Droplet Sampling in Cumulus Clouds

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Abstract

An analysis is made of 150 cloud droplet samples obtained by the impaction method in cumulus clouds varying in vertical depth from 750 to 7000 ft.

From a consideration of the spectra relating numbers of droplets with droplet diameter, a mode diameter of about 8 μ is found. A secondary mode diameter of about 15 μ is in evidence in some clouds. In the main numbers of droplets are between 100 and 300 per cm^3 but extreme values of about 20 and 1000 occur.

Spectra relating water content with droplet diameter show that in clouds between about 750 and 2500 ft thick the mode diameter is about 8 μ, whereas in clouds between about 4000 and 7000 ft thick the mode diameter is about 18 μ. The highest value of water content found is about 5 g m^{-3}.

Evidence is found that mean volume diameter tends to increase with height above cloud base and that high values of water content are due to larger droplets rather than to greater numbers of droplets per cm^3.

A droplet distribution formula given by Best is examined and the constants involved are found to depend on the largest size of droplet present.

1. Introduction

A method of sampling cloud droplets using magnesium oxide coated slides has been described by MAZUR (1943). Results obtained using this method for sampling in stratocumulus clouds have been given by FRITH (1951). In this paper, which represents an extension of Frith's work, results obtained from droplet sampling in cumulus clouds are presented and examined. The samples were taken on ten flights during the summer of 1951.

2. Experimental Technique

The instrument used for sampling the droplets was the same as that used and described by Frith. Briefly, it contains a slot into which a magnesium oxide coated glass slide can be fitted and a shutter mechanism which can expose the slide for a certain time interval. The impactor was pushed through an open window near the second pilot's seat and, when flying through a suitable cloud, operation of the shutter would expose the slide to the droplets. The effect of the droplets striking the magnesium oxide layer is to cause small pits. After each flight the slides were microphotographed and counts were made of the numbers of pits having diameters falling between certain specified limits.

The exposure interval of the instrument given by Frith was 0.010 sec but a subsequent calibration has given the value of 0.013 sec. Furthermore, the value used by Frith for the ratio of the diameter of a droplet to that of the pit made by it was 0.85. Subsequent evidence (LEVINE and KLEINKNECHT 1951) suggests that this figure should be 0.71. The values of 0.013 and 0.71 have been used for the exposure time and ratio of droplet diameter to pit diameter respectively in this report.

The camera used to photograph the slides contained a graticule on which were a number of circles of decreasing diameter so that a photograph of the graticule was superimposed on each droplet sample. After making allowance for the factor 0.71 referred to above, the droplet diameters corresponding to the series of graticule circles were 5.3, 7.5, 10.4, 14.9, 21.4, 29.9, 42.1, 59.9, 84.0 and 119 microns. The droplets were counted by assessing the numbers which, as far as could be judged by eye, had approximately the same diameters as the graticule circles. The average number of droplets counted on all the samples was about 400, the largest being 2,034 and the smallest 42.

According to figures given by MAY (1945) and quoted by Frith, this type of impactor is 100 per cent efficient in collecting droplets having diameters of 4.5 μ and greater but the efficiency of catch falls off to 10 per cent for droplets having diameters as small as 1.5 μ. The smallest size range used for droplet counting was 0—5.3 μ so that for size ranges greater than this the counts can be considered reliable. For this particular range of diameters, however, it is probable that the droplet counts are underestimates but it is not easy to give a reliable figure for the average efficiency of catch within this range, because of the difficulty of distinguishing between droplets of different sizes. It is also not certain that May's figures are correct, particularly since the smallest droplets on the samples showed no tendency to be deflected to the outside of the slide. Distribution of droplets of all sizes on all samples were quite random and the samples illustrated in Fig. 5 are typical. The efficiency of catch has therefore been taken as unity throughout the entire range of diameters. The effect of this on spectra involving water content will be negligible but there will be some, though in the opinion of the author, small, effect on the spectra involving numbers of droplets.

The volume of air of which a droplet sample is representative is between 2 and 3 cm^3 so that any comparatively large droplets which occur in concentrations of less than about 2 per cm^3 are not normally collected. Reliable counts of such droplets are therefore not available and are better obtained by a technique such as that used by GARROD (1957). The effect of this on spectra involving droplet numbers will be negligible but the effect on computed values of water content will be to lead to underestimates in some cases.

The flights were made in cumulus clouds varying in vertical extent from about 750 to 7,000 ft. In the thicker clouds samples were generally taken at height intervals of about 1000 ft but in the thinner clouds the height interval was generally about 100 ft and several samples were often taken at the same level. In all 150 samples were taken during the ten flights.

3. Observations

Summaries of the basic information available and of derived data, meaned for each flight are given in Table 2. The basic information is given in rows 1—6 and the derived data are given in rows 7—18. The figures in Table 2 are arranged with the flights in order of sampling thickness to facilitate investigating variations with cloud depth. The detailed basic information available included, for some samples, remarks relating to precipitation and estimates of visibility but these are not presented in this report. A fuller account is given by DURBIN (1956).

4. Results

The results are treated in three main sections: —

a. A general statistical analysis and discussion of the droplet number and water content distributions obtained.

b. The variation with height of the droplet diameters, numbers of droplets per cm^3 and water content in each cloud.

c. The applicability of a formula given by Best to the size distributions obtained.

a: I. Variation between samples.

From the counts made of the numbers of droplets in the different categories for all the 150 samples it was clear that there was little consistency between them. For example, in Flight 7, the results of which are given in Table 1, most samples contained droplets in category 6 (29.9 μ), only 7 contained droplets in category 7 (42.1 μ) and only one contained droplets in category 8 (59.9 μ). On the other hand one sample taken on this flight contained no droplets having diameters bigger than 10.4 μ. It was also apparent that samples taken within 100 ft or so of each other were

Table 1. Details of height, size, water content, temperature, and remarks for the samples taken on Flight 7 (24/9/51)

Item No.												
1.	Sample No.	*78*	*79*	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*
2.	Sampling height (ft)	2950	3100	3400	3400	3900	3400	4500	4500	4600	4600	5000
3.	Temperature (°F)	—	50.0	47.5	47.3	45.7	45.0	43.5	43.5	43.0	43.0	42.0
4.	Total no. of drops counted	469	183	131	304	442	347	133	42	58	195	46
5.	Percentage no. of droplets in:											
	Category 1 (5.3 μ)	56.1	20.2	4.6	50.3	9.7	17.6	19.5	2.4	12.1	46.7	23.9
	Category 2 (7.5 μ)	39.9	29.9	29.8	34.5	26.0	25.9	17.3	7.1	15.5	24.1	13.0
	Category 3 (10.4 .)	4.1	24.0	32.8	8.5	34.2	27.9	30.1	11.9	24.1	7.7	13.0
	Category 4 (14.9 μ)	—	21.9	25.9	5.9	20.8	19.3	24.1	23.8	25.9	8.2	23.9
	Category 5 (21.4 μ)	—	4.4	6.1	0.7	7.9	8.3	8.3	40.5	20.7	11.3	23.9
	Category 6 (29.9 μ)	—	0.5	0.8	—	1.1	0.9	0.8	14.3	1.7	2.1	2.2
	Category 7 (42.1 μ)	—	—	—	—	—	—	—	—	—	—	—
	Category 8 (59.9 μ)	—	—	—	—	0.2	—	—	—	—	—	—
	Categories 9 and 10: Nil for all samples											
6.	No. of droplets per cm^3	207	77	64	145	197	173	62	19	29	89	20
7.	Mean droplet diameter (μ)	6.5	10.1	11.3	7.2	11.3	10.7	11.0	18.2	13.1	9.1	12.9
8.	Mean volume diameter (μ)	6.7	12.0	13.0	8.3	14.0	12.9	13.1	20.6	15.5	13.0	15.8
9.	Water content (g m^{-3})	0.03	0.07	0.07	0.04	0.28	0.18	0.07	0.09	0.05	0.11	0.05
10.	Best's constant "a" (μ)	6.6	19.5	—	13.8	—	20.9	20.9	27.5	22.9	—	24.0
11.	Best's constant "n"	10.0	3.8	—	2.7	—	3.6	3.6	5.5	4.2	—	3.7
	Remarks											
12.	Precipitation reported[1]	s	—	—	—	—	h	m	—	s	s	—
13.	Estimated visibility (yd)	—	—	—	—	—	100	—	—	200	200	—
14.	Additional remarks	—	—	—	—	w	—	w	w	—	—	w
Item No.												
1.	Sample No.	*89*	*90*	*91*	*92*	*93*	*94*	*95*	*96*	*97*	*98*	*99*
2.	Sampling height (ft)	5100	5200	5550	5650	5950	6050	6200	6200	6700	6700	6800
3.	Temperature (°F)	42.1	41.0	40.0	40.0	38.0	39.0	38.5	39.0	37.5	38.0	39.5
4.	Total no. of drops counted	178	296	217	162	274	76	374	282	91	92	273
5.	Percentage no. of droplets in:											
	Category 1 (5.3 μ)	0.6	28.7	34.6	14.8	20.4	6.6	11.8	38.7	0.0	7.6	11.0
	Category 2 (7.5 μ)	8.4	19.6	18.3	6.8	21.5	17.1	12.6	18.8	9.9	10.9	29.3
	Category 3 (10.4 μ)	9.0	12.5	11.5	9.9	27.4	11.8	7.7	13.8	15.4	6.5	23.1
	Category 4 (14.9 μ)	28.7	11.5	19.8	32.1	14.2	26.3	21.4	15.2	13.2	26.1	19.0
	Category 5 (21.4 μ)	42.1	23.0	13.4	29.6	12.4	28.9	40.9	11.3	35.2	39.1	11.3
	Category 6 (29.9 μ)	10.1	4.1	2.3	5.1	3.6	9.2	5.6	2.1	23.1	8.7	5.1
	Category 7 (42.1 μ)	1.1	0.7	—	1.2	0.4	—	—	—	3.3	1.1	1.1
	Category 8 (59.9 μ)	—	—	—	—	—	—	—	—	—	—	—
	Categories 9 and 10: Nil for all samples											
6.	No. of droplets per cm^3	75	130	101	71	127	36	178	136	41	39	129
7.	Mean droplet diameter (μ)	18.4	12.4	11.0	15.6	11.5	15.8	15.9	10.2	20.1	17.2	10.5
8.	Mean volume diameter (μ)	20.6	16.5	14.2	18.7	15.0	18.5	18.5	13.5	23.4	21.1	16.3
9.	Water content (g m^{-3})	0.37	0.31	0.15	0.26	0.23	0.12	0.59	0.17	0.27	0.17	0.29
10.	Best's constant "a" (μ)	29.5	28.8	24.5	25.7	26.9	26.9	26.9	24.0	33.9	29.6	—
11.	Best's constant "n"	4.4	3.4	3.2	5.0	3.3	4.9	4.4	3.2	4.5	4.4	—
	Remarks											
12.	Precipitation reported[1]	—	—	—	m	m	m	—	—	—	—	—
13.	Estimated visibility (yd)	200	200	—	200	—	100	100	100	—	—	—
14.	Additional remarks[2]	—	—	t	—	—	—	—	—	w	—	—

Note Dashes in item 5 are to be interpreted as "no droplets in the category.
Dashes in items 12—14 indicate that no observations were made.

[1] s = slight, m = moderate, h = heavy.
[2] w = wispy, t = thick.

not obviously related in their droplet distributions. This flight is typical of all ten flights and considered as a whole the droplet distributions from all flights show how greatly the droplet content of a cumuli-form cloud differs from point to point in both the horizontal and vertical.

An attempt has been made to overcome the analytical difficulties which arise as a result of having a large number of samples to deal with by grouping them according to the flight on which they were taken and obtaining meaned values of the various parameters under consideration. These means are presented in Table 2 and although they are not truly representative of individual clouds they afford the best method of distinguishing between the droplet characteristics of clouds formed under different conditions of atmospheric stability.

a: II. Droplet diameters above and below which ten per cent of the droplets, obtained as averages for each flight, remain.

Rows 7 and 8 of Table 2 give values of the droplet diameters, meaned for each flight, below which are contained ten per cent and ninety per cent of the total number of droplets. It will be seen that ten per cent of the droplets have diameters less than 3—6 μ but ten per cent are also comprised of droplets having diameters greater than between about 9 and 28 μ.

a: III. Spectra relating droplet diameter and droplet number.

To examine the mean droplet spectra of these clouds it was first necessary to make the ranges appropriate to each size equal. This was done for each flight by finding the percentage number of droplets within each category for the different samples, obtaining the mean percentage numbers for all the samples taken during the flight and dividing by the range of diameters bounding the category. The figures obtained are plotted in Fig. 1 (a) which shows "mean percentage number of droplets per unit diameter range" plotted against droplet diameter. The areas under the curves are equal and correspond numerically to 100 droplets.

It will be seen from Fig. 1 (a) that there is a wide variation between the mean spectra for the different clouds sampled though in view of the small volume of each cloud in which

Table 2. Composite table of basic and derived data

1. Flight No.	3	6	4	5	8	7	10	9	1	2
2. Date (1951)	17/7	17/9	24/7	25/7	26/9	24/9	26/9	26/9	19/6	26/6
3. Lowest Sampling Level (ft)	3300	5200	3450	3200	2050	2950	3980	3460	3900	5000
4. Highest Sampling Level (ft)	4050	6150	5400	5460	4560	6800	8850	8450	10020	12000
5. Sampling Depth (ft)	750	950	1950	2260	2510	3850	4950	4990	6120	7000
6. Number of Samples taken	16	21	10	14	17	22	22	12	9	7
7. Diameter below which 10 per cent of droplets remain (μ)	4.0	4.7	4.0	3.4	4.0	4.8	5.3	3.9	6.0	5.7
8. Diameter above which 10 per cent of droplets remain (μ)	11.0	17.0	9.3	16.3	18.3	15.0	21.0	28.0	17.6	14.5
9. Mode diameter of droplet number spectra (μ)	8.0	8.5	8.0	7.5	7.5	7.5	8.0(15)	7.5(15)	7.5	9.0
10. Diameter below which 10 per cent of total water remains (μ)	5.5	9.0	4.0	8.0	5.5	8.0	11.5	15.5	8.0	8.0
11. Diameter above which 10 per cent of total water remains (μ)	14.0	47.0	11.0	17.5	19.0	25.5	48.0	73.0	24.0	18.0
12. Mode diameter of water content spectra (μ)	8.0	15.0	7.5	15.0	7.5	21.0	15.0	23.0	10.0	13.0
13. No. of droplets (μ) per cm^3	184	173	199	259	243	97	205	110	344	277
14. Mean droplet diameter (μ)	9.1	13.0	8.1	12.0	10.7	12.7	18.8	16.7	13.2	11.7
15. Mean volume diameter (μ)	10.1	15.8	8.6	13.9	11.3	15.5	19.2	24.9	14.9	13.1
16. Water content (g m^{-3})	0.1	0.4	0.1	0.4	0.2	0.2	0.8	1.5	0.5	0.3
17. Best's constant "*a*" (μ)	13.2	28.4	11.6	22.1	14.3	24.1	32.0	48.7	19.6	17.1
18. Best's constant "*n*"	7.1	5.1	5.9	4.2	6.0	4.3	4.1	3.5	5.0	7.0
19. No. of samples used to obtain values of "*a*" and "*n*"	10	5	9	14	16	18	15	9	6	7

Note Figures given in rows 7 to 18 are means of the values for the samples taken on each flight it was possible to take samples this is not surprising. Considering the shapes of these curves it will be seen that they generally have a single maximum and a variable amount of positive skew but some have, or tend to have, a secondary maximum at a diameter greater than that of the primary one.

The peaks of these curves are given in row 9 of Table 2. It will be seen that each curve has a primary mode at about 8 μ, irrespective of cloud depth. In two cases secondary maxima occur at about 15 μ. It should be noted that although the secondary maxima tend to be more evident in the clouds of greatest depth this is not always so and presumably other factors as well as depth contribute to the nature of these spectra.

On the whole there is a tendency for the curves for the thinner clouds to be narrower and to have higher peaks than those for the thicker clouds and it seems that the smallest droplet sizes are more frequent in the thinner clouds. This can be better illustrated by combining the flights into two groups

(1) Flights 3, 6, 4, 5, and 8 which have sampling depths between about 750 and 2,500 ft and

(2) Flights 7, 10, 9, 1, and 2 which have sampling depths between 3,850 and 7,000 ft.

The average distribution in these two groups is plotted in Fig. 2 (a) from which it will be seen that the mode diameter is about the same for the two groups of clouds, being about 8 μ. It is of interest to note that significant numbers of droplets of at least 60 μ diameter can exist on occasion in even the thinnest clouds, about 0.1 per cent of the droplets having diameters greater than 60 μ in clouds 750 to 2500 ft thick. When the cloud depth increases to between about 4000 and 7000 ft the proportion of these droplets also increases, about one per cent having diameters greater than about 60 μ. These latter facts are not evident from Fig. 2 (a), however, due to the inconvenient scale at the larger diameters.

a: IV. Analysis of computed values of water content.

Knowing the airspeed at which a sample was taken, the area of the impactor slide which was photographed and the time of exposure of the slide to the droplets it is possible to compute values of water content. This was done for all the 150 samples and the percentages within the different categories of the water contents for each sample were also computed. The figures obtained show some tendency for the samples taken in the lower part of a cloud to have higher percentages of water composed of small droplets and lower percentages composed of large droplets than in the upper part of a cloud.

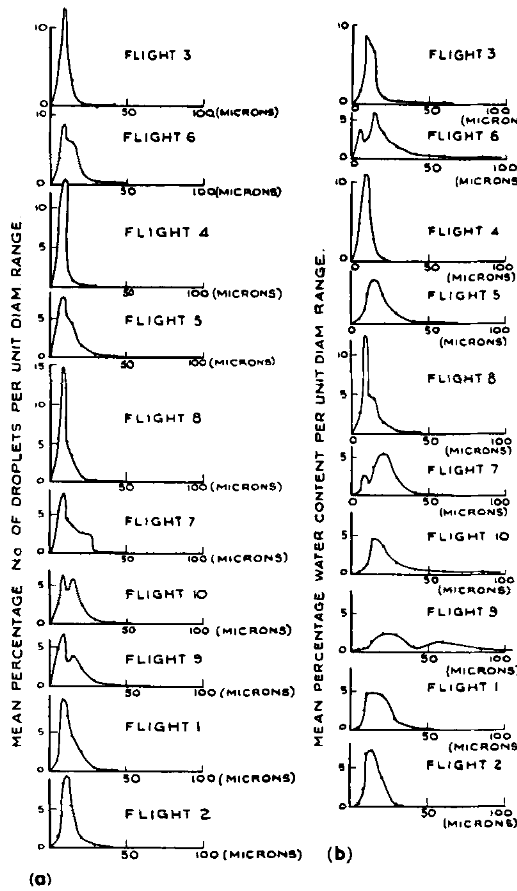


Fig. 1. Mean spectra relating droplet diameters with (a) droplet numbers (b) water contents.

In the same way as for the size-number analysis, cumulative mean water content curves were plotted. These are not reproduced but the droplet diameters below which are contained ten per cent and ninety per cent of the total water, meaned for each flight, are given to the nearest 0.5 μ in rows 10 and 11 of Table 2. It will be seen that ten per cent of the water is composed of droplets having

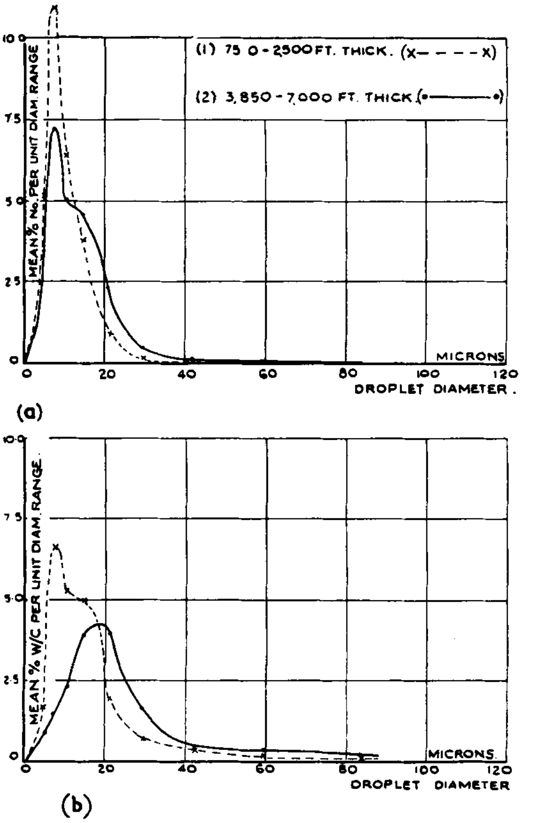


Fig. 2. Comparison of the mean spectra relating droplet diameter with (a) droplet numbers (b) water content for two groups of five cumulus clouds.

diameters less than a value lying between 4 and 16 μ and ten per cent is composed of droplets having diameters greater than a value between 11 and 73 μ.

To examine the distribution of water content with droplet diameter, values of "percentage water content per unit diameter range", meaned for each flight, were computed in the same way as that described in para *a: III*. The figures obtained are plotted against droplet diameter in Fig. 1 (b). Compared with Fig. 1 (a), Fig. 1 (b) throws greater emphasis on the effect of the large droplets compared with the small since the ordinate is proportional to the cube of the diameter. Plotted in this way the droplet diameter corresponding to maximum water content does not always show a well defined mode.

Diameters corresponding to peak water contents are given in row 12 of Table 2. These values are, in general, considerably larger than the mode diameters for the droplet number distributions. A comparison of the distribution of water content with droplet diameter for two groups of clouds, 750 to 2500 ft thick and 3850 to 7000 ft thick has been made in the same way as for the droplet number analysis. The results, which are plotted in Fig. 2 (b), show that as the cloud depth increases the water content spectrum as a whole moves towards the larger droplet diameters, maxima occurring at about 8 μ and 18 μ respectively.

b. Relations between droplet parameters.

Another method of investigating the physical properties of cloud droplets is to compute the following parameters:

(1) Mean droplet diameter (μ)

(2) Mean volume diameter, defined to be the diameter of a droplet which contains the mean of the total volume of water in the sample (μ)

(3) Number of droplets per cm^3

(4) Water content ($g\ m^{-3}$)

and to examine the manner in which these vary with height above cloud base and with each other.

These parameters were computed for all the samples and the values, meaned for each cloud, are given in rows 13—15 of Table 2. The first part of the subsequent analysis is devoted to a consideration of the variations of these parameters with height. The variation of mean diameter and mean volume diameter are clearly in the same direction and differ only in magnitude. A detailed analysis of the two parameters separately is therefore unnecessary and in what follows only the variations with height of mean volume diameters are considered. Apart from numerical values the conclusions from this analysis may be considered to apply to both parameters.

b: I. Variation of mean volume diameter with height.

Fig. 3 shows graphs of mean volume diameter against height of sample for the ten flights. It is pointed out that it would only be possible to obtain a true indication of the vertical variation of any one of the above parameters if there were no variation in the horizontal or with time. It is largely a matter of chance whether a particular sample be taken in a thin or dense region of the cloud so that to obtain a representative indication of the variation with height it would be necessary to take a large number of samples at each level. This would enable mean values to be calculated for each level but the procedure is still not entirely satisfactory unless several aircraft take simultaneous samples at different heights. Also, one must be certain that all the samples have been taken in the same cloud. It is often possible with isolated large cumulus clouds to confine sampling to one cloud but not, as a rule, with small clouds. Furthermore, if the tops of the cumulus clouds vary, samples taken at the same level are possibly associated with cells in different stages of development. The sampling in any one cloud took about 30 minutes so that the curves cannot be regarded as representative of a particular stage of development.

In Fig. 3 are plotted, for each flight, all the computed values of mean volume diameter against height. Pecked curves have been drawn visually through the points for eight of the ten flights and these give evidence of an increase in mean volume diameter with height. The points plotted for the remaining two flights show no such tendency and although this is understandable, due to the shallowness of the cloud, in the case of Flight 6 (Fig. 3 (f)) it is not clear why the tendency is not there for the points of Flight 9 (Fig. 3 (j)).

Values of mean volume diameter were, in the main, found to vary from between 5 and 10 μ near the bases of clouds to between 17 and 27 μ near the tops. There were larger values, however, and these are particularly noticeable among the points plotted for Flights 9 and 10 during both of which precipitation was reported in the cloud. Values of mean volume diameter, meaned for each flight, are given in row 15 of Table 2. Fig. 5 shows a photograph of the sample in Flight 10 for which the mean volume diameter was 40.3 μ.

Figs. 3 (h), (j) and (k) represent plots of the values obtained from samples taken in the same area and general synoptic condition, those of Figs. 3 (h) and 3 (j) in the morning with a time interval of about one and a half hours and Fig. 3 (k) in the afternoon another three hours later. These three flights therefore give some indication of the development of the droplet sizes throughout a summer day with the cloud depth increasing from about 2500 to 5000 ft and producing precipitation. Cloud top temperature on Flight 10 was $-1.5°$C and it seems likely that only the coalescence

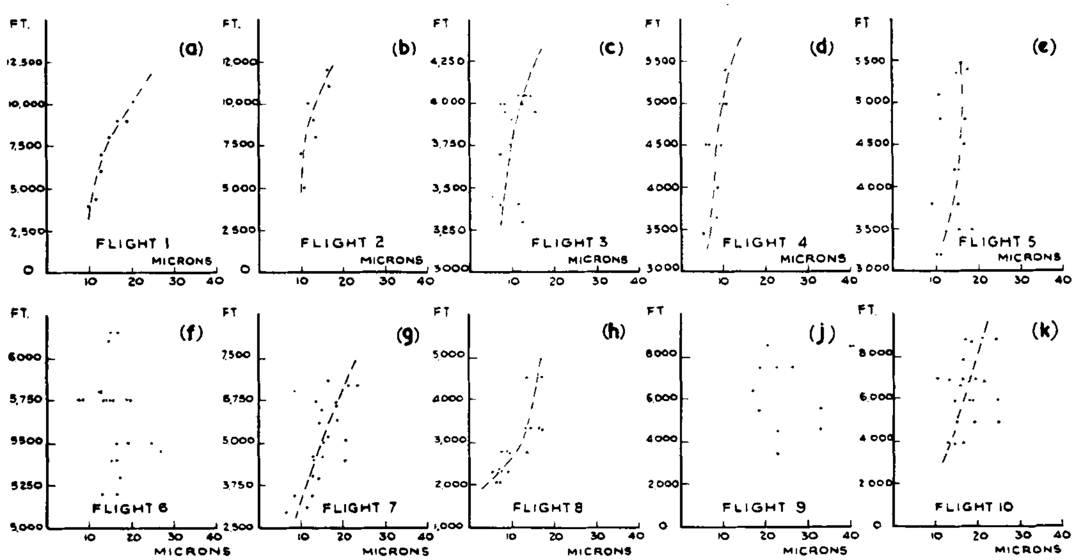


Fig. 3. Variation of mean volume diameters with height above ground.

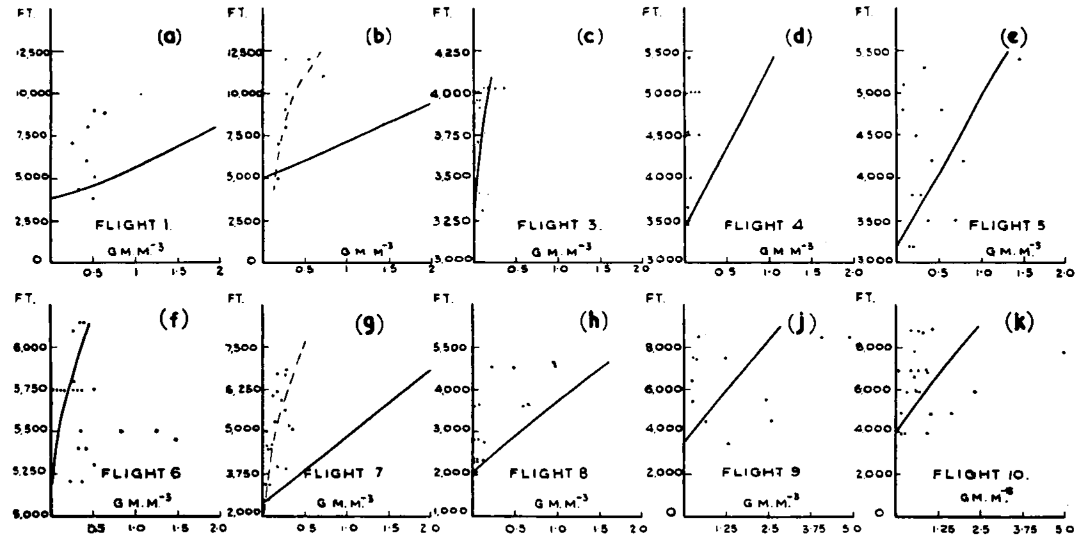


Fig. 4. Variation of water content with height above ground. (The full line curves represent theoretically computed adiabatic values.)

and not the Bergeron mechanism was operating to produce the rainfall.

In all these clouds values of mean volume diameter similar to those found near the top of the cloud were found in the lower regions. Furthermore, due presumably to factors of change with time and space and the general inhomogeneity of the cloud, there is a large scatter from any mean curves drawn through the values.

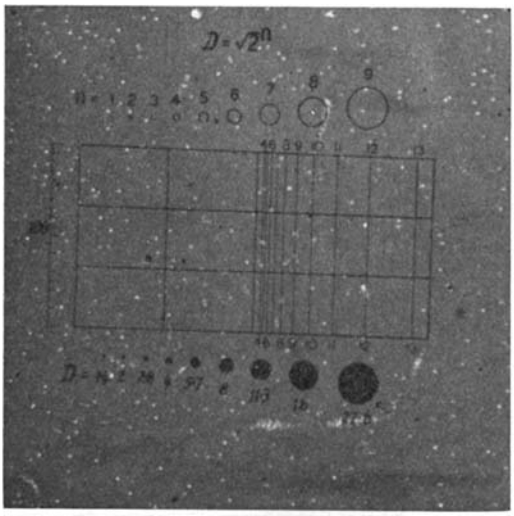
b: II. Variation of water content with height.

The same considerations as outlined for the analysis of mean volume diameters apply to water contents, the results of which are plotted in Fig. 4. Evidence of a systematic increase of water content with height is confined to Flights 2 and 7, mean pecked curves having been drawn visually through the plotted points for these flights. For the remaining flights the evidence for such an increase is not pronounced and hardly exists at all for those clouds less than 2500 ft thick. However, the results from several flights show that the largest values of water content are often found near the top of the cloud even though there is not a systematic increase in the values from the base.

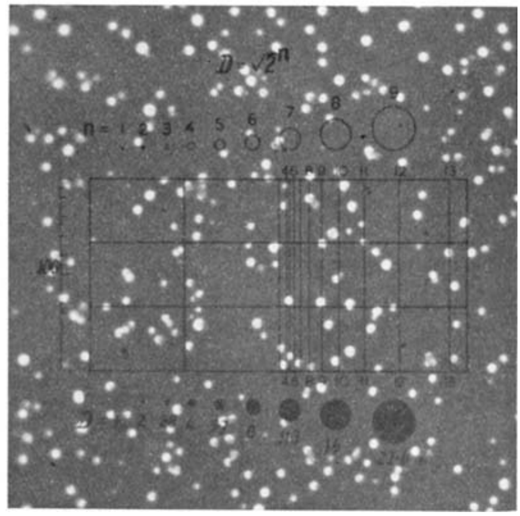
Features of these clouds are the occurrence of local high values of water content almost anywhere within them and in particular that comparatively large values can occur in thin clouds.

Values of water content computed from the droplet samples taken in the five clouds which were less than 2500 ft thick usually varied between about 0.01 and 0.5 g m^{-3} but values up to 1.4 g m^{-3} also occurred. In the remaining clouds the water content values were mainly between about 0.1 and 1.0 g m^{-3} but very much larger values were sometimes found. The highest value was 4.97 g m^{-3} and this occurred in the cloud examined during Flight 9 and in which precipitation was observed. Values of water content, meaned for each flight, are given in row 16 of Table 2. A sample having a water content of 4.86 g m^{-3} is illustrated together with other typical droplet samples in Fig. 5.

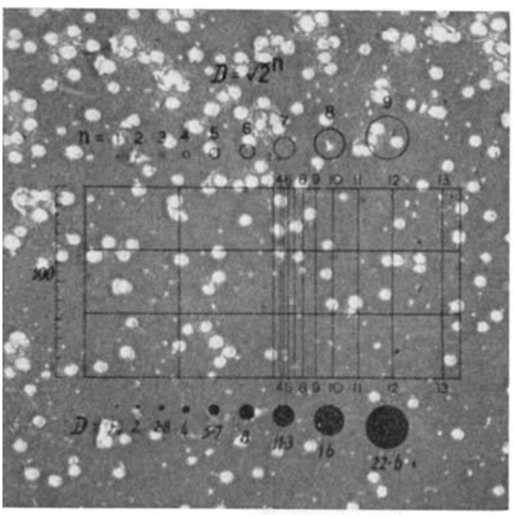
In order to see how the observed values of water content compare with the theoretical adiabatic values, the latter were computed using cloud base temperatures obtained either from the flight data or from the relevant Te-Phi-gram. The values are plotted as full line curves in Fig. 4 from which it will be seen that, on the whole, computed values of water content are greater than the observed values but this is not always so. For example, some of the observed values on Flights 9 and 10



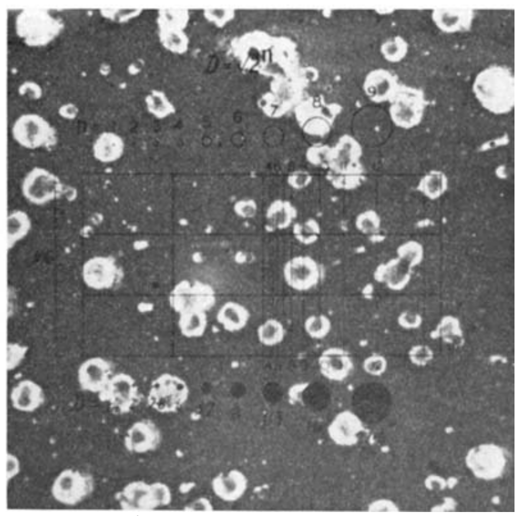
Sample No. 100
Mean volume diameter 7.16 microns
No. of droplets per cc 203
Water content 0.04 gm.m^{-3}



Sample No. 2
Mean volume diameter 11.62 microns
No. of droplets per cc 397
Water content 0.33 gm.m^{-3}



Sample No. 9
Mean volume diameter 20.1 microns
No. of droplets per cc 252
Water content 1.07 gm.m^{-3}



Sample No. 126
Mean volume diameter 40.34 microns
No. of droplets per cc 142
Water content 4.86 gm.m^{-3}

Fig. 5. Typical cloud droplet samples.

were greater than the calculated values. Rain was reported on these two flights but this fact does not explain the high water content values since precipitation elements did not contribute to them. It is probable that the largest droplets were descending through the cloud when impacted. This could also apply to the results of Flight 6 possibly as a result of turbulence. The cloud sampled on this flight was only 1000 ft thick but a large

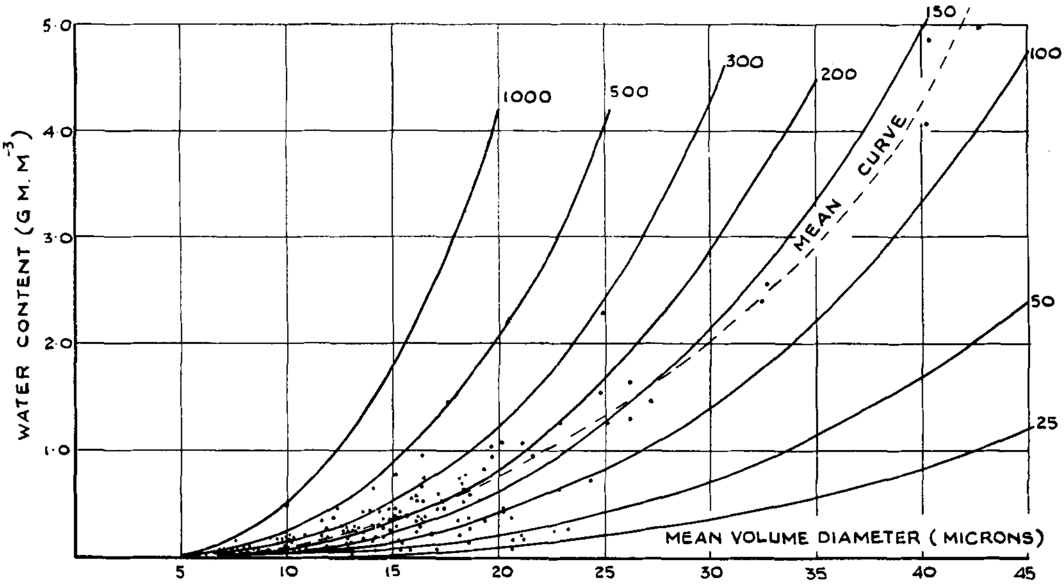


Fig. 6. Relationship between water content, mean volume diameter and number of droplets per cm³.

number of water content values, greater than the theoretical adiabatic values were observed in the lower 500 ft.

Adiabatic values of water content would strictly be found only in those regions of the cloud in which no entrainment, mixing or precipitation occurs. Mixing and entrainment will cause the actual values to be less than those calculated from adiabatic ascent in which there is no interchange between the rising cloud mass and the environment and therefore lower-than-adiabatic values would suggest some interchange. As most of the values observed are lower it seems likely that this interchange in fact occurs over most of the cloud although not necessarily everywhere within it. On the other hand, precipitation is normally associated with some increase in the values lower down at the expense of the higher regions and greater-than-adiabatic values can occur in the lower regions even before precipitation is observed. The extent of any mixing and precipitation obviously depends on many factors such as speed of updraughts, state of development and age of the cloud so that all that can be safely concluded from these results is that the application of calculated water contents to given clouds is, at the best, a rough process and in the main, except where there is precipitation, will usually lead to over estimates.

b: III. Variation of numbers of droplets per cm³ with height.

Graphs showing the variation of the numbers of droplets per cm³ with height were plotted but are not reproduced in this paper. There was nowhere any evidence of a systematic variation and in the main there were between 100 and 300 droplets per cm³ in any of the clouds. However, local extreme values, as high as 976 per cm³ and as low as 19 per cm³ occurred and there was a tendency for higher values to be found near the base of the cloud. Mean figures of droplets per cm³ for each flight are given in row 13 of Table 2.

b: IV. Variation of water content with mean volume diameter and number of droplets per cm³.

The relationship between mean volume diameter, D, water content, W, and number of droplets per cm³, N, is

$$W = \frac{\pi}{6} N D^3$$

Curves of W against D for different values of N are shown superimposed on the plotted points for the 150 samples in Fig. 6 giving an overall presentation. A mean curve, shown dotted, has been drawn through the points.

It will be seen that the mean curve differs very little from the theoretical curve corresponding to $N=150$ for mean volume diameters greater than about 20 μ and that all but 4 of the 150 samples lie between the curves for $N=25$ and $N=500$. The mean curve shows that the tendency is for higher values of water content to be due to higher values of mean volume diameter rather then higher values of number of droplets per cm^3.

c. An examination of Best's equation for the droplet distribution in clouds.

An equation suggested by BEST (1951) which is frequently used to relate quantities of water and droplet size within a cloud is

$$1 - F = \exp\left[\left(-\frac{d}{a}\right)^n\right]$$

where F is the fraction of liquid water comprised of droplets with diameters less than "d" and where "a" and "n" are constants. The equation can be rewritten in the form

$$\log_{10}\log_{10}\frac{1}{1-F} = n\log_{10} d - n\log_{10} a + 0.3617$$

which represents a straight line of slope n. The constant "a" is seen to be the value of "d" for which $\log_{10}\log_{10}\frac{1}{1-F} = 0.3617$.

To find values of the constants "a" and "n" values of $\log_{10}\log_{10}\frac{1}{1-F}$ were plotted against $\log_{10}d$ for all the samples. "d" is the maximum droplet diameter corresponding to any graticule circle and was taken to be midway between the diameter of that circle and the next bigger one. The values of "d" are therefore 6.38, 8.95, 12.68 etc. microns (see section 2).

For many of the samples the relationship between $\log_{10}\log_{10}\frac{1}{1-F}$ and $\log_{10}d$ was not that of a straight line but a curve. For most of the samples, however, the curvature was not very great and it was possible to draw the best straight lines through the points fairly accurately by eye.

For the largest droplet size present F is unity and $\log_{10}\log_{10}\frac{1}{1-F}$ is infinity. F If be taken as 0.99 the value of $\log_{10}\log_{10}\frac{1}{1-F}$ drops to 0.301. Hence, for values of F approximately equal to unity, a very small change in F makes a significant difference to the nature of the curve. For this reason it was decided that the point corresponding to the largest droplet size present was unrepresentative and was not used in assessing the best straight lines. The percentage of water considered was therefore that for values of $\log_{10}\log_{10}\frac{1}{1-F}$ up to the greatest but one size.

Within the above restrictions it was possible to obtain values of "a" and "n" for 108 of the 150 samples. For the remaining 42 samples the curvature was considered too great to merit drawing straight lines. The main reason for this appears to be because the largest droplets of some samples, while being small in number, have a large size range. Deviations from a straight line will, however, always occur to some extent.

Values of "a" and "n", meaned for each flight, together with the number of samples from which the mean values were obtained are given in rows 18 and 19 of Table 2. The mean values for all the 108 samples were "a" $= 23.0$ μ and "n" $= 5.1$. An approximate empirical formula relating F and "d" for cumulus clouds up to 7000 ft thick is thus

$$1 - F = \exp\left[-\left(\frac{d}{23}\right)^{5.1}\right]$$

In an attempt to correlate the values of the two constants with other parameters graphs were plotted of the constants against (1) water content (2) number of droplets per cm^3 and (3) maximum droplet diameters. It was found that

(1) "a" increased in a fairly regular manner and "n" decreased in a most irregular manner with increasing water content,

(2) "a" and "n" did not show any regular variation with numbers of droplets per cm^3,

(3) "a" increased almost linearly and "n" decreased rather irregularly with increasing maximum droplet diameter.

Graphs showing the variations of "a" and

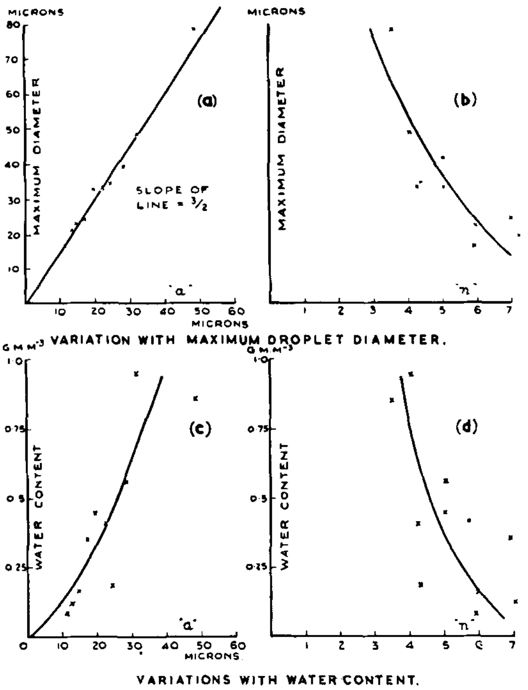


Fig. 7. Variation of Best's constants "*a*" and "*n*" with mean values of maximum droplet diameter and water content for the ten flights. (Values of the constants were obtained from 108 samples.)

"*n*" with maximum droplet diameter and water content are shown in Fig. 7.

The most useful of the four curves (which were drawn by eye) is that shown in Fig. 7 (a) from which it will be seen that the points lie fairly close to a straight line of slope $^3/_2$ which passes through the origin. It therefore seems that in practice a good approximation to the value of the constant "*a*" is about $^2/_3$ of the diameter of the largest droplet present. By way of confirmation the 108 values of "*a*" were listed, regardless of flight, under the representative diameters used, viz. 10.41, 14.95, 21.29 etc. μ. The table obtained showed a scatter which was to be expected due to different samples having different numbers of droplets at the maximum size. The complete table is not reproduced but the mean values are shown in Table 3.

The weighted mean value of the ratio $\frac{a}{D_{max}}$ by this method is 0.68 which agrees well with the value quoted above.

It seems therefore, that while the empirical formula

$$1 - F = \exp\left[-\left(\frac{d}{23}\right)^{5.1}\right]$$

serves as an approximation to the relationship between "*d*" and "*F*" in cumulus clouds up to 7000 ft thick, the values of "*a*" and "*n*" for individual typical droplet samples which differ in their overall water content or maximum droplet size will be more representative if obtained from Fig. 7.

5. Discussion

Impactor techniques for cloud droplet sampling have been used by other workers (MAZUR 1943, DIEM 1948, SQUIRES and GILLESPIE 1952).

The work of Squires and Gillespie in Australia was largely devoted to the presentation of a new type of cloud droplet impactor (which also used magnesium oxide coated slides) and results were given for only nine impactions taken at one level on one flight through a cumulus cloud from which precipitation fell. The highest value of water content found was 1.6 g m^{-3} which is not in disagreement with values published in this report. However the largest value of the number of droplets per cm^3 was 93 and this seems rather small. The data given by Diem and Mazur have been analysed by Best. Mazur gives results from eleven flights in cumulus clouds but the greatest

Table 3. Mean values of Best's constant "a" for different maximum droplet sizes.

Maximum diameter (μ) ...	10.41	14.95	21.39	29.95	42.1	59.9	84	119
No. of samples...	7	12	22	32	22	7	2	4
Mean "*a*" (μ) ...	7.3	12.05	14.45	22.0	25.42	43.4	52.5	70.7
Ratio $\frac{a}{D_{max}}$	0.70	0.81	0.67	0.73	0.60	0.72	0.63	0.59

number of samples taken on any flight was only six. The largest mean water content found was 0.49 g m^{-3} and the largest mean value of the mean volume diameter was 17.3 μ. Diem's results which were obtained using an oil technique include only two flights in cumulus clouds with maximum values of water content and mean volume diameter of 0.21 g m^{-3} and 17.1 μ respectively. The results of the present paper are not in disagreement with these workers but in view of the much greater number of samples examined, present a fuller picture of the processes.

The manner in which water is distributed in droplet form throughout a cumulus cloud depends primarily on the life and extent of the cloud. An exact analysis requires knowledge of the positions in the cloud at which the samples were taken and further requires that all samples be taken at the same time. The best that can be done to satisfy the first requirement is to state roughly the location within the cloud at which the sample was taken though this is not always obvious. The second requirement cannot be fulfilled at all and in consequence results which have been obtained using a single shot impactor must be treated with reserve especially when several samples are grouped together to obtain mean values which are considered to be representative of the cloud. It should also be remembered that impactors of the type used and in quoted references underestimate the numbers of very small droplets and also are not suitable for obtaining reliable counts of those droplets which are present in very small concentrations.

6. Conclusions

With the above reservations in mind the following conclusions may be drawn from this report:

(1) Mean spectra of droplet diameter against droplet number have a mode at about 8 μ. A secondary maximum at about 15 μ was partly in evidence in some clouds and fully evident in others.

(2) Graphs of droplet diameter against water content have revealed a mode diameter at about 8 μ for clouds between about 750 and 2500 ft thick but for clouds between about 4000 and 7000 ft thick the mode is at about 18 μ. This increase in the mode diameter probably represents an aspect of development from a small cloud to a bigger one. Larger clouds have higher water contents and the bulk of the water is contained in larger droplets.

(3) In clouds between 750 and 2500 ft thick about one droplet in 1000 has a diameter larger than 60 μ. In clouds between about 4000 and 7000 ft thick about one droplet in 100 has a diameter larger than 60 μ.

(4) Mean droplet diameters and mean volume diameters tend to increase with height, the latter having values of about 5—10 μ near cloud bases and 20—25 μ near cloud tops.

(5) Water contents tend to have larger values in thicker clouds. In the main, values are up to about 0.5 g m^{-3} in clouds up to about 2500 ft thick and up to about 1.0 g m^{-3} in clouds of up to about 7000 ft thick. Higher values can occur locally, however, and a value of almost 5 g m^{-3} has been found in cloud between 4000 and 5000 ft thick which was precipitating.

On the whole observed values of water content are less than adiabatic values and this is doubtless due to dilution. However, higher-than-adiabatic values are frequently found and this may well be due to modification associated with the early stages of precipitation. In general it seems that adiabatic values are an unreliable guide to the disposition of water within a cloud.

(6) The number of droplets per cm^3 is in the main between 100 and 300 in most parts of cumulus clouds but there is a trend rowards higher values near the bases.

(7) Higher values of water contents in cumulus clouds appear to be due to larger droplets rather than to greater numbers of droplets per cm^3.

(8) The formula relating quantities of water and droplet diameter, given by Best overestimates the importance of the larger droplets in relation to the smaller ones to such an extent that it was possible to obtain values of the constants "*a*" and "*n*" for only about 70 per cent of the samples. However, it appears that the value of "*a*" is governed by the largest size of droplet on the sample and a good approximation to it may be taken as $^2/_3$ of the diameter of the largest droplet. Similarly, a reasonable estimation of the value

of "*n*" can be obtained from its variation with maximum droplet diameter though the nature of the variation is not as well defined as in the case of "*a*".

(9) Future work in the field of cloud droplet distributions could more usefully be undertaken using a technique which allows continuous sampling during a traverse through a cloud. Neglecting the time taken for the aircraft to traverse the cloud, this would enable reasonably accurate investigations of the droplet distribution at a given level to be made and successive traverses at the same level would provide valuable information on cloud development.

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REFERENCES

Best, A. C., 1946: The size distribution of cloud particles. *Met. Res. Pap. (Met. Off., London).* No. 309.

Best, A. C., 1851: Drop-size distribution in cloud and fog. *Quart. J. R. Met. Soc.* **77**, p. 418.

Diem, M., 1948: Messungen der Grosse von Wolkenelementen II. *Met. Rundschau* **1**, p. 261.

Frrith, R., 1951: The size of cloud particles in stratocumulos cloud. *Quart. J. R. Met. Soc.* **77**, p. 441.

Garrod, M. P., 1957: Recent developments in the measurements of precipitation elements from aircraft. *Me.t Res. Pap. (Met. Off., London) No. 1050.*

Levine, J. and Kleinknecht, K. S., 1951: Adaptation of a cascade impactor to flight measurements of droplet sixe in clouds. *N.A.C.A. R.M. E SIGOS.*

May, K. R., 1945: The cascade impactor. An instrument for sampling coarse aerosols. *J. Sci. Inst.* **22**, p. 187.

Mazur, J., 1943: The number and size distribution of water particles in natural clouds. *Met. Res. Pap. (Met. Off., London) No. 109.*

Squires, P. and Gillespie, G. A., 1952: A cloud droplet sampler for use on aircraft. *Uuart. J. Roy. Met. Soc.* **78**, p. 387.