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Final Report

RAINDROP-SIZE STUDIES

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ABSTRACT

Qualitative analysis of raindrop-size distributions in heavy showers indicates that some of their prominent features can be explained by the combined effects of wind-shear sorting of drops and of the splashing of large drops upon surface obstructions.

Computational studies which account for the effects of cloud-droplet accretion, raindrop coalescence, and evaporation processes indicate that, in steady-state rain, the origin of large drops lies in snow-aggregation processes above the melting layer. Extending this finding to speculate upon observed differences between heavy shower drop-size distributions in June as compared to October, it is suggested that the relative predominance of the ice-crystal or water-drop processes in convective storms may be indicated by features of the ground-level drop-size distributions.

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1. INTRODUCTION

Whereas the contract for which this report is the conclusion is formally a 1-year agreement, the instrumentation and the results reported herein represent the fruition of considerable previous effort some of which has been Air Force supported, but much of which received support from the U.S. Public Health Service, the Atomic Energy Commission, and the National Science Foundation. The material reported here is that mainly pertinent to two hypotheses which are set forth in the concluding section and which are based upon our experimental studies of raindrop-size distributions and our computational investigations of their evolution. Side investigations are not reported here for the sake of clarity.

2. RAINDROP-SIZE MEASUREMENT

The study of raindrop sizes began over 70 years ago with the studies of Lowe (1892). Interest in this work was indulged by means of manual measurements using impaction techniques (Lowe, 1892; Wiesner, 1895) and the ingenious flower-pellet method of Bentley (1904) until about 1908. A long lapse of activity then ensued until Kohler (1925) and Niederdorfer (1932) revived some interest in drop sizes. A vigorous renaissance in this area occurred in connection with the emergence of radar as a weather-monitoring device during and after World War II. Not until the late 1940's, however, were serious efforts made to adapt electronic and other modern techniques to the problem of obtaining routine raindrop-size measurements capable of representing rain quantitatively and continuously.

Of all the efforts in this area which have been supported with variable degrees of adequacy since about 1948, only two have produced data of significance in falling rain. One of these is the photographic technique of Jones and Dean (1953), and the other is the photoelectric method used for the present work.

2.1 THE PHOTOELECTRIC RAINDROP-SIZE SPECTROMETER

The spectrometer (Fig. 1) consists of two basic components: a light source which provides a collimated beam 0.5 cm thick by 4.0 cm high, and a photometer unit which views a segment of the light beam. The sensitive field defined by the intersection of the beam and the optical field of the photometer has dimensions of 10.0 by 3.5 by 0.5 cm. The unit is rotated about a vertical axis at a rate which causes the sensitive field to sweep out 9,330 cm^3 sec^{-1}. Raindrops traversed by the sensitive field scatter light to the photometer in proportion to their surface area. The electronic pulses thus produced are recorded as they occur by means of an oscillograph. Details are reported by Dingle and Schulte (1962).

Concentrations of drops of 0.5 mm and larger diameter have been found to vary from about 3,000 m^{-3} for the first few minutes of a thundershower of rainfall intensity greater than 50 mm hr^{-1}, to about 500 m^{-3} for rain with intensity less than 3 mm hr^{-1} from stratus-type clouds.

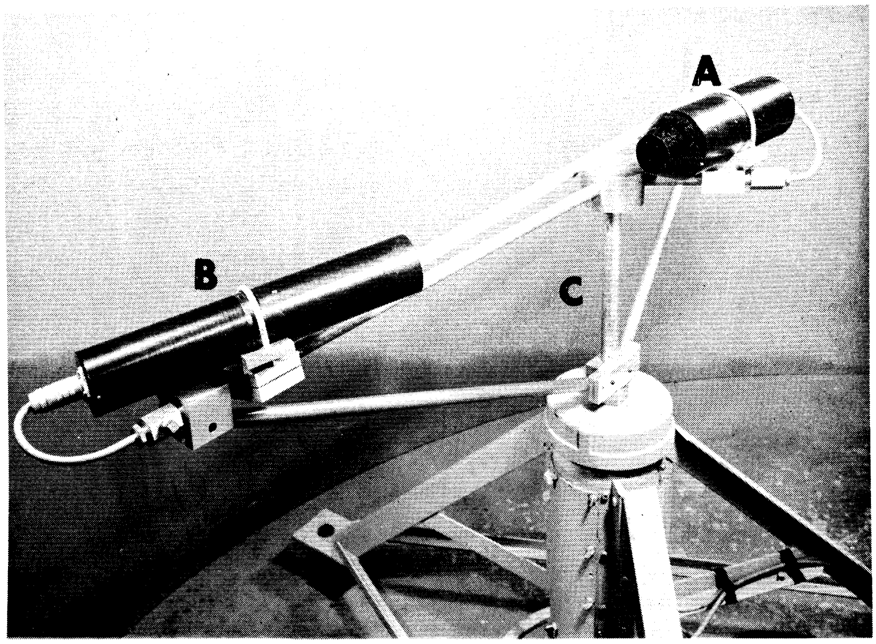

Fig. 1. The photoelectric raindrop-size spectrometer: (A) light source, (B) photometer, (C) vertical shaft and axis of rotation.

2.1.1 Form of Data Output

It is clear to the person practiced in these matters, that the oscillograph trace currently used does not provide for the most expeditious reduction and analysis of the field data. It does require a manual-visual digitization process which becomes tedious and takes time, but in return it presents all the information sensed by the instrument in a form well-suited to exploratory study of the character and distribution of drop sizes. Because this is virgin territory, this form of data is considered desirable for the present; because the oscillograph also offered the least expensive of the available alternatives, it was accepted.

2.1.2 Alternative Forms of Data Output

Since the signal generated at the photometer by each drop is an electronic pulse capable of activating the oscillograph galvanometer, it is also capable of activating other output devices. Essentially this means that the readout of data is limited only by the funds available for this part of the system.

Two items of information, the size (d^2) and the time of occurrence, are available for each drop. As they have been used to the present time, the drop sizes have been summarized by 0.1 mm or 0.2 mm diameter increments 1 min at a time for the most part. It appears at the present writing that greater detail than this is not particularly informative. Direct electronic digitalization of the pulses through a square-root amplifier and an associated bank of counters, summarized each minute in the form of an IBM card, is perfectly feasible using appropriate "off-the shelf" components. Such a system both reduces the error of measurement encountered using manual techniques and makes possible a reasonably prompt analysis of the results. In terms of the currently recognized need for raindrop-size data at various elevations in a storm, it is absolutely necessary that electronic digitalization and summarization in time be used to tidy the data accumulation process and to make current analysis possible. The photoelectric raindrop-size spectrometer is in principle ideally suited both to airborne operation and to appropriate digitalization of its primary output.

3. ANALYSIS OF RAINDROP-SIZES IN HEAVY SHOWERS

The raindrop-size spectra observed in three showers, exhibiting rainfall intensities of 2 to 3+ in./hr show some interesting contrasts which appear to show an important seasonal effect. The data presented for consideration below were gathered in (1) a thunderstorm associated with a cold front on 8 October 1959, (2) a heavy shower, without thunder, associated with a cold front on 23 October 1959, and (3) a thunderstorm associated with a pre-cold frontal squall line on 16 June 1960.

3.1 THUNDERSTORM OF 8 OCTOBER 1959

At noon on 8 October 1959 a low pressure system was centered over Minnesota, from which a cold front extended southward along the Mississippi River. The cyclone center moved northeastward at about 25 mi hr^{-1} and the associated cold front passed through Ann Arbor, Michigan, at about 2330 EST on 8 October. There was a very narrow band of showers along the cold front. The radar operated at Willow Run Airport, 10 mi ESE of Ann Arbor, showed that the line of showers was oriented from SSW to NNE and had a maximum width of about 20 mi. A series of stepped-gain measurements of echo intensities, a few minutes prior to the onset of rain, revealed that the cell which produced the shower in Ann Arbor was one of the two strongest cells in the area. The onset of this shower was quite abrupt. The isolated large drops which often appear at the beginning of a thundershower were not evident, but instead the initial rain comprised a wide range of raindrop sizes. Measurements of the raindrop-size spectra started with the first drops of rain.

The drop-size distributions were computed using 1-min samples each corresponding to a sample volume of 0.56 m^3. A plot of the intensities computed for this strom is shown in Fig. 2 (right). The grouping of intensities into four periods is a striking feature but it has not been observed in any other of the showers so far studied.

The distributions of raindrop sizes for each minute of this storm were plotted on semi-logarithmic paper. The consecutive 1-min samples which (1) represented approximately the same rainfall intensity and (2) were judged to have essentially the same drop-size distribution were averaged, and the resulting distributions are shown in Fig. 2 (left). Curve 1 in this figure is the average of the first 4 min of the storm when the rainfall intensity averaged 51.6 mm hr^{-1} and varied from 50.6 to 57.2 mm hr^{-1}. The general semi-logarithmic shape, but with a deficit of the middle-sized drops and an excess of small drops, has been observed by some others. As with the data of Atlas and Chmela (1957) the curve dips downward from semi-logarithmic at $D = D_0$, the median volume drop diameter.

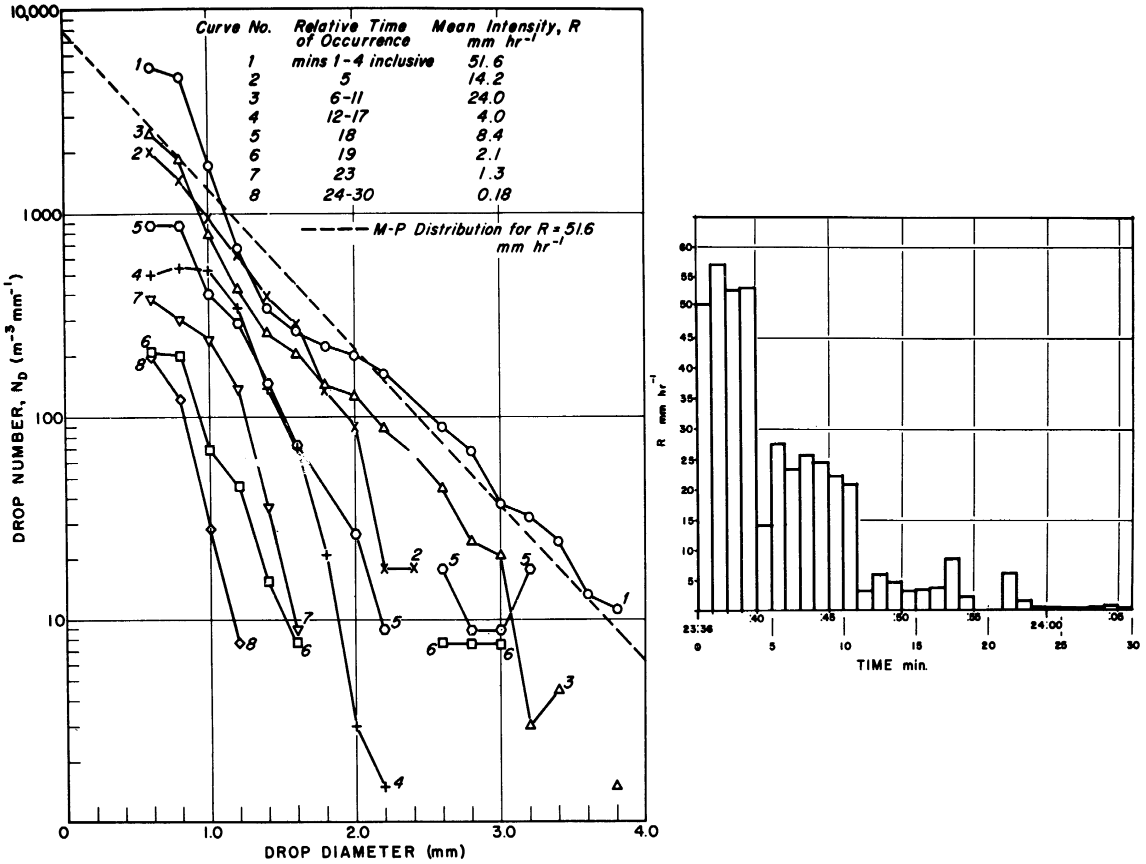

Fig. 2. Results for the 8 October thunderstorm: (left) drop-size distributions and (right) minute-by-minute rainfall intensities.

The dashed line represents the empirical formulation of Marshall and Palmer (1948) for a rain of 51.6 mm hr^{-1}. The Marshall-Palmer expression is:

$$N_D = N_0 \exp(-\lambda D)$$

where $N_D \Delta D$ is the number of drops per unit volume in the diameter interval between D and $D+\Delta D$, and λ is a function of rainfall intensity only.

The other grouped data are shown respectively by curves 3 (for minutes 6-11, incl.), 4 (for minutes 12-17, incl.), and 8 (for minutes 24-30, incl.).

Interesting details are shown by the relationships between intensity of rainfall, timing (or position) with respect to the principal elements of the rain system, and the raindrop-size distribution. Although curve 2 represents rainfall of only 14.2 mm hr^{-1} (averaged over 1 min), it contains more water in the 1.4 and 1.6 mm drop sizes than the 51.6 mm hr^{-1} shower which preceded, and more in the sizes between 1.0 and 1.8 mm than the 24.0 mm hr^{-1} shower which followed. Obviously, the principal decrease of intensity was the result of a depletion of the number of drops larger than 2 mm in diameter.

Curve 6, on the other hand, appears to contain some rain characteristic of the residual drizzle from the stable after portions of a rainstorm (as curve 8) plus some characteristic of the preceding brief shower (curve 5). In summary it appears that, in the light rain portions, the large proportion of the water resides in drop sizes of 1.0 to 2.0 mm which appear in the heavier portions to be depleted in favor of the large (above 2.0 mm) drops.

3.2 HEAVY SHOWER, WITHOUT THUNDER, OF 23 OCTOBER 1959

The synoptic picture on 23 October was quite similar to that of 8 October, the common features being a low-pressure center moving northeastward through Minnesota and over Lake Superior while a cold front moved steadily eastward through Lower Michigan reaching Ann Arbor at about 2230 EST. The main difference between the two days is found in that the pressure trough associated with the cold front was narrow and sharp in the earlier storm, whereas that of 23 October was very broad. Consequently the weather in Ann Arbor during the evening of 23 October consisted of numerous showers extending over a period of about 4 hr. At about 2000 EST, PPI data from the Willow Run radar station indicated three distinct bands of showers oriented in a SSW-NNE line. The line farthest west was about 22 mi from Ann Arbor, and the spacing between the bands was about 15 mi. These three bands were observed to move eastward with a fairly constant speed but as they passed 10-15 mi east of Ann Arbor, their banded structure disappeared and only isolated cells remained. It appeared that very small pressure waves or instability lines were being propagated ahead of the cold front, and were then dissipating approximately 100 mi east of the front. At 2040 EST, the cold front appeared as a fourth band about 40 mi west of Ann Arbor. Its orientation was N-S and it was moving eastward at just over 20 mi hr^{-1}.

Drop-size measurements began at 2131 hr and continued until 2301 hr. The computed 1-min intensities of the rain are shown in Fig. 3, which indicates the showery nature of the rainfall. The 1-min intensity of 79.5 mm hr^{-1} beginning at 2235 occurred at about the time of the passage of the cold front, and is the most intense minute of rainfall that we have recorded. The regularity of the intensities over 4-6 min intervals shown in Fig. 2 for the 8 October storm is not evident at all in the showers of 23 October.

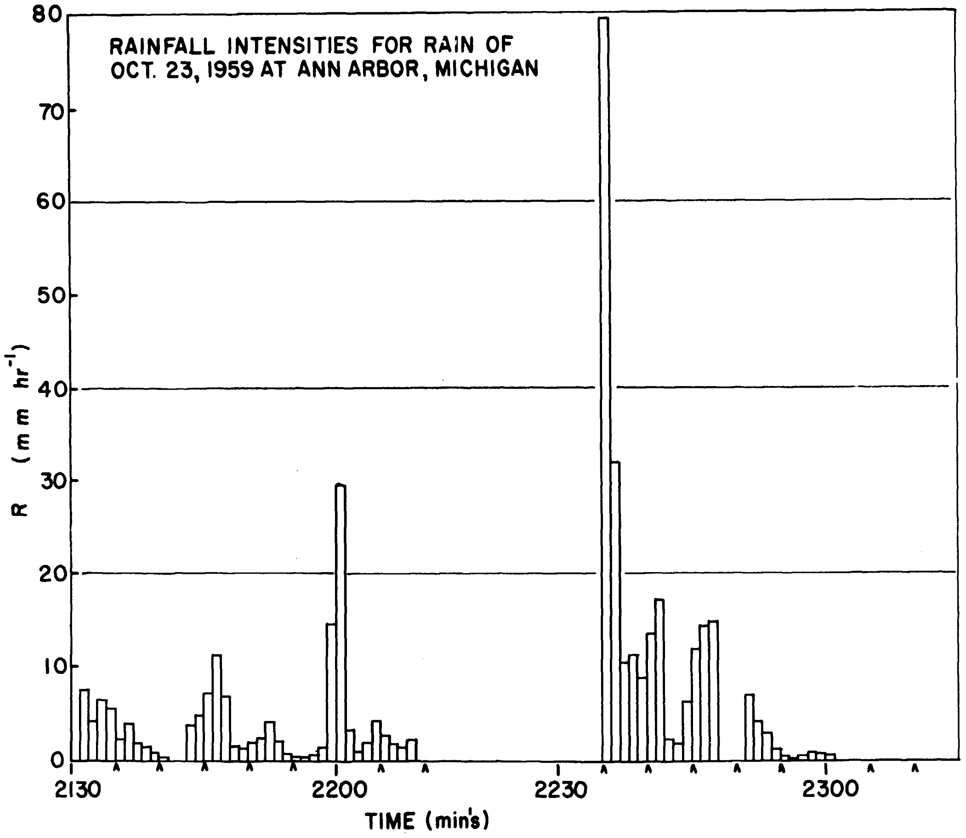

Fig. 3. Minute-by-minute intensities of rainfall showing the sharp 79.5 mm hr^{-1} shower of 23 October 1959.

The drop-size distributions were again plotted by 1-min intervals and analyzed. Those shown in Fig. 4 are (1) that for the 1 min of 79.5 mm hr^{-1} intensity, (2) that for the next minute during which the intensity was 31.7 mm hr^{-1}, and (3) that for minutes 3-6, inclusive, which averaged 10.9 mm hr^{-1}.

3.3 THUNDERSTORM OF 16 JUNE 1960

At 2400 EST on 15 June a low pressure center was situated over northeastern Nebraska with an associated cold front stretching southward. An active squall line was about 150 mi east of the cold front. The storm center moved toward ENE at about 25 mi hr^{-1}, arriving over Lake Huron by 2400 EST on 16 June. The squall line passed Ann Arbor, Michigan, about 1700 EST on 16 June giving about 30 mm of rain in 1 hr. The intensity of rainfall was 60 to 70 mm hr^{-1} over several minutes of the storm. The rain stopped at 1800 hr, but with the approach of the cold front, rain began again at 1945 hr and 8 mm of additional rain fell over the next hour.

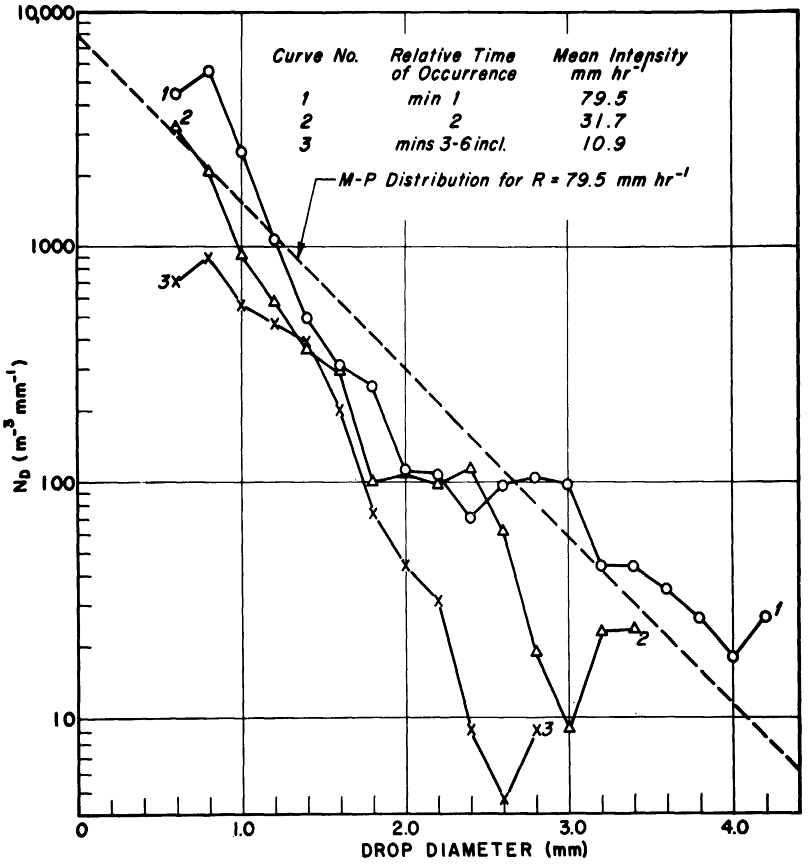

Fig. 4. Drop-size distributions for the heavy shower of 23 October 1959.

A plot of the intensity of rainfall during the storm is shown in Fig. 5. The showery nature of the rain is clearly indicated. The showers prior to 1700 EST were associated with isolated cells in the warm air, whereas the heavy shower beginning at 1704 hr was due to the passage of the squall line. Radar information available for the duration of the storm showed that the initial rain in Ann Arbor (at 1604 hr) came from the northwest corner of a fairly large convective cell which was moving toward the northeast. Another shower arrived over Ann Arbor at about 1625 hr when an intensity of 39.5 mm hr^{-1} was recorded, but the most interesting part of the rain was that which occurred after 1704 hr. Two major cells of convection are clearly evident in Fig. 5. One minute intensities of over 40 mm hr^{-1} were observed, separated by 3 min of rain at a rate less than 9 mm hr^{-1}. Note particularly the pre- and post-shower light rain periods (1704, 1719; 1705, 1718).

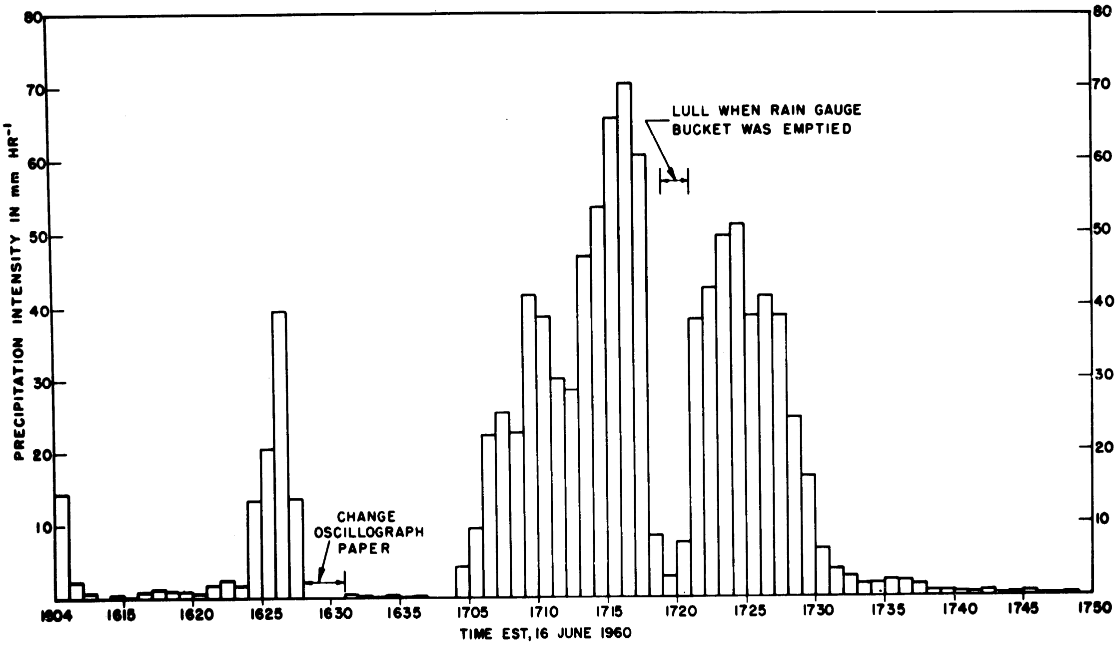

Fig. 5. Minute-by-minute intensities of rainfall for the 16 June 1960 series of showers. Note the break in the time scale between 1635 and 1705 EST.

Distributions of raindrop sizes were obtained for each minute of rain recorded. In Fig. 6, comparisons of pairs of distributions are made. In the top of Fig. 6 the first minute of the main shower, beginning at 1704 EST is represented by curve 1. Its main characteristics are the relatively greater numbers of large drops and lesser numbers of small drops. This verifies the familiar observation of isolated large drops at the beginning of a shower. Curve 2, the distribution for the minute beginning at 1719

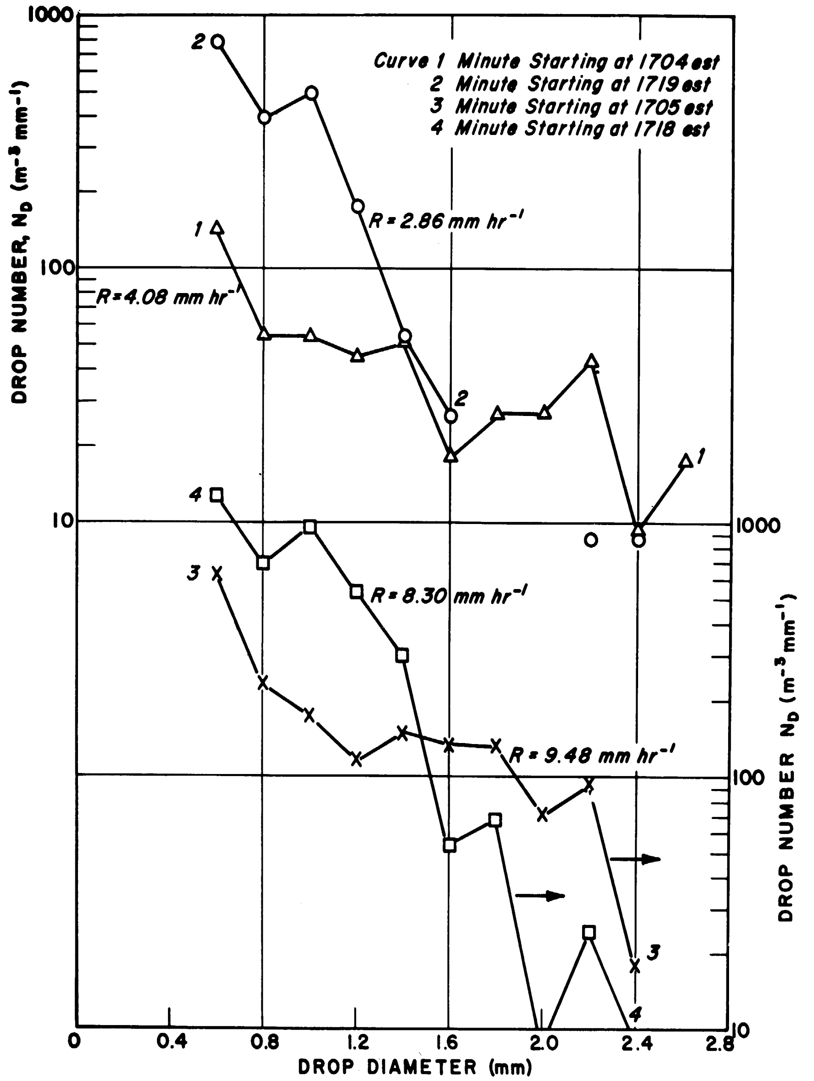

Fig. 6. Raindrop-size distributions for comparable intensities of rainfall before and after the main shower of 16 June 1960. The pre-shower spectra show a relative excess of large drops and a deficit of small ones.

hr, is for the rain occurring near the end of the first convective cell and is drawn so that a direct comparison can be made with curve 1. It is clear that the distributions are quite distinct even though the intensities are in the same range (i.e., 4.1 mm hr^{-1} for curve 1 and 2.9 mm hr^{-1} for curve 2). The bottom of Fig. 6 gives a similar comparison between the 1-min distributions beginning at 1705 hr and 1718 hr, and these are labelled curve 3 and curve 4, respectively. The relationship of these distributions to the entire shower can be seen by referring to Fig. 5.

The remainder of the distributions between 1706 hr and 1730 hr were plotted minute by minute and analyzed. Although minor differences were observed, these were not considered significant for the present purpose and the distributions were consequently grouped into various intensity intervals. Four grouped distributions are shown in Fig. 7. These have average intensities of 65.5, 50.2, 39.9, and 24.2 mm hr^{-1} and account for all minutes of the shower between 1706 hr and 1730 hr which had intensities greater than 16.5 mm hr^{-1}. The M-P distribution function for the average of the three most intense minutes of the storm (65.5 mm hr^{-1}) is shown by the dashed curve in Fig. 7.

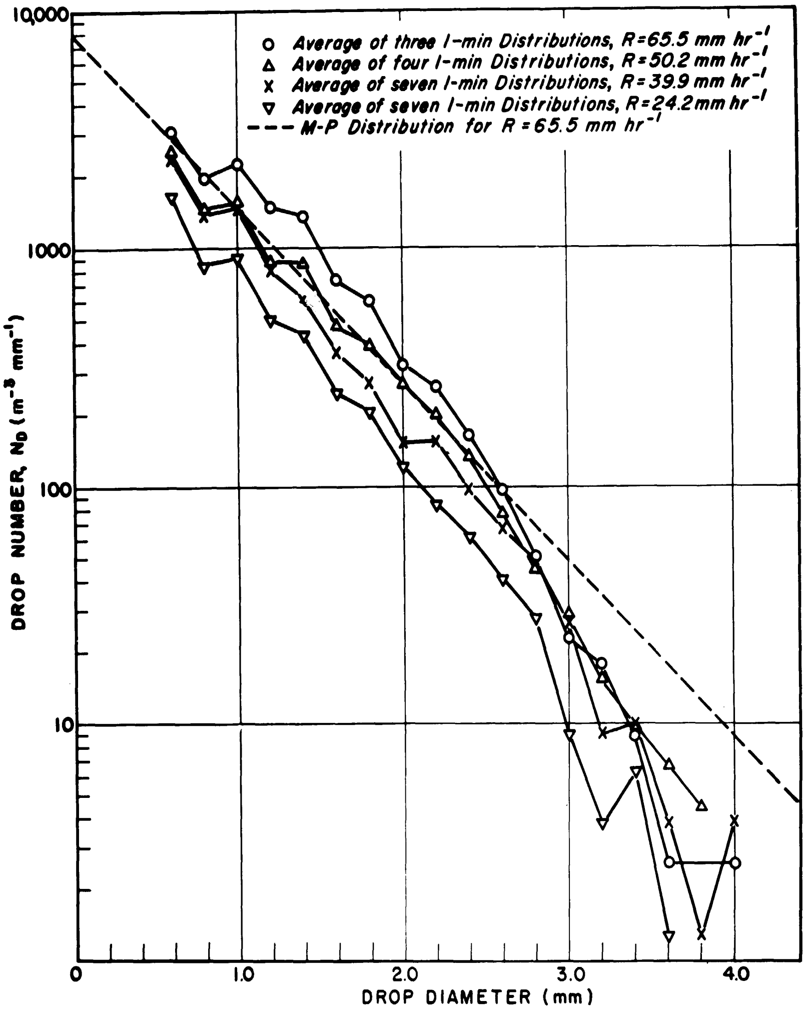

Fig. 7. Combined drop-size spectra for the showers of 16 June 1960 in the interval 1706 to 1730 EST (see Fig. 5). The 1-min spectra have been grouped according to rainfall intensity intervals.

Especially pertinent to the present discussion is the marked contrast of the spectra for the two heaviest rain categories in this shower (65.5 and 50.2 mm hr^{-1}) with those of the October showers (51.6 and 75.9 mm hr^{-1}). Whereas the October showers both exhibit the "middle size-range deficit" relative to a semilogarithmic distribution (Dingle and Hardy, 1962), the June shower exhibits the opposite.

3.4 DISCUSSION

Several points of interest are raised by comparing the above data. In interpreting the contrasts among these showers, two points appear to stand out:

(1) that wind-shear sorting of raindrops may tend to give an excess of large drops in the forepart of a storm, and

(2) that in those parts of a rain shower that have an excess of large drops, an excess of small drops may be generated by (a) aerodynamic breakup of large drops, and (b) splattering of large drops upon impact at the surface.

Using the best available information on the wind profiles, namely the Flint, Michigan, soundings, computations of the wind-shear sorting of drops falling from the cloud base were made for each of the above weather events. Figure 8 gives the results of these computations for drops of 4.0, 2.0 and 0.5 mm diameter, respectively. The wind-shear sorting in the 23 October rain appears to be quite different from that in the other rains; however, the drop-size distributions of the heaviest rains of 8 and 23 October are strongly similar in character. Noting that the 16 June shower is intermediate between these in intensity, but that its maximum intensity occurred toward the end rather than the beginning of the shower, one must anticipate less evidence of the wind-shear sorting process in this case.

Considering the contributions of aerodynamic breakup and splashing of large drops, it is not possible on the basis of the present data to determine which process predominates. Both are associated with large drops, and in the October rains, a relative excess of large and of small drops appears, whereas in the June shower the relative excess numbers of drops appears in the middle size range. Thus, wind-shear sorting of the falling rain may affect the observations so as to give an excess of large drops in the forepart of a rain shower, and the increased aerodynamic breakup and/or splash of the large drops may contribute to the observed small drop excess in the same portions of the shower.

Aside from the above considerations, that of the seasonal differences between June and October may be significant in explaining the observed

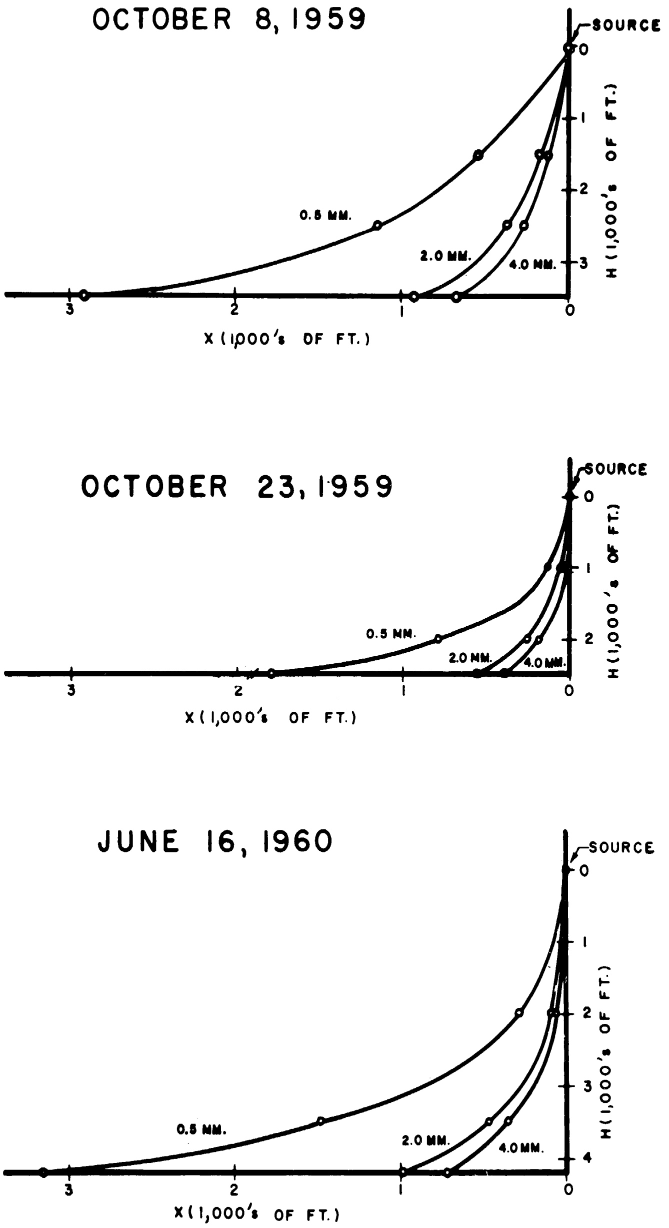

Fig. 8. Trajectories of specified drops with respect to the cloud base under the influence of wind shear for the showers of 8 and 23 October 1959, and 16 June 1960.

prominent differences among the drop-size spectra. Assuming that showers of comparable 1-min-average intensities are generated by clouds of comparable depth, the level of the melting region will reflect seasonal changes and will govern the extent of the snow-aggregation process above, and the water-drop processes below that level. The influence of these effects upon shower drop sizes is not easily analyzed because of the important role of turbulence in these storms: however, our analyses of steady-state-rain systems are suggestive.

4. STUDIES OF THE EVOLUTION OF RAIN

Our observations give us detailed information about the end product of a rain-producing system. To infer information about the origin of the rain it appears useful to pursue a backward course of reasoning as far as applications of theory can be made profitably. Three processes can be traced quite well: (1) evaporation in the unsaturated air below the cloud base, (2) accretion of cloud droplets by the falling raindrops, and (3) coalescence of raindrops with each other. Going back one step further, the melting layer is encountered in middle-latitude stratiform systems. Above this level, the precipitation is in the form of snow, and snow aggregates of widely varying size are formed. In falling through the melting layer, these become the initial raindrop population at the top of the water cloud.

By assuming such a series of processes operating so that the liquid water and drop-size spectrum are exactly restored at each level as the rain falls, its properties as a rain-producing system may be examined by the use of the electronic computer.

4.1 DIGITAL EXPERIMENTS

Hardy (1962,1963) presents a detailed account of these studies. To start a computational experiment on steady state rain, a raindrop-size distribution is assumed for the melting level. As this rain falls through and below a cloud, the evolution of the drop-size distribution under coalescence, accretion and evaporation processes is computed.

The computational process is not simple because it involves the modification of the size spectrum, expressed by fixed finite size intervals, as the drops at first grow by the two processes of accretion and coalescence working at the same time, and later as they lose mass by evaporation. The nature of the solution that was finally found to be adequate for the growth phase is indicated diagrammatically in the top of Fig. 9. Preliminary studies showed that the coalescence process was adequately represented by iterating over successive 100-m thick layers, whereas 200-m thick layers were sufficiently refined for the accretion calculations. The effects of the two processes working together were approximated very well by the procedure indicated in the diagram.

Since the combination of drops did not generally conform to the initially assumed size increments, it was necessary to adjust the evolving spectrum of drop sizes by a pro-rating scheme which is indicated in the

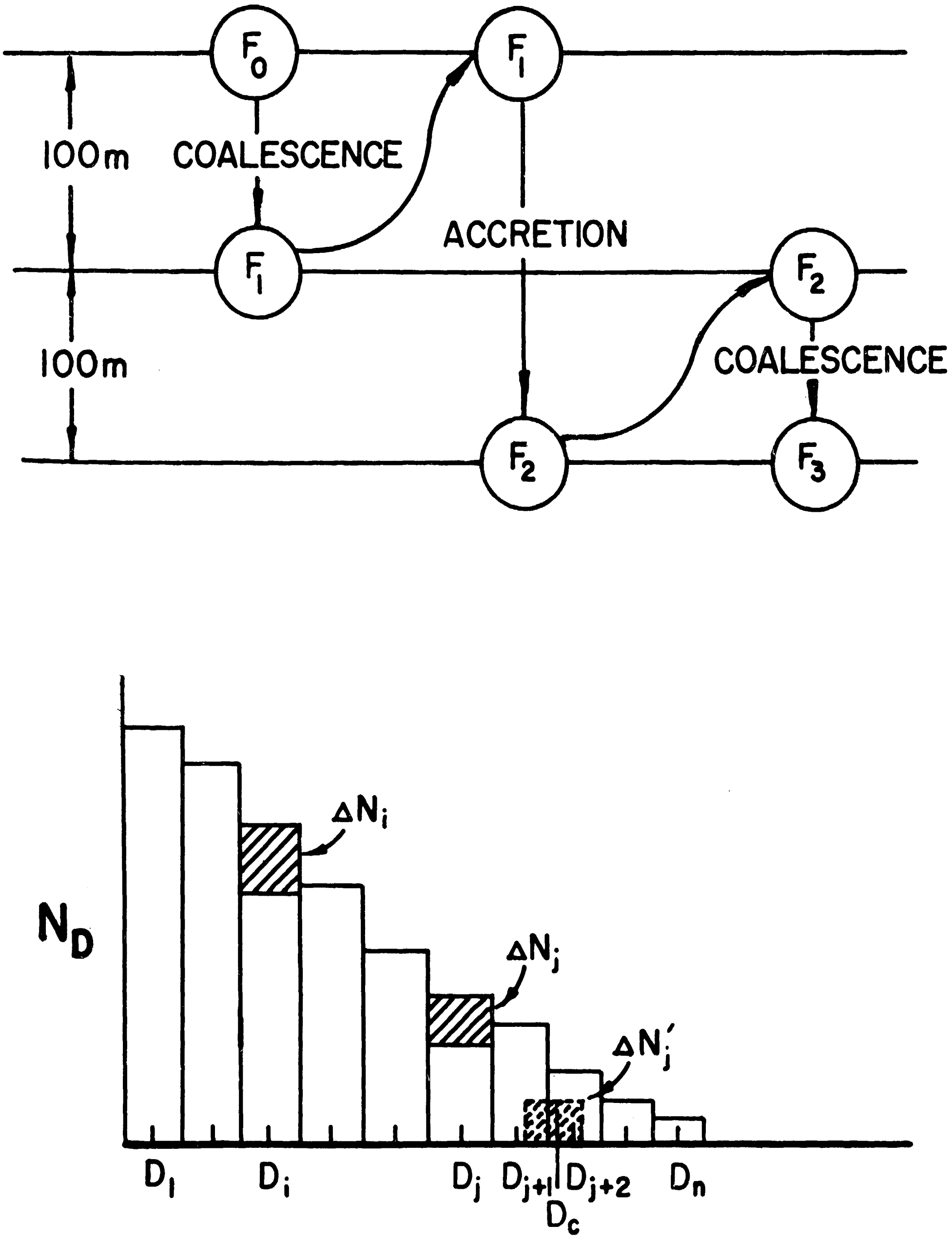

Fig. 9. Illustration of the computational steps used to account for coalescence and accretion effects (top) and to adjust the evolving drop-size spectrum (bottom).

lower part of Fig. 9. The method was tested against computations of a similar nature that were done manually by Mason and Ramanadham (1954). giving the results shown in Fig. 10. The difference between the two computed curves are explained in terms of the more detailed structure of the model used for the computer solution (see Hardy, 1962).

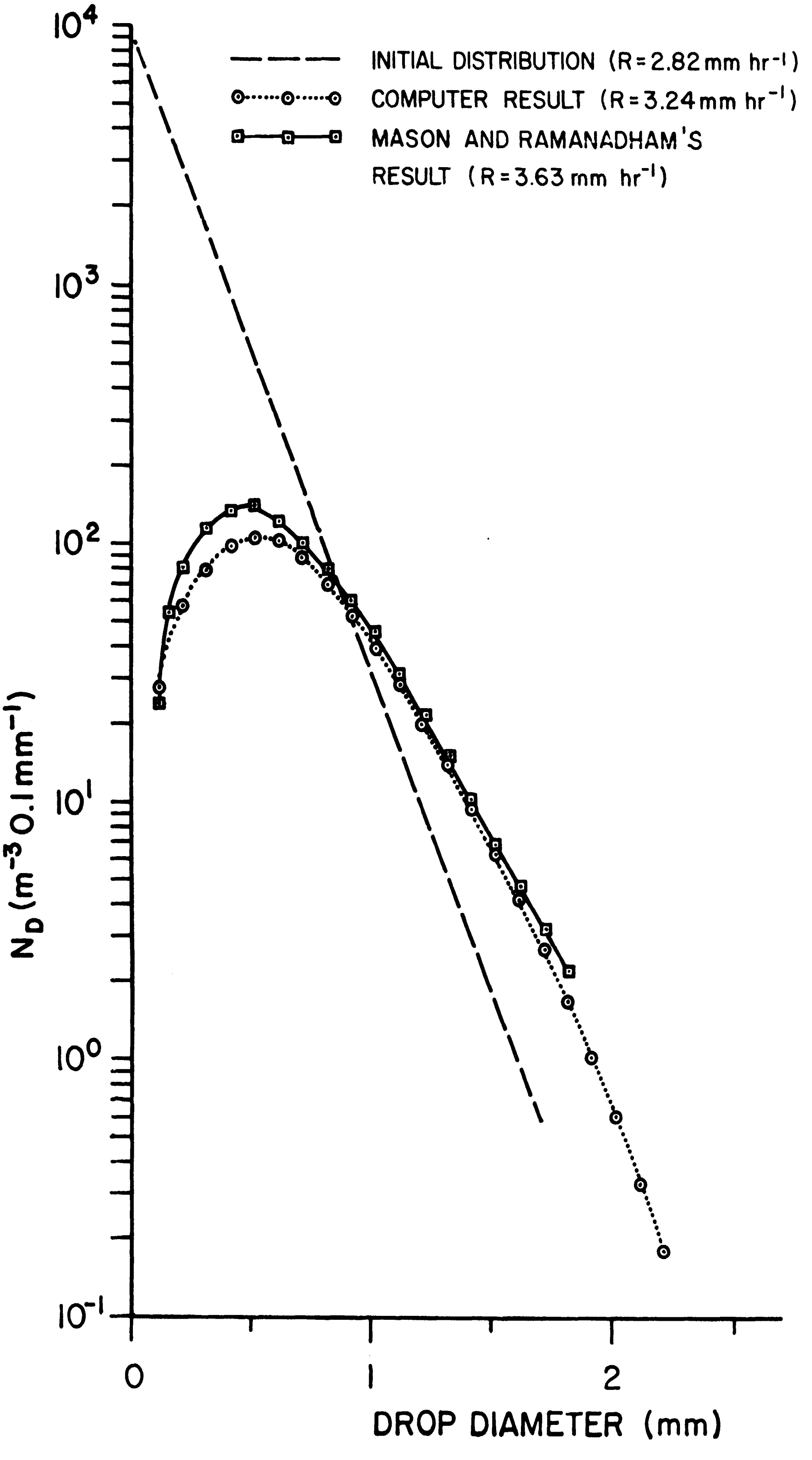

Fig. 10. Change of drop-size distribution after a fall of 1 km through cloud plus a fall of 1 km through an atmosphere at 15 C having 90 per cent relative humidity. Comparison against the results of Mason and Ramanadham (1954).

4.2 ESTIMATION OF THE DROP-SIZE SPECTRUM ALOFT FROM THAT OBSERVED AT THE SURFACE

Using the method outlined above, and relating the computations to conditions accompanying an observed occurrence of nearly steady-state rain, it was readily found that an assumed size distribution of the type formulated by Marshall and Palmer (1948) at the melting level could not evolve by the processes we have discussed into size distributions such as those recorded by the raindrop-size spectrometer. Hardy (1962) chose specifically the observed size spectrum for 31 July 1961 at Flagstaff, Arizona. Computations for the conditions of this place and time, using an assumed Marshall-Palmer size spectrum at the melting level, led to the result shown in Fig. 11. Successive adjustments of the assumed initial drop-size spectrum and cloud liquid water content led finally to the results shown in Fig. 12.

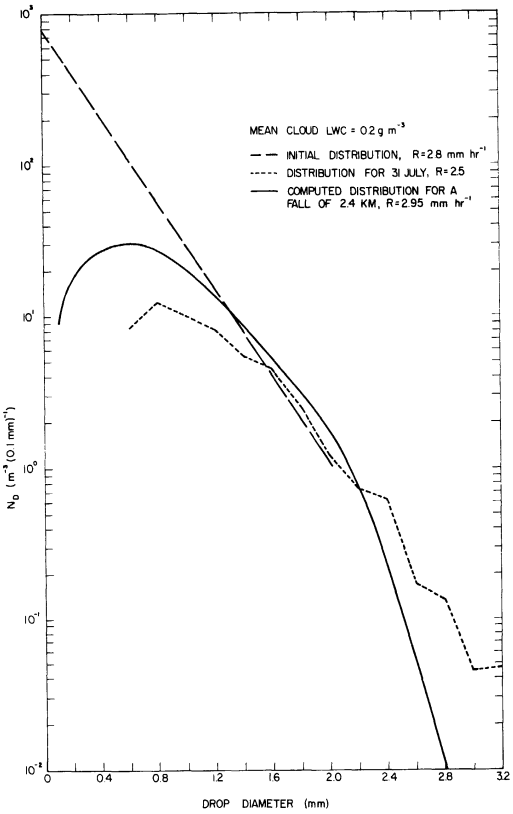

Fig. 11. Comparison of observed drop-size spectrum with that computed for the conditions of the day assuming a Marshall-Palmer distribution at the melting level. Flagstaff, Arizona, 31 July 1961.

A comparison of the assumed initial drop-size spectra shown in Figs. 11 and 12 shows that it is necessary to have a larger number of big drops

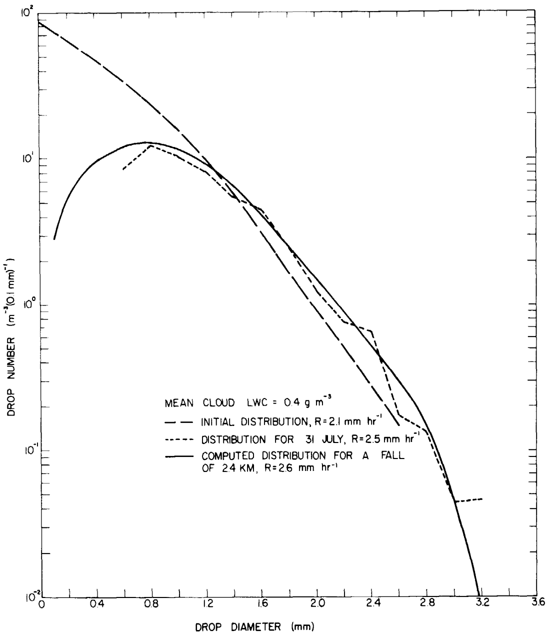

Fig. 12. Final result of cut-and-try experiments showing an initial melting level drop-size distribution that could yield the observed ground level size spectrum under the conditions of the day. Flagstaff, Arizona, 31 July 1961.

initially than is represented by a Marshall-Palmer distribution. The most likely source of these is found in the melting of snowflake aggregates. As these fall from the melting layer, the smallest drops are depleted by coalescence and evaporation, whereas the large drops are augmented by accretion and coalescence, and reduced only slightly by evaporation. The drop-size spectra observed at the ground therefore reflect strongly the influence of the snow-aggregation processes above the melting layer.

5. CONCLUSIONS

5.1 HYPOTHESIS 1

The peculiar form of the ground-level drop-size distribution that is frequently observed in a heavy shower (Figs. 2 and 4) may be explained in terms of (1) wind-shear sorting of the drops which provides a large proportion of big drops, and (2) the splash of these same big drops as they impact upon the ground, etc., thus generating a large number of small drops.

It is not possible to eliminate all suspicion of splash from ground-level drop-size observations although it can be controlled somewhat. Verification of this hypothesis requires the observation of drop-size spectra at various elevations above the ground.

5.2 HYPOTHESIS 2

In steady-state rain, computations show that large drops observed at ground-level must be produced from a broad drop-size distribution originating at the melting level. It is implicit that this upper level size spectrum in turn reflects the extent to which snow agglomerates develop above the melting layer.

Although the implications of these computations are less clear with respect to the evolution of heavy shower rain, the prominent differences observed between the drop-size spectra of the October showers (of intensity 51.6 and 79.5 mm hr^{-1}, respectively) and those of the June shower (of 65.5 and 50.2 mm hr^{-1} intensity) may be related to the extend of snow aggregation and the level of melting in the respective rain systems. By virtue of the seasonal temperature differences, the melting region was lower in the October storms than in the June shower, then the snow-cloud was probably also deeper in the October than in the June rains, and the water-cloud less deep. These conditions suggest a reduced snow-aggregation effect in the June rain relative to those of October. They also suggest that the fall-distance through which the cold-season raindrops must remain intact without benefit of a residual ice skeleton was small compared to that for the warm-season rain.

5.3 OBSERVATION ON THE ROLE OF THUNDERSTORM ELECTRICITY

The similarity of form of the size distribution in the two October showers suggests that thunderstorm electricity has no important influence over the final stages of drop-size spectrum development. Because other factors may also be involved, this point should be studied carefully in additional heavy shower situations.

5.4 SUMMARIZATION

Although we are only beginning to explore the new information available to us by virtue of raindrop-size observations, these findings indicate a great deal of potential of our methods for the study of water in the air.

Important gaps in our information remain. The most crucial of these at the present time appear to be

(1) adequately detailed cloud liquid water measurements,

(2) raindrop-size spectra aloft, and

(3) knowledge of the cloud and precipitation characteristics above the melting level.

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