# Measurements of Precipitation Particles in Warm Cumuli over Southeast Texas

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## ABSTRACT

Precipitation particles $>250\ \mu$ were sampled in the upper regions of warm cumuli over southeast Texas using a foil-belt particle sampler. It was found that relatively high concentrations of drops can occur. Concentrations exceeding 1000 $m^{-3}$ were found in nearly 25% of the clouds. Drop sizes 1 mm in diameter were found fairly often, and 2-mm drops were occasionally sampled.

The effect of cloud height on the precipitation characteristics was found to be quite pronounced. Higher concentrations and broader distributions generally were found in the tallest clouds. The height of clouds plays a more important role in determining drop concentration and size distribution range than do updrafts or downdrafts.

In a comparison between concentration of precipitation particles and average cloud water content ($CWC_m$), it was found that large quantities of drops were associated with low $CWC_m$. Conversely, large values of $CWC_m$ were associated with small numbers of drops $>250\ \mu$ in diameter.

The 1968 clouds generally contained much higher concentrations of drops and had broader distributions of drop sizes than did the 1969 clouds. Smaller clouds investigated during 1968 were nearly as proficient in developing large drops as much taller clouds studied during 1969. The 1968 clouds seemed to have precipitation particle characteristics that were similar to trade-wind cumuli investigated by Brown and Braham, while the drop characteristics of the 1969 clouds were more nearly like the cumulus congestus studied in Missouri, also by Brown and Braham.

## 1. Introduction

Over the years it has been established that rain may fall from warm clouds, that is, clouds which exist almost entirely below the melting level. The Bergeron (ice crystal) mechanism does not explain the initiation of rain in such clouds since ice particles cannot exist if the cloud is everywhere warmer than 0C, and in fact, are an unlikely occurrence at temperatures down to several degrees below 0C. The development of rain in warm cumulus clouds is believed to be due to the coalescence of liquid droplets. The coalescence mechanism requires that cloud drops occur in a range of sizes, so that relatively few large drops may act as collectors of cloud water as they fall relative to the more numerous smaller drops. Braham (1968) points out that the role of coalescence in initiating rain should vary considerably among clouds of different types occurring in different regions and in different seasons; he suggests that the coalescence process probably is most effective in clouds of warm, humid air masses.

Measurements of large drops in warm cumuli over southeast Texas were used in a study to determine some of the size distribution characteristics. Collections were made during flights in May of 1968 and 1969 for the purpose of studying the natural precipitation characteristics of warm clouds, and the feasibility of modifying them. Aircraft and instrumentation were supplied by the National Center for Atmospheric Research (NCAR). The measurements of large drops were made using the sampler developed by Brown (1958, 1961), and was essentially the same model as that used by Brown and Braham (1963). A permanent and measureable record of drop sizes and numbers is provided when precipitation particles impinge on a thin metal foil backed by a wire mesh, the size of the impression being related to the momentum of the drop. The smallest drop size which will leave a definite imprint depends on the type and thickness of the foil, the type of backing, and the impact speeds. For the NCAR sampler and for typical airplane speeds, the threshold size for liquid drops was about 250 $\mu$ diameter. The foil is mounted on a continuous, wire-mesh belt about 5 m long, which is driven past an aperture by an electric motor that is activated by the scientist aboard the aircraft. Dimensions of the aperture are 1.24 cm by 1.59 cm, and the belt moves at a speed of 1.27 cm $sec^{-1}$.

Other instruments aboard the airplane, which provided supporting data for the study, were the reverse-flow thermometer, the Bendix dew point hygrometer, the Johnson-Williams liquid-water-content meter, and standard static-pressure and airspeed sensors. A detailed description of these instruments can be found in an NCAR (1965) technical note. All measurements, including foil travel information, were recorded on magnetic tape, and then processed on the NCAR computer. Auxiliary information was available in the form of time-lapse photographs, recorded commentary from the scientist, and PPI-scope photographs of the 10- and 3-cm radars at Texas A&M.

The large-scale flow patterns generally were more favorable for deep convection during the 1968 flights than they were for the 1969 flights. During the 1968 flights, moderate, occasionally strong, southeast winds produced an influx of moist air in the lower levels. Fronts or convergence zones provided lifting, and minor troughs aloft caused further instability. The synoptic conditions during the 1969 flights were characterized by more stable conditions. The low-level winds generally were much lighter than in 1968, and occasionally had a continental trajectory. Aloft the atmosphere was stable and quite dry. Occasional localized convergence and moisture influx provided favorable conditions for convection.

The clouds investigated fall in the class of large cumulus mediocris or small cumulus congestus. They reached maximum heights in the neighborhood of 2.5–4.5 km, and had bases around 1.0–1.5 km. Individual clouds usually were 1–2 km wide, but often a cluster of two or more would form a cloud region that extended for as much as 5 or 10 km.

## 2. Procedures of data reduction

The records from 133 individual segments of foil were analyzed. These were exposed on 13 flights during 90 penetrations through 40 different clouds. Forty-one of the segments were obtained in 1968, and 92 in 1969. The criteria that were used in choosing these particular segments were: 1) the sample must be from a warm cloud, and 2) the cloud water content (CWC), as measured by the Johnson-Williams liquid-water-content meter, should indicate a homogeneous cloud region during the sampling. Care was taken to exclude any cases where there was even the slightest evidence of the existence of ice particles.

The exposure times for these segments range from as little as 1.8 sec to a maximum of 12 sec with an average of $\sim$5.6 sec. The airspeed generally was around 85 m sec$^{-1}$ so that the length of cloud traversed during a single sample averaged about 480 m. The smallest volume sampled was 0.0264 m$^3$, the largest 0.2190 m$^3$, and the average $\sim$0.095 m$^3$. The airspeed used in calculating the sample volume was the average, graphically determined from computer output, for the time interval covered by the sample.

The foil length exposure was recorded as a function of time. This information, along with check-stop points on the foil, permitted a correlation of particular sections of foil to the corresponding cloud regions.

The foil impressions were sized from a magnified image formed by direct illumination of a section of the foil with a high-intensity light source, passing the reflected light through a lens, and reflecting it again from a mirror onto a screen. The calibration relating the impression size to drop size was published by Brown (1961). This calibration was extrapolated[1] to larger drop sizes.

After all impressions had been sized and counted, the number of particles in each 100 $\mu$ size interval was normalized to a reference volume of 1 m$^3$. Certain characteristic parameters were derived for the normalized distributions. These are:

1) $D_0$, the median volume diameter that divides the drop-size spectrum such that half of the distribution water content is contained in drops having diameters $>D_0$, and half in drops having diameters $<D_0$.

2) $Z$, the radar reflectivity factor, defined by Battan (1959) as the volume summation of $D_i^6$.

3) PWC, the precipitation-water content contributed by the drops in the sample.

Most of the supporting data used in the analysis and interpretation of the drop samples were available in one of the recorded forms mentioned earlier. The penetration altitude is available from the transcript of the scientist's comments and/or measured static pressure. The mean and maximum cloud water contents in the cloud region covered by each segment were determined graphically from the computer output. The estimated height of the top of the cloud came from the scientist's comments. Updrafts and downdrafts were difficult events to identify; only those cases that have been fairly well substantiated by scientist's comments and/or recorded pressure changes have been identified as samples obtained in regions of vertical motion.

## 3. Summary and analysis of data

Two of the most important variables in the coalescence process are the updraft velocity and the depth of cloud through which the larger drops have passed. The height of the top of the cloud is a measure of the former. Estimated summit heights are available for all but one of the samples. A minimum estimate of the latter is given by the depth of cloud below the measurement level. The penetration altitude is measured, and the heights of the bases of the clouds are known indirectly from surrounding station reports, estimates from radiosonde data in the vicinity, and cloud-base reports during ascent and descent.

In order to obtain more homogeneous samples, the data have been stratified according to the height of the cloud tops. Since flight penetrations usually were made in the upper-third of each cloud, the depth of the cloud below flight level and the height of the cloud top are correlated positively. Thus, the data may also be con-

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[1] A similar extrapolation was made by Mr. R. Lyons of the University of Chicago Cloud Physics Laboratory (private communication).

sidered as being indirectly stratified according to penetration level. Sub-sample statistics, including average values for the distribution parameters, are shown in Table 1. Since information as to top height was not available in one instance, only 132 samples were included in the stratification.

### a. *Total sample*

Of the 133 cloud sections within the whole sample, about 9% had no drops with diameters $\geqslant 250\ \mu$. These cases are nearly evenly divided between the three cloud-top categories (Fig. 1). This is not to be interpreted as a measure of the productivity of the clouds. The samples were selectively chosen because the scientist usually activated the foil belt only when he thought large drops were present. The mean and median concentrations for the sample as a whole are 593 and 264 $m^{-3}$, respectively. Twenty percent of the cases had concentrations over 1000 $m^{-3}$, 6% over 3000 $m^{-3}$, and 1.5% over 4000 $m^{-3}$. The frequency distributions of drop concentration for the three groups of cloud heights (Fig. 1) shows that the tallest clouds, and therefore those with greatest cloud depths, have the highest concentrations. The most pronounced difference occurs for clouds with tops >13,500 ft. The clouds in the middle group are much more similar to the smaller clouds than they are to the larger. The difference between the average concentrations for clouds in categories 1 and 2 is 166 $m^{-3}$, whereas the difference between clouds in categories 2 and 3 is 763 $m^{-3}$ (Table 1). There seems to be a gap in the frequency distribution around concentrations of 2000–2800 indicating a bimodal distribution.

Table 1. Average values of the distribution parameters for three groups of data, classified according to the height of the cloud top (1968 and 1969 data combined).

| Cloud parameter | Curve reference no. 1 | 2 | 3 |
|---|---|---|---|
| Cloud tops ($10^3$ ft) | 8–11 | 11–13.5 | >13.5 |
| Penetration altitude ($10^3$ ft) | 7.9–10 | 10–12.6 | 12–13.5 |
| No. of samples | 27 | 60 | 45 |
| No. of clouds | 9 | 21 | 11 |
| Average $N$ ($m^{-3}$) | 205 | 371 | 1134 |
| Average $D_0$ ($\mu$) | 360 | 491 | 588 |
| Average $Z$ ($mm^6\ m^{-3}$) | 10.36 | 59.16 | 228.41 |
| Average PWC (gm $m^{-3}$) | 0.0157 | 0.0285 | 0.0903 |

The mean drop-size distributions for the three classes of cloud height are presented in Fig. 2. In the mean, the deeper clouds (which were probed at higher altitudes) have a broader distribution of drops and higher

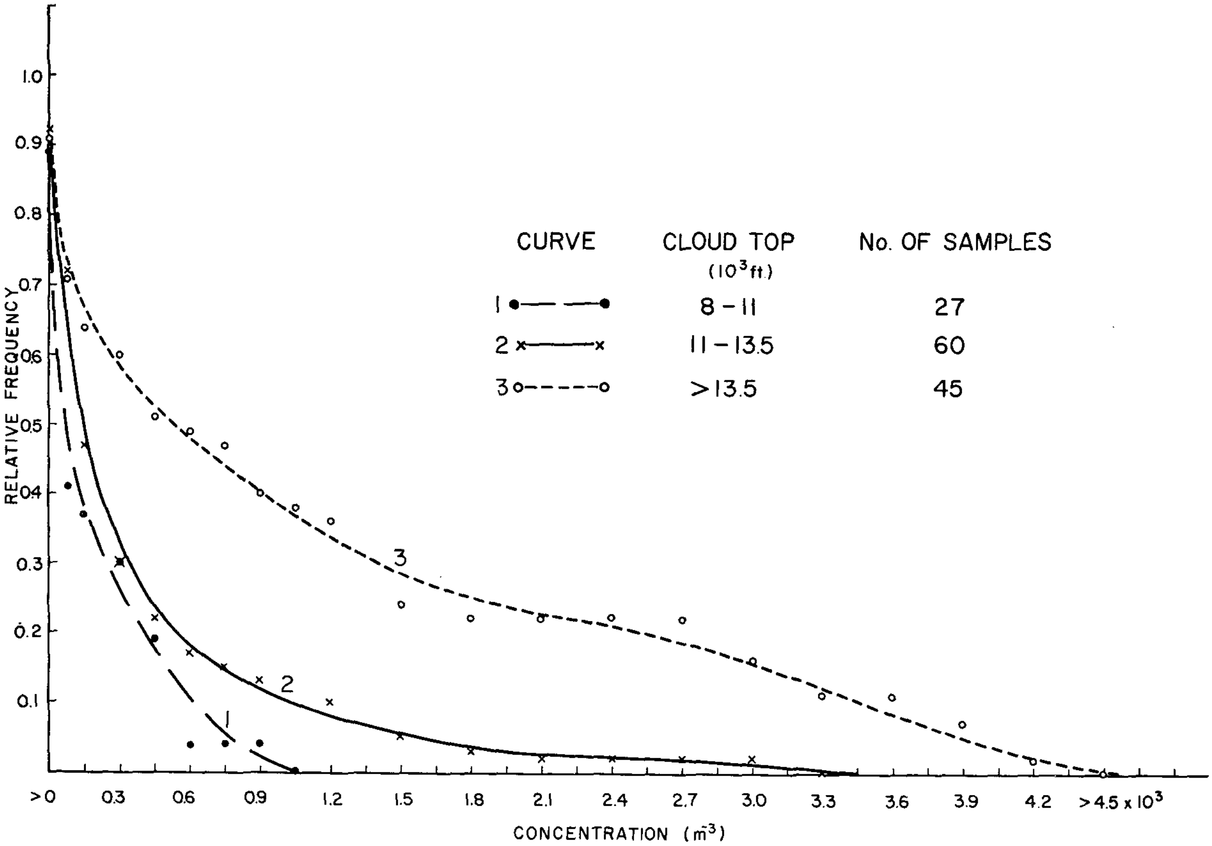


Fig. 1. Relative frequency curves of large-drop (>250 $\mu$ diameter) concentrations, with samples classified according to estimated cloud tops [categories 1, 2 and 3 as defined in Table 1 (1968 and 1969 data)].

concentrations at all sizes >250 μ in diameter than do smaller clouds (which were probed at lower altitudes). The deepest clouds have concentrations which are about a factor of 5 greater than those for the smallest clouds up through drop sizes of 600 μ, and are nearly an order of magnitude larger at 800 μ. The intermediate clouds have concentrations of about a factor of 1.1–2 greater than the small clouds through 750 μ sizes; this ratio increases to about 3 at the larger sizes. If curve 2 can be considered as representing an intermediate stage of development between the lowest and highest height categories, then the relatively larger increase in concentration for drops >750 μ suggests that continued growth of larger drops in the evolving large-drop populations causes a broadening of the distribution.

As might be expected from the differences that were noted in drop distributions, the precipitation-water content (PWC) calculated for individual samples tended to be largest in the tallest clouds also (see Fig. 3). Again the biggest differences occurred between clouds with tops above 13,500 ft and clouds of smaller extent. In fact, the middle group of clouds differs from the smallest primarily because of six or seven samples with high PWC. For cloud tops <13,500 ft, most of the samples (66%) had PWC <10 mg m$^{-3}$, with 84%

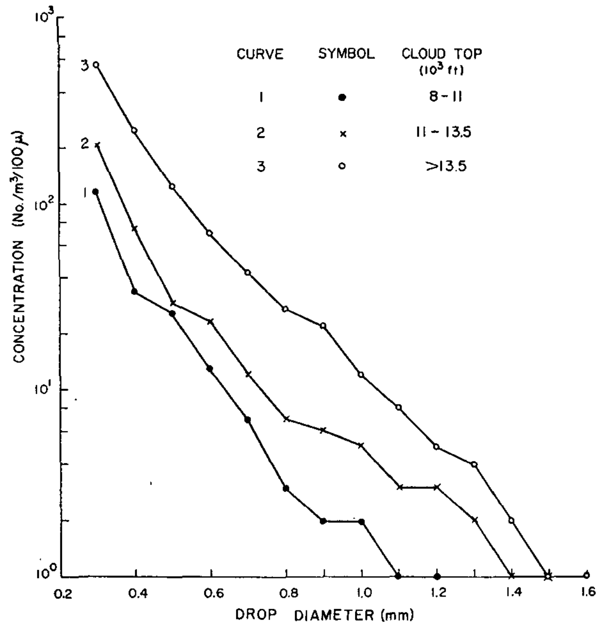


FIG. 2. Mean drop-size distributions in warm cumuli over southeast Texas for drop diameters >250 μ. Samples have been classified according to estimated cloud tops [categories 1, 2 and 3 as defined in Table 1 (1968 and 1969 data)].

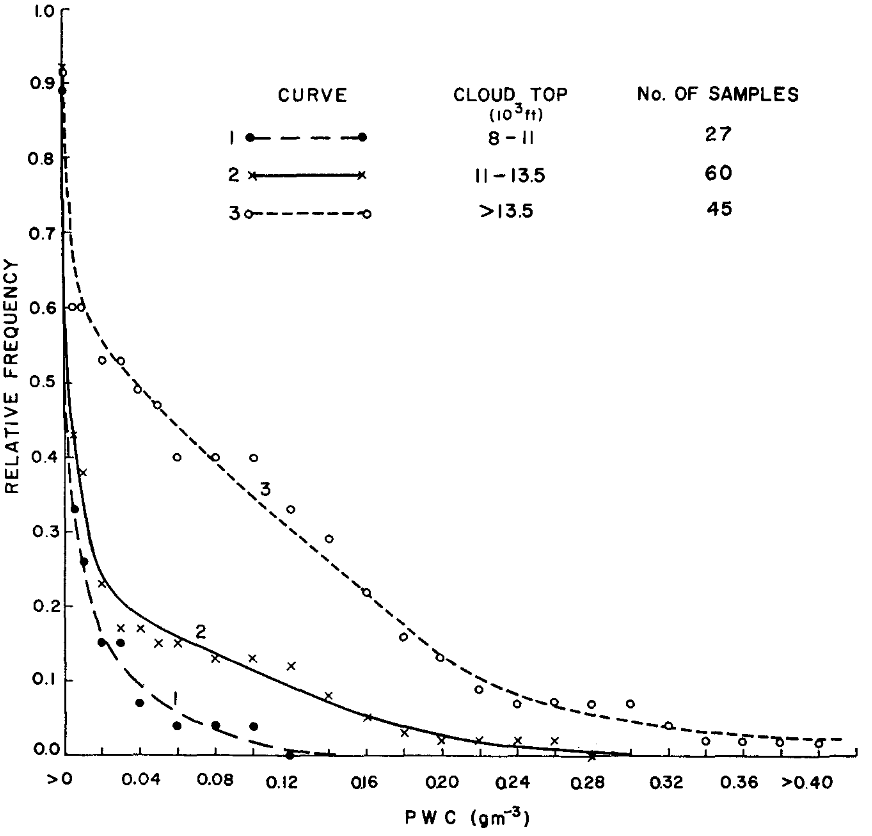


FIG. 3. Relative frequency curves of liquid-water contents, with samples classified according to estimated cloud tops [categories 1, 2 and 3 as defined in Table 1 (1968 and 1969 data)].

TABLE 2. Contingency table showing the distribution of precipitation-water content (PWC) and the mean cloud water content ($CWC_m$) (all units, gm $m^{-3}$) in the cloud regions where the large drops were sampled. The number of occurrences is given in each cell (1968 and 1969 data combined).

| PWC | CWC$_m$<br>0–0.50 | 0.51–1.00 | 1.01–1.50 | 1.51–2.00 | 2.01–2.50 | >2.50 | Total |
|---|---|---|---|---|---|---|---|
| 0 –0.050 | 34 | 31 | 13 | 14 | 7 | 3 | 102 |
| 0.051–0.100 | 1 | 2 | 1 | | | | 4 |
| 0.101–0.150 | 6 | 2 | 3 | | | | 11 |
| 0.151–0.200 | 3 | 4 | 1 | 1 | | | 9 |
| 0.201–0.250 | 3 | | | | | | 3 |
| >0.250 | 2 | 1 | 1 | | | | 4 |
| Total | 49 | 40 | 19 | 15 | 7 | 3 | 133 |

TABLE 3. Contingency table showing the concentration (number $m^{-3}$) of drops $>250\ \mu$ in diameter and the average cloud water content ($CWC_m$, gm $m^{-3}$) in the cloud region where the large drops were sampled. Number of occurrences is given in each cell (1968 and 1969 data combined).

| Concentration | CWC$_m$<br>0–0.50 | 0.51–1.00 | 1.01–1.50 | 1.51–2.00 | 2.01–2.50 | 2.51–3.00 | >3.00 |
|---|---|---|---|---|---|---|---|
| 0–200 | 28 | 19 | 9 | 12 | 4 | 2 | |
| 201–500 | 4 | 6 | 4 | 2 | 3 | 0 | 1 |
| 501–1000 | 4 | 6 | 2 | | | | |
| 1001–1500 | 4 | 6 | 2 | 1 | | | |
| 1501–2000 | 1 | 1 | | | | | |
| 2001–2500 | 1 | | | | | | |
| 2501–3000 | 2 | 0 | 1 | | | | |
| 3001–3500 | 2 | 1 | | | | | |
| 3501–4000 | 1 | 1 | 1 | | | | |
| 4001–4500 | 2 | | | | | | |

having values <30 mg $m^{-3}$. About 10% of the samples in the lower two cloud-height categories had PWC >100 mg $m^{-3}$, while 40% of the samples in the highest cloud group had PWC >100 mg $m^{-3}$. A flatness of all three curves between 60 and 100 mg $m^{-3}$ indicates a bimodality, with the second mode occurring somewhere above 100 mg $m^{-3}$ .This would seem to suggest that a broadening of the drop distribution and/or a marked increase in large-drop concentration occurs about the time when the PWC attains values of 50–60 mg $m^{-3}$.

Mean cloud-water contents ($CWC_m$) and corresponding precipitation-water contents do not appear to be correlated (see Table 2). There are indications, however, that in cloud regions where the $CWC_m$ is very high (>1.5 gm $m^{-3}$), the PWC tends to be low. The bimodal character of the distribution of PWC, discussed above, is apparent in the marginal totals also.

Similarly, the concentration of large drops and mean cloud-water content are not well correlated (Table 3). However, large numbers of precipitation particles were found only in regions where $CWC_m < 1.5$ gm $m^{-3}$. Conversely, where $CWC_m$ was large, relatively small numbers of precipitation particles (<500 $m^{-3}$) were found. Brown and Braham (1959) observed that similar relationships held in trade-wind cumuli. They concluded that these relationships probably exist as a result of the particle growth mechanism whereby coalescence growth rates are directly proportional to cloud-water content.

The median volume diameters ($D_0$) tended to be larger in the higher clouds (see Fig. 4 and Table 1). Both of the two larger cloud groups (curves 2 and 3)

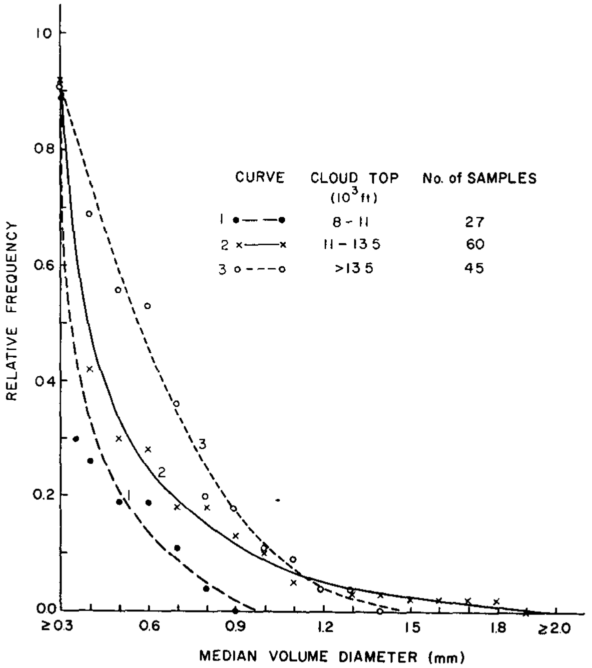


FIG. 4. Relative frequency curves of median volume diameter, with samples classified according to estimated cloud tops [categories 1, 2 and 3 as defined in Table 1 (1968 and 1969 data)].

contained samples with large $D_0$, and in fact, the highest median volume diameters are found in the second category, where two samples had a $D_0 > 1450\ \mu$. However, both of these samples were from clouds whose estimated summits were near the 13,500-ft level that separates the upper two categories. Since estimates of cloud tops very easily could be off by 500–1000 ft, both of the cases actually may belong in the highest cloud

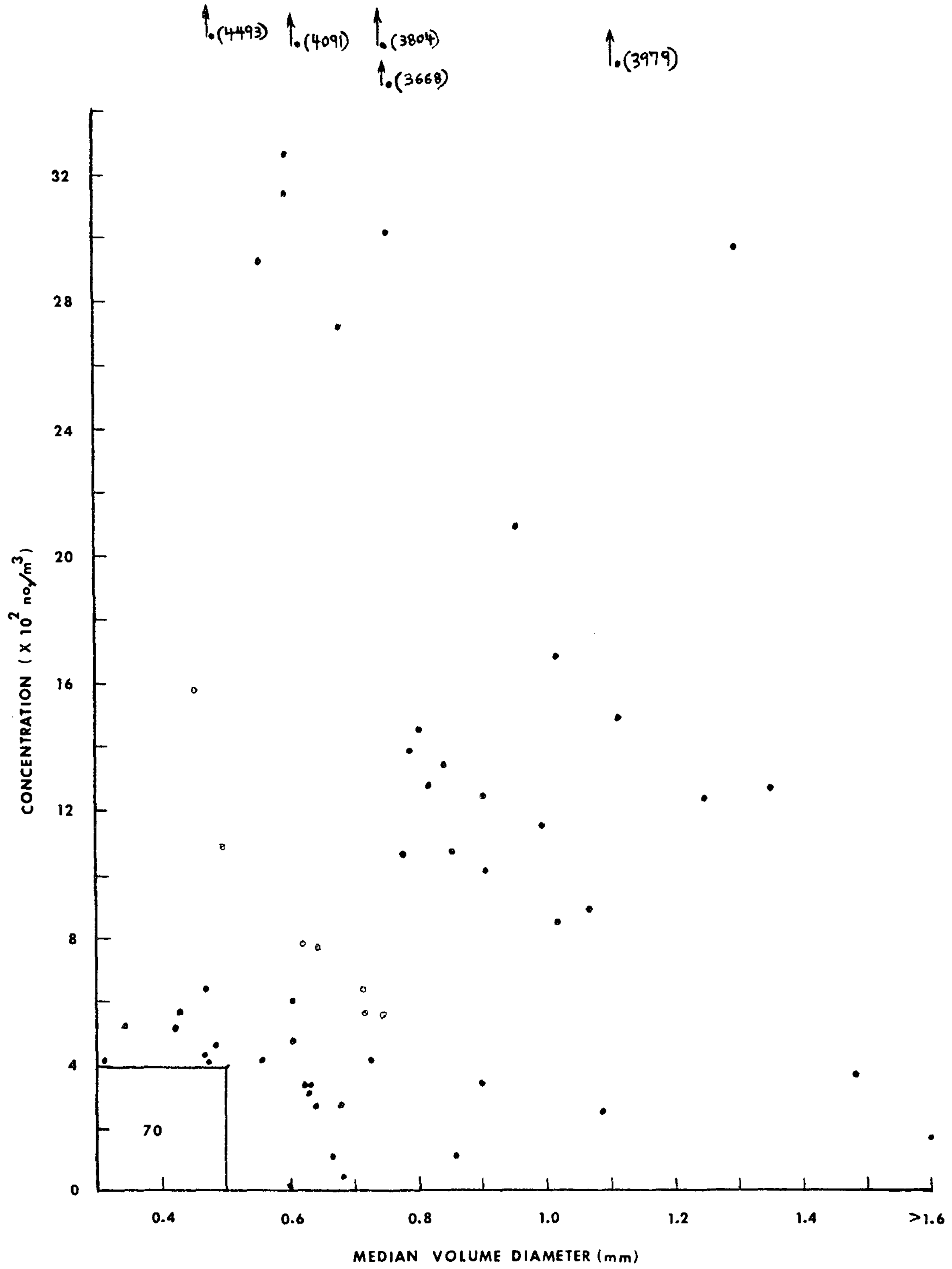


FIG. 5. Median volume diameter vs concentration of drops ($\geq 250\ \mu$ in diameter) for 1968 and 1969 data.

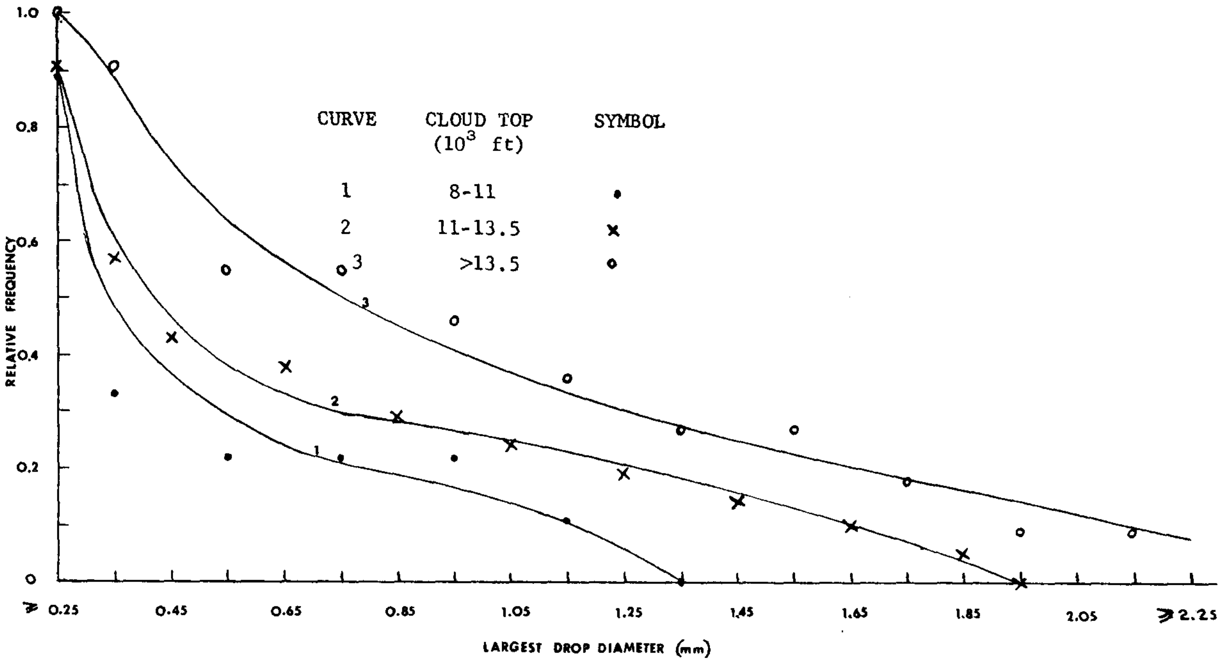


Fig. 6. Relative frequency curves of largest drop sizes observed in individual clouds (considering all penetrations of cloud), with data classified according to estimated cloud tops [categories 1, 2 and 3 as defined in Table 1 (1968 and 1969 data)].

category. Mean diameters are less than 500 $\mu$ in about 64% of all the samples. Even with sample volumes as small as those represented in these collections, 8% of the samples had a $D_0 > 1000\ \mu$, the largest being 1868 $\mu$.

The median volume diameters are approximately correlated with concentrations up to about 1200–1800 $\mathrm{m}^{-3}$ (see Fig. 5). With higher concentrations, the median volume diameters show a tendency to become smaller again. This seems to suggest that as the concentration of drops increases to about 1200–1800 $\mathrm{m}^{-3}$, there also is a tendency for the size distribution to broaden. As larger drops are introduced into the distribution, the median volume diameter tends to increase. For concentrations $> 1200$–$1800\ \mathrm{m}^{-3}$, the smaller drops account for most of the additional numbers. The very high concentration of drops in the lower end of the range of sizes of precipitation particles offsets the size advantage of the relatively fewer larger drops so that a greater proportion of PWC is contributed by the smaller drops. This results in a lowering of $D_0$.

The largest drops measured were $\sim 2.3$ mm in diameter, but drops 1 mm in diameter were found fairly often in these warm cumuli. About 30% of the clouds contained drops $\geqslant 1.05$ mm. There was a tendency for the largest drops to be found in the highest clouds (see Fig. 6). The maximum drop sizes in clouds with tops between 11,000 and 13,500 ft tended to be midway between the largest drop sizes found in the largest and smallest clouds. However, as many clouds contained drops $> 1$ mm in the intermediate group as in the highest group.

A special subsample of 52 segments has been studied to determine the characteristics for regions of cloud in which there was pronounced vertical motion. Mean drop-size distributions for the updraft and downdraft regions of cloud, stratified according to the estimated height of the cloud top, are presented in Fig. 7. A comparison of the four distributions indicates that in the mean:

1) In clouds with tops below 13,000 ft, the downdraft sections have broader drop distributions and higher concentrations of precipitation particles than the updraft sections have.

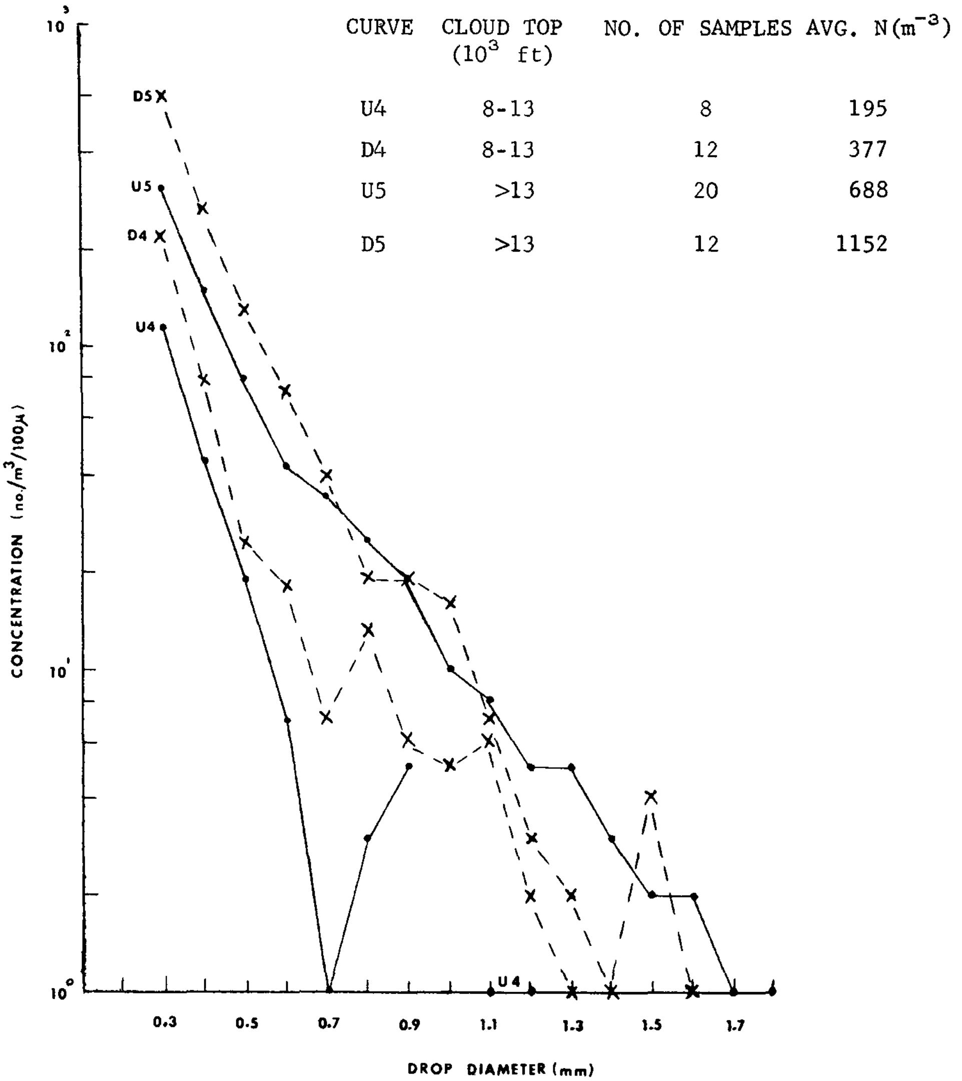
2) In clouds with tops above 13,000 ft the downdraft sections have higher concentrations of precipitation particles, but about the same range in drop sizes.

3) The height of clouds plays a more important role in determining drop concentration and size distribution range than does the updraft or downdraft criterion. For example, the updraft section of clouds with tops $> 13{,}000$ ft has a broader distribution and higher concentrations of precipitation particles than has the downdraft section of clouds with tops $< 13{,}000$ ft.

### *b. Comparison between the samples for each year*

The data for the two years have been analyzed separately for the purpose of comparison. Table 4 contains information on sample size and average distribution parameters for each year; it also shows the sample size and average concentrations published by Brown and Braham (1959) for trade wind cumuli.

The frequency distributions of concentration (Fig. 8) and the average total concentrations (Table 4) for



| CURVE | CLOUD TOP ($10^3$ ft) | NO. OF SAMPLES | AVG. N($m^{-3}$) |
|---|---|---|---|
| U4 | 8-13 | 8 | 195 |
| D4 | 8-13 | 12 | 377 |
| U5 | >13 | 20 | 688 |
| D5 | >13 | 12 | 1152 |

FIG. 7. Mean drop-size distributions in warm cumuli over southeast Texas for drop dia meters >250 μ. Samples have been classified according to type of vertical motion (U, updraft; D, downdraft) and estimated cloud tops (1968 and 1969 data).

samples stratified according to height of the top of the cloud show that, in both years, the tallest clouds tended to have the highest concentrations. This is consistent with the findings for the combined (total) sample. However, the intermediate cloud group is very similar to the high-cloud distribution in the 1968 case, while in 1969 it is much more similar to the small-cloud group. This suggests that in 1968 the smaller clouds were

TABLE 4. Average values of the distribution parameters for three groups of data, classified according to the height of the cloud top for 1968 and 1969 independently. Average values of concentrations (drop sizes 250–650 μ) for trade-wind cumuli, taken from Brown and Braham (1959), are also shown. See Fig. 10. for 1968 curves 1, 2, 3 and 1959 curves 6, 7, 8.

| | 1968 | | | 1969 | | | 1959 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Curve reference no. | | | Curve reference no. | | | Curve reference no. | | |
| Cloud parameter | 1 | 2 | 3 | 1 | 2 | 3 | 6 | 7 | 8 |
| Cloud tops ($10^3$ ft) | 8–11 | 11–13.5 | >13.5 | 8–11 | 11–13.5 | >13.5 | 6–9 | 9–12 | >12 |
| Penetration altitude ($10^3$ ft) | 9.43–9.6 | 11–12 | 12–12.1 | 7.9–10 | 10–12.6 | 12–13.5 | 5.5–7 | 7–9 | 7–9 |
| No. of samples | 14 | 12 | 15 | 13 | 48 | 30 | 46 | 35 | 12 |
| No. of clouds | 2 | 5 | 3 | 7 | 16 | 8 | 46 | 35 | 12 |
| Average $N$ ($m^{-3}$) | 356 | 1193 | 1802 | 43 | 166 | 804 | 870 | 2540 | 1520 |
| Average $D_0$ ($\mu$) | 477 | 680 | 828 | 233 | 444 | 469 | — | — | — |
| Average PWC (mg $m^{-3}$) | 29.69 | 107.26 | 135.5 | 0.63 | 8.78 | 67.76 | — | — | — |

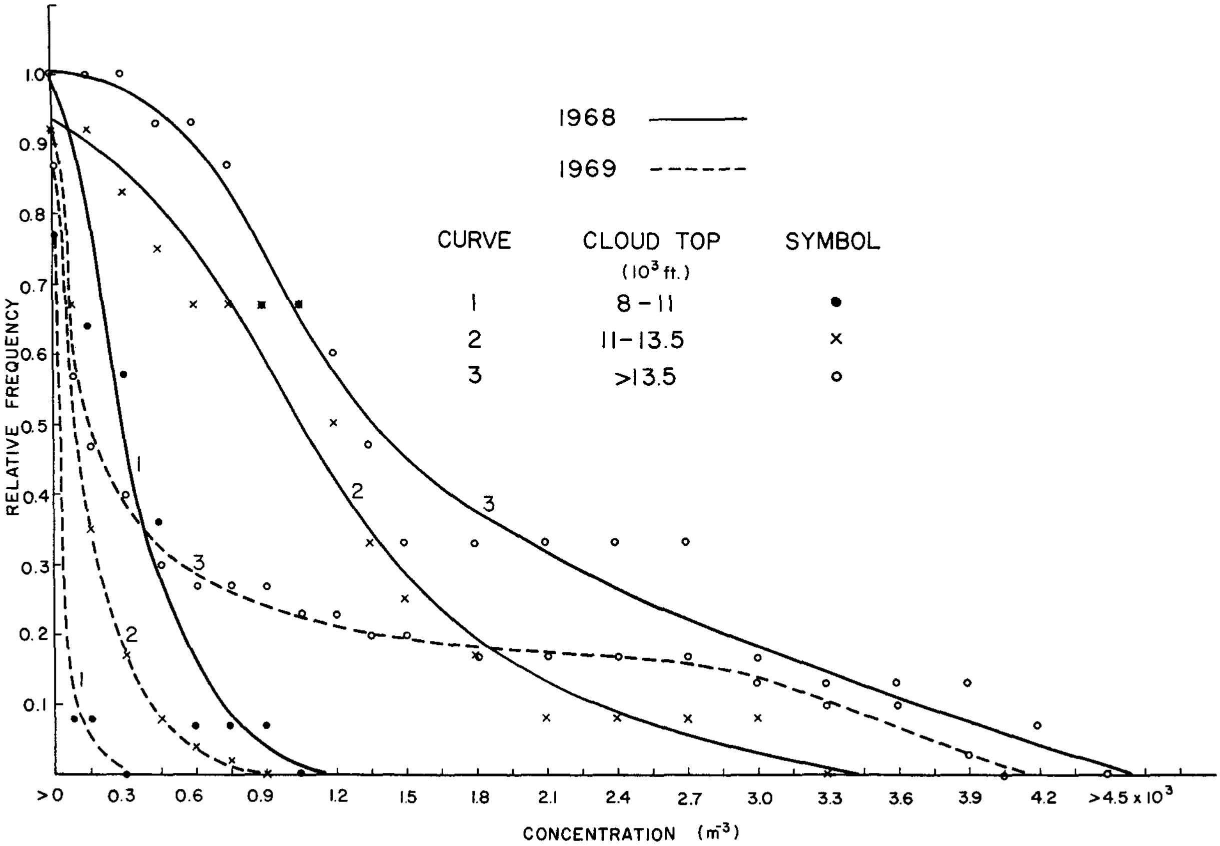


Fig. 8. Relative frequency curves of large-drop (>250 μ diameter) concentrations, with samples classified according to estimated cloud tops [categories 1, 2 and 3 for each year as defined in Table 4].

better producers of large drops than in 1969. Also, except for about seven samples in the tallest cloud category in 1969, curve 3 (1969) would be similar to curve 1 (1968). This means that, neglecting a few samples, the concentrations in the tallest clouds in 1969 would be almost as low as concentrations found in the lowest clouds in 1968. A comparison of the average concentrations for each year (Table 4) reveals that the 1968 average concentrations are 7–8 times larger than the 1969 concentrations in the first two cloud categories, and are more than double the 1969 concentrations in the third category.

Mean drop-size distributions, for samples stratified according to height of the top of the cloud, are presented separately for each of the two years in Fig. 9. As was noted in the mean distributions for both years combined, the distributions for each individual year indicate that, in the mean, the taller cumuli have a broader distribution and higher concentrations of drops >250 μ in diameter than do smaller cumulus clouds. Here also, as in the frequency distribution of concentration, the clouds of medium depth (curve 2) are more like the tallest clouds (curve 3) in 1968 but are more similar to the smallest clouds (curve 1) in 1969. The mean size distributions in 1968 for cloud heights in categories 1 and 2 are broader than are found in the

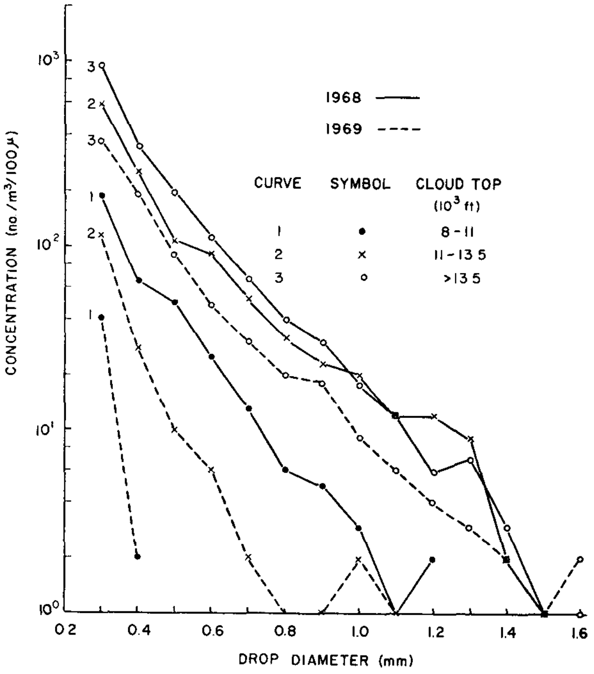


Fig. 9. Mean drop-size distributions in warm cumuli over southeast Texas for drop diameters >250 μ. Samples have been classified according to estimated cloud tops [categories 1, 2 and 3 for each year as defined in Table 4].

TABLE 5. Same as Table 3 except for 1968 data only.

| Concentration | CWC$_m$<br>0–0.50 | <br>0.51–1.00 | <br>1.01–1.50 | <br>1.51–2.00 | <br>2.01–2.50 | <br>2.51–3.00 | <br>>3.00 |
|---|---|---|---|---|---|---|---|
| 0–200 | 4 | 3 | | | | | |
| 201–500 | 2 | 1 | 1 | 2 | | | |
| 501–1000 | 2 | 5 | 2 | | | | |
| 1001–1500 | 3 | 5 | 2 | 1 | | | |
| 1501–2000 | 1 | | | | | | |
| 2001–2500 | 1 | | | | | | |
| 2501–3000 | 2 | 0 | 1 | | | | |
| 3001–3500 | 1 | | | | | | |
| 3501–4000 | | | | | | | |
| 4001–4500 | 2 | | | | | | |

1969 distributions for similar cloud-height categories. Not much difference is apparent between the two years in the breadth of the mean size distributions for the tallest clouds.

Table 3 gave the mean cloud-water content vs the large-drop concentration for the combined data. Tables 5 and 6 present the same information for 1968 and 1969, respectively. The feature that stands out most when comparing these tables is the fact that much higher values of CWC$_m$ were observed in 1969, and the proportion of samples with CWC$_m$ $>1.5$ gm m$^{-3}$ also was much higher in 1969 (24% vs 7%). In each year there is a pronounced tendency for the highest drop concentrations to be associated with low cloud-water contents.

## 4. Discussion

In the upper regions of the warm cumuli that were investigated over southeast Texas, it was found that relatively high concentrations of precipitation particles can occur. Concentrations exceeding 1000 m$^{-3}$ were found in nearly 25% of the clouds. Drop sizes 1 mm in diameter were found fairly often, and 2-mm drops were occasionally sampled. The precipitation water content generally is found to be less than 0.1 gm m$^{-3}$.

The effect of cloud height on the precipitation characteristics was found to be quite pronounced. Higher concentrations and broader distributions generally were found in the tallest clouds. Consequently, the largest median volume diameters usually were associated with the highest clouds.

In comparisons between concentration of precipitation particles and CWC$_m$, it was found that large quantities of drops were associated with low CWC$_m$. Conversely, large values of CWC$_m$ were associated with small numbers of drops $>250\,\mu$ diameter. Brown and Braham (1959) found that the same relationship was true for trade-wind cumuli.

Brown and Braham have studied characteristics of large-drop distribution in both trade cumuli (1959) and cumulus congestus over Missouri (1963). Properties of these cloud populations are listed in Table 7 along with those of the Texas clouds. Considering only drops between 250 and 650 $\mu$ diameter, they found that 4.45 mm$^6$ m$^{-3}$ was the lowest reflectivity value associated with the trade-wind shower. The reflectivities of the Texas warm cumuli were recomputed for this restricted size range for comparison with reflectivity characteristics of cumuli in the two other above-mentioned regions. From these data, it appears that the following general observations can be made concerning the warm cumuli studied:

1) More than half of the warm clouds in southeast Texas will develop drop concentrations of at least 100 m$^{-3}$ in some part of the cloud if they contain any large drops at all. This result is midway between the findings of the other two regions. The 1968 clouds had much higher concentrations and consequently they compare better with the trade-wind cumuli, while the 1969 data are in close agreement with data obtained from the Missouri clouds.

TABLE 6. Same as Table 5 except for 1969 data only.

| Concentration | CWC$_m$<br>0–0.50 | <br>0.51–1.00 | <br>1.01–1.50 | <br>1.51–2.00 | <br>2.01–2.50 | <br>2.51–3.00 | <br>>3.00 |
|---|---|---|---|---|---|---|---|
| 0–200 | 24 | 16 | 9 | 12 | 4 | 2 | |
| 201–500 | 2 | 5 | 3 | 0 | 3 | 0 | 1 |
| 501–1000 | 2 | 1 | | | | | |
| 1001–1500 | 1 | 1 | | | | | |
| 1501–2000 | 0 | 1 | | | | | |
| 2001–2500 | | | | | | | |
| 2501–3000 | | | | | | | |
| 3001–3500 | 1 | 1 | | | | | |
| 3501–4000 | 1 | 1 | 1 | | | | |
| 4001–4500 | | | | | | | |

TABLE 7. Summary of precipitation particle measurements obtained in Texas cumuli and those reported by Brown and Braham (1959, 1963) in trade-wind cumuli and cumulus congestus in Missouri. ($N$ denotes concentration of precipitation particles per cubic meter.)

| | 1968 | 1969 | Totals | Trade wind cumuli | Cumulus (Missouri) |
|---|---|---|---|---|---|
| Traverses with usable data | 41 | 92 | 133 | 104 | 133 |
| Number of clouds | 10 | 30 | 40 | 104 | 58 |
| Clouds providing at least one measurable particle ($\geqslant 250\ \mu$ diameter) | 10<br>(100%) | 27<br>(90%) | 37<br>(92.5%) | 94<br>(90%) | 44<br>(76%) |
| Clouds with $N \geqslant 100\ \mathrm{m}^{-3}$ | 10<br>(100%) | 14<br>(47%) | 24<br>(60%) | 80<br>(77%) | 25<br>(43%) |
| Clouds with $N \geqslant 1000\ \mathrm{m}^{-3}$ | 7<br>(70%) | 2<br>(7%) | 9<br>(22.5%) | 50<br>(48%) | about<br>(20%) |
| Clouds with computed radar reflectivity $Z \geqslant 4.45\ \mathrm{mm}^6\ \mathrm{m}^{-3}$ (considering size range 250–650 $\mu$ diameter only) | 7<br>(70%) | 2<br>(7%) | 9<br>(22.5%) | 53<br>(51%) | 8<br>(14%) |

2) Overall, particle concentrations $>1000\ \mathrm{m}^{-3}$ are relatively infrequent. However, a very large difference is apparent between 1968 and 1969. Again the 1968 data are in better agreement with trade-wind cumuli findings and the 1969 results compare reasonably well with the midwest results of Brown and Braham.

3) A large fraction of the 1968 cases had radar reflectivities computed that were greater than or equal to the tropical precipitation threshold value, while a very small fraction of the 1969 clouds had such large $Z$ values. Again a large difference between the two years was apparent with the 1968 data corresponding better with the trade-wind data, and the 1969 results comparing well with the midwest results.

The apparent tendency for the 1968 Texas clouds to be more favorable producers of large drops than trade-wind cumuli may stem from the selectivity used in sampling. The trade-wind cumuli were sampled essentially at random, whereas data from the present study many times were collected only when the scientist aboard judged large drops to be present.

The mean drop-size distributions for trade-wind cumuli are reproduced in Fig. 10 from the Brown and Braham (1959) paper along with those for the 1968 Texas clouds in order to illustrate the similarities that exist between the distributions from the two regions. In interpreting this graph, it should be noted that cloud bases in the trade-wind region generally are about 1500 ft lower than average cloud bases of Texas cumuli; therefore, although the average heights of the tops of clouds from the two regions differ by 2000 ft, the average thicknesses of the clouds in each region probably compare more favorably. Thus, cloud depths for clouds in categories 1, 2 and 3 are about the same as those in categories 6, 7 and 8, respectively. The small clouds of the trade-wind region are far better producers of large drops than are the small clouds of Texas. The concentrations in the small trade-wind clouds (curve 6) are a factor of 2–3 greater than those for the 1968 small clouds (curve 1), over all size ranges to 600 $\mu$. Trade-wind cumuli of heights >9000 ft and the 1968 Texas clouds of heights >11,000 ft (both representing depths of greater than 7000 ft) have very similar distribution characteristics. The trade cumuli tend to have higher concentrations in the smaller drop sizes and slightly lower concentrations in the larger sizes. However, clouds of about 4000–5000 ft thickness in the trade-wind region (curve 6) contain nearly as many drops as do Texas clouds that are nearly 3000 ft thicker (curve 2); they

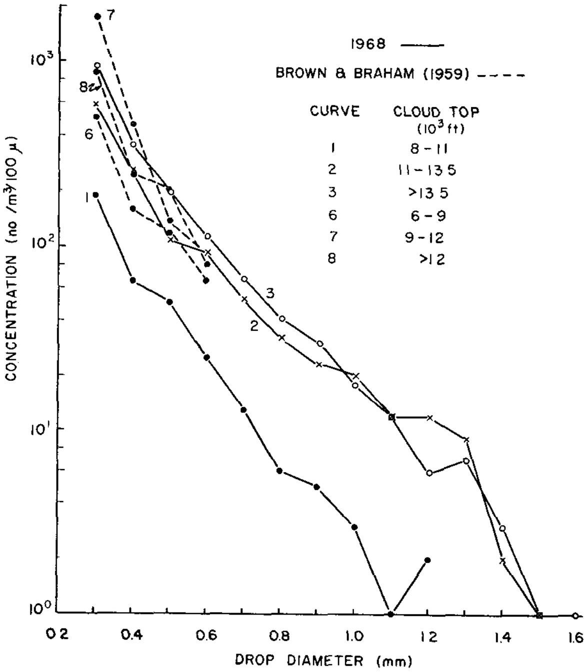


FIG. 10. Mean drop-size distributions in trade-wind cumuli and in warm cumuli over southeast Texas for drop diameters $>250\ \mu$. Samples have been classified according to estimated cloud tops [categories 1, 2, 3, 6, 7 and 8 defined in Table 4].

also have a very similar distribution of drop sizes. The trade-wind cumuli may have more numerous giant condensation nuclei available than the Texas clouds, which would explain the occurrence of the higher average concentration of drops that was found (Table 4).

The preceding comparisons indicate that, on the whole, the efficiency of Texas cumuli in developing precipitation particles in large numbers is somewhere between that found in the larger cumulus congestus of Missouri and that found in the trade-wind cumuli. Furthermore, the marked differences between the 1968 and 1969 findings suggest that the concentration of and the source of hygroscopic nuclei and/or the prevailing synoptic conditions play an important role in determining the drop distributions of these clouds. Further studies that investigate the effect of different weather patterns on the distribution and concentration of large drops within clouds would be highly productive.

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## REFERENCES

Battan, L. J., 1959: *Radar Meteorology*. University of Chicago Press, 161 pp.

Braham, R. R., Jr., 1968: Meteorological basis for precipitation development. *Bull. Amer. Meteor. Soc.*, **49**, 343–353.

Brown, E. N., 1958: A technique for measuring precipitation particles from aircraft. *J. Meteor.*, **15**, 462–466.

——, 1961; A continuous recording precipitation particle sampler. *J. Meteor.*, **18**, 815–818.

——, and R. R. Braham, Jr., 1959: Precipitation-particle measurements in trade-wind cumuli. *J. Meteor.*, **16**, 609–616.

——, and ——, 1963: Precipitation-particle measurements in cumulus congestus. *J. Atmos. Sci.*, **20**, 23–28.

National Center for Atmospheric Research, 1965: Aircraft and instrumentation in atmospheric research. NCAR Tech. Note TN-6, pp. II B 44-II B 48.