for monsoon rain.
Figs. 4(a)—4(f). Variation of the number of drops of particular diameter groups per m² of air with intensity of precipitation.
The variation of the number of drops per m$^3$ 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 peaked 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
TABLE 1

| Date (1956) | Type of rain | Z  (mm³/m³) |
|------------|--------------|-------------|
| 3 Aug      | Monsoon      | 129 I⁻⁴⁶   |
| 30 Aug     | ''           | 133 I⁻⁴³   |
| 19 Sep     | ''           | 263 I⁻⁵⁰   |
| 8 Oct      | ''           | 105 I⁻⁴⁸   |
| 31 Aug     | Thunderstorm | 479 I⁻⁴¹   |
| 20 Sep     | ''           | 251 I⁻⁴³   |
| 27 Sep     | ''           | 159 I⁻⁴⁸   |
| 8 Oct      | ''           | 191 I⁻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 m² 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. 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 m³ 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 occur 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

| Year | Journal | Volume, Issue, Pages |
|------|---------|----------------------|
| 1959 | Indian J. Met. Geophys. | 10, 2, p. 125 |
| 1960 | Ibid. | 11, 4, p. 323 |
| 1961 | Ibid. | 12, 4, p. 553 |
### APPENDIX I

| Time (sec) | \(I\) (mm/hr) | \(N\) (M² s⁻¹) | \(W\) (mm² m⁻³) | Time (sec) | \(I\) (mm/hr) | \(N\) (M² s⁻¹) | \(W\) (mm² m⁻³) |
|-----------|---------------|----------------|----------------|-----------|---------------|----------------|----------------|
| 31 AUGUST 1956 | | | | 29 SEPTEMBER 1956 (contd) | | | |
| 0 | 3.7 | 164 | 26 | 149 | 907 | 1.9 | 1043 | 372 | 124 |
| 35 | 10.1 | 445 | 67 | 414 | 945 | 1.47 | 1022 | 390 | 106 |
| 83 | 14.6 | 365 | 54 | 547 | 988 | 0.75 | 650 | 237 | 59 |
| 119 | 13.2 | 451 | 67 | 502 | 1040 | 2.93 | 1802 | 460 | 196 |
| 152 | 9.1 | 512 | 81 | 350 | 1077 | 1.95 | 1332 | 446 | 145 |
| 190 | 4.7 | 299 | 49 | 201 | 1112 | 2.60 | 1355 | 417 | 175 |
| 225 | 2.5 | 413 | 101 | 128 | 1152 | 2.50 | 1519 | 484 | 177 |
| 262 | 1.1 | 363 | 138 | 61 | 1187 | 3.25 | 1816 | 615 | 239 |
| 300 | 0.4 | 219 | 79 | 24 | 1223 | 1.44 | 1180 | 406 | 114 |
| 348 | 0.5 | 213 | 78 | 27 | 1263 | 0.73 | 949 | 317 | 66 |
| 396 | 0.6 | 236 | 109 | 32 | 1302 | 0.53 | 724 | 287 | 50 |
| 449 | 3.7 | 260 | 107 | 78 | 1346 | 0.35 | 544 | 336 | 35 |
| 494 | 3.9 | 339 | 147 | 132 | 1392 | 0.25 | 367 | 163 | 24 |
| 538 | 20.1 | 1211 | 471 | 731 | 1450 | 0.19 | 245 | 123 | 16 |
| 572 | 15.4 | 1116 | 515 | 748 | 1523 | 0.28 | 152 | 61 | 18 |
| 605 | 17.5 | 1858 | 904 | 683 | 1595 | 0.17 | 121 | 45 | 11 |
| 639 | 34.4 | 1366 | 501 | 1184 | 1678 | 1.01 | 141 | 31 | 46 |
| 674 | 50.8 | 2334 | 876 | 1863 | 1788 | 1.60 | 296 | 79 | 67 |
| 706 | 28.2 | 1951 | 555 | 1055 | 1793 | 2.50 | 310 | 69 | 109 |
| 737 | 40.7 | 2805 | 714 | 1564 | 1832 | 2.33 | 296 | 61 | 102 |
| 768 | 50.0 | 2997 | 765 | 1955 | 1880 | 2.40 | 287 | 71 | 101 |
| 817 | 67.4 | 5660 | 2039 | 2531 | 1923 | 1.60 | 235 | 55 | 70 |
| 857 | 36.4 | 3142 | 930 | 1351 | | | | |
| 890 | 35.6 | 2987 | 768 | 1464 | | | | |
| 27 SEPTEMBER 1956 | | | | | 0 | 2.47 | 1530 | 640 | 103 |
| 90 | 7.6 | 206 | 43 | 264 | 37 | 1.18 | 731 | 237 | 84 |
| 90 | 24.0 | 408 | 71 | 725 | 72 | 4.0 | 1778 | 488 | 265 |
| 123 | 35.7 | 257 | 43 | 1123 | 108 | 5.0 | 1447 | 341 | 324 |
| 155 | 5.8 | 123 | 33 | 181 | 140 | 4.9 | 1506 | 495 | 285 |
| 192 | 19.0 | 404 | 104 | 628 | 174 | 11.9 | 3090 | 720 | 673 |
| 223 | 19.7 | 484 | 93 | 699 | 213 | 5.5 | 1987 | 493 | 341 |
| 252 | 25.2 | 956 | 183 | 915 | 242 | 3.0 | 1462 | 436 | 202 |
| 280 | 25.0 | 1364 | 309 | 919 | 274 | 2.3 | 1132 | 330 | 155 |
| 310 | 21.4 | 847 | 162 | 798 | 314 | 2.3 | 1232 | 357 | 160 |
| 342 | 25.6 | 1139 | 300 | 905 | 344 | 2.47 | 1275 | 378 | 168 |
| 375 | 25.8 | 999 | 204 | 941 | 379 | 1.80 | 1140 | 340 | 122 |
| 403 | 18.7 | 341 | 106 | 746 | 422 | 1.82 | 1413 | 485 | 141 |
| 435 | 19.4 | 1793 | 429 | 812 | 454 | 2.90 | 1405 | 441 | 102 |
| 465 | 29.7 | 2717 | 629 | 1264 | 488 | 1.90 | 1518 | 555 | 146 |
| 500 | 30.7 | 2486 | 597 | 1267 | 522 | 1.90 | 1219 | 356 | 141 |
| 530 | 50.0 | 2871 | 573 | 1953 | 553 | 5.5 | 328 | 57 | 235 |
| 590 | 29.4 | 3201 | 835 | 1253 | 585 | 8.2 | 478 | 82 | 283 |
| 597 | 14.5 | 2093 | 572 | 652 | 655 | 16.1 | 1666 | 478 | 609 |
| 630 | 3.3 | 1785 | 612 | 223 | 724 | 39.5 | 1620 | 449 | 1479 |
| 685 | 3.5 | 1410 | 395 | 212 | 765 | 71.2 | 3679 | 719 | 2851 |
| 747 | 2.1 | 1408 | 470 | 155 | 840 | 7.2 | 2620 | 844 | 422 |
| 785 | 1.3 | 1292 | 499 | 111 | 900 | 9.9 | 2165 | 548 | 520 |
| 828 | 1.5 | 1354 | 527 | 118 | 957 | 5.1 | 1730 | 500 | 300 |
| 870 | 2.4 | 1992 | 643 | 170 | 1012 | 3.9 | 2167 | 687 | 269 |
\begin{table}
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\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|}
\hline
Time (sec) & \(I\) (mm/hr) & \(N\) (M\(^{-2}\) sec\(^{-1}\)) & \(n\) (m\(^2\)) & \(W\) (mm\(^3\) m\(^{-2}\)) & Time (sec) & \(I\) (mm/hr) & \(N\) (M\(^{-2}\) sec\(^{-1}\)) & \(n\) (m\(^2\)) & \(W\) (mm\(^3\) m\(^{-2}\)) \\
\hline
27 SEPTEMBER (contd) & & & & & 8 OCTOBER 1956 (contd) & & & & \\
1139 & 1.26 & 937 & 294 & 98 & & & & \\
1196 & 1.60 & 1452 & 444 & 131 & & & & \\
1260 & 0.79 & 1168 & 481 & 77 & & & & \\
1310 & 0.56 & 1194 & 479 & 87 & & & & \\
1377 & 0.85 & 1038 & 490 & 79 & & & & \\
1429 & 0.47 & 880 & 399 & 50 & & & & \\
1475 & 0.69 & 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 & 469 & 93 & & & & \\
1770 & 1.00 & 944 & 395 & 67 & & & & \\
1827 & 1.00 & 1321 & 534 & 73 & & & & \\
1892 & 1.40 & 1253 & 427 & 116 & & & & \\
1990 & 0.30 & 504 & 259 & 33 & & & & \\
8 OCTOBER 1956 & & & & & & & & & \\
0 & 57.5 & 3782 & 848 & 2288 & & & & \\
40 & 83.0 & 4256 & 1044 & 2174 & & & & \\
85 & 40.2 & 5475 & 1686 & 1988 & & & & \\
120 & 21.1 & 3644 & 1303 & 980 & & & & \\
160 & 39.7 & 4233 & 1179 & 1557 & & & & \\
205 & 58.4 & 5308 & 1688 & 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 & 1889 & 458 & & & & \\
485 & 4.0 & 2275 & 813 & 269 & & & & \\
530 & 4.9 & 1757 & 516 & 290 & & & & \\
585 & 14.9 & 2537 & 935 & 302 & & & & \\
620 & 20.7 & 3873 & 1593 & 1066 & & & & \\
660 & 7.7 & 1797 & 522 & 411 & & & & \\
700 & 10.8 & 2564 & 634 & 274 & & & & \\
745 & 15.6 & 2754 & 546 & 750 & & & & \\
785 & 18.2 & 5085 & 1966 & 949 & & & & \\
840 & 19.9 & 4089 & 1258 & 1020 & & & & \\
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