The Microstructure and Colloidal Stability of Warm Clouds

Part I — The Relation between Structure and Stability

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(Manuscript received March 22, 1957)

Abstract

Observations on the droplet spectra of different kinds of warm clouds have shown that systematic differences in microstructure exist between the various cloud types. These differences in microstructure are related in a simple way to differences in observed colloidal stability.

1. Introduction

It is well known that clouds warmer than freezing sometimes produce rain, especially in maritime air. However, the factors which determine whether a warm cloud will rain are not well understood. It is generally agreed that the raindrops form by coalescence of cloud droplets; it must be expected that the existence of large droplets in a cloud will assist this process, both because the collection efficiency of large drops is greater than that of small ones (Pearcey and Hill, 1957) and because, even with a constant collection efficiency the mass rate of growth of a droplet increases like r^4.

This expectation has been confirmed by observations of droplet spectra in various types of cloud.

2. Observations

Cloud droplet spectra have been measured in various kinds of cloud: continental, "transitional" and maritime cumuli, the orographic cloud of the windward slope of the island of Hawaii, and "dark stratus", which is seen at times over the sea. The measurements were made with the sampler described by Squires and Gillspie (1952). Before 1953, the droplets were impacted on a layer of magnesium oxide. As no reliable calibration could be derived for this layer, only the droplet concentrations are known definitely. From 1954 on, a layer of soot has been used. The calibration of this layer is known with a probable error which is less than 5 % for $d > 20$ microns but increases to about 15 % for $d = 5$ microns.

In cumuli, the observing runs were made at various levels with the intention of securing representative data for the whole cloud. Some of the data on droplet concentrations in continental and maritime cumuli have been published elsewhere (Squires, 1956). The Hawaiian orographic cloud and the observational procedure used have been described by Squires and Warner (communicated). It need only be remarked that it forms on the island of Hawaii when the trade wind is fairly strong, and that this slope is quite regular from the coast up to 6,500 ft, averaging about 5 %.

The full results of observations in this cloud have been given by SQUIRES and WARNER (loc. cit.). In "dark stratus" layers which occur at times over the sea, samples were taken on horizontal passes through the middle of the cloud.

The observations before 1954, using a magnesium oxide layer, were made over south-eastern Australia and over the adjacent seas. Later observations using a soot layer were made near Hilo, Hawaii in 1954 and in inland Australia in 1956. "Maritime" cumuli include only those which were observed over the sea in an unmodified maritime air mass. "Continental" cumuli include those observed over the land in an air mass which was estimated to have spent at least two full days over the land surface. "Transitional" cumuli include those forming in an air mass which had been over the land for less than two days.

3. Results

The droplet spectrum has been found to change rapidly and erratically in all clouds sampled. Nevertheless, these variations are not so great as to mask the characteristic differences between the various kinds of cloud. These differences are illustrated in Figs. 1—4, which show the mean spectra found in individual examples of four different cloud types. In each case, the liquid water content and droplet concentration given is that corresponding to the mean spectrum. These four figures illustrate the fact that, as between these four categories of cloud, low droplet concentrations are strongly associated with broad droplet spectra and large average and maximum droplet sizes, and high concentrations with narrow spectra and small average and maximum droplet sizes. Statistical evidence of this association is shown in Fig. 5. Here, the mean droplet concentration found in a single traverse through a cloud has been plotted against the diameter of the largest droplet found in any sample taken during the traverse. Each sample corresponds to about 30 cm³ of cloud air. Each point in Fig. 5 represents, on the average, eight samples. Fig. 5 shows not only that low droplet concentrations are associated with large maximum droplet diameters, but also illustrates the difference in microstructure between "dark stratus", the Hawaiian orographic cloud, maritime cumuli and continental cumuli. It is apparent that the latter three form a series

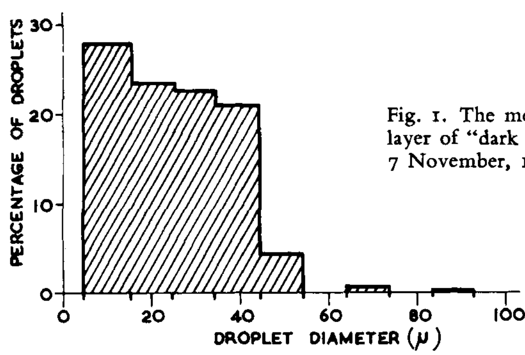

Fig. 1. The mean droplet spectrum (seven samples) in a layer of "dark stratus" at 6,500 ft over Hilo, Hawaii, on 7 November, 1954. Droplet concentration = 24 cm^{-3}; l.w.c. = 0.34 g m^{-3}.

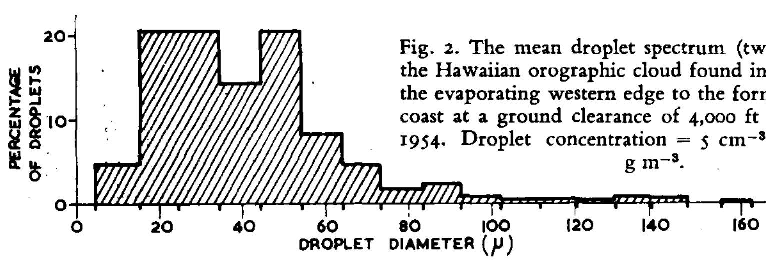

Fig. 2. The mean droplet spectrum (twelve samples) in the Hawaiian orographic cloud found in a traverse, from the evaporating western edge to the forming edge at the coast at a ground clearance of 4,000 ft on 2 December 1954. Droplet concentration = 5 cm^{-3}, l.w.c. = 0.40 g m^{-3}.

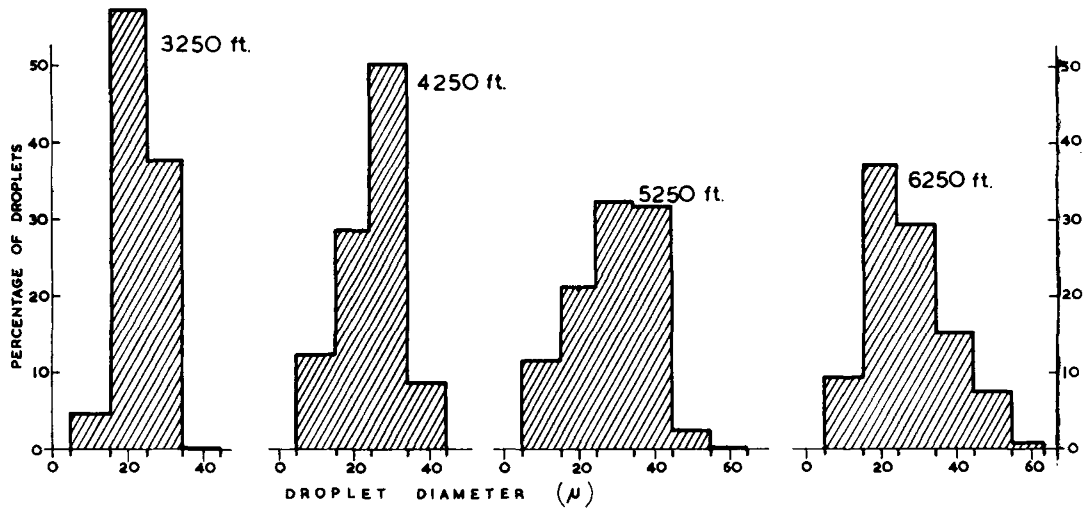

Fig. 3. The mean droplet spectrum at four levels in a tradewind cumulus off the east coast of Hawaii on 23 October 1954. Cloud base was at 2,200 ft, cloud top at 9,500 ft. There was some light rain in parts of the cloud, and turbulence was moderate. Droplet concentrations (n) per cm³ and l.w.c. (w) g per m³:

3250′, $n = 74$, $w = 0.50$;
4250′, $n = 51$, $w = 0.53$;
5250′, $n = 27$, $w = 0.50$;
6250′, $n = 30$, $w = 0.42$.

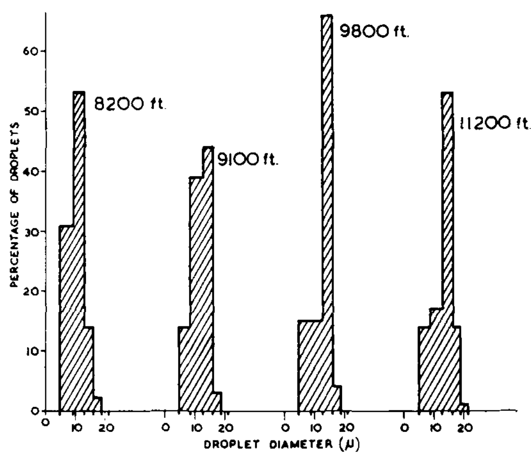

Fig. 4. The mean droplet spectrum at four levels in a continental cumulus over the Blue Mountains north-west of Sydney on 2 November 1956. Cloud base was 7,200 ft, cloud top at 12,000 ft. Droplet concentrations (n) per cm³ and l.w.c. (w) g per m³:

8,200′, $n = 490$, $w = 0.35$
9,100′, $n = 270$, $w = 0.29$
9,800′, $n = 250$, $w = 0.31$
11,200′, $n = 350$, $w = 0.48$.

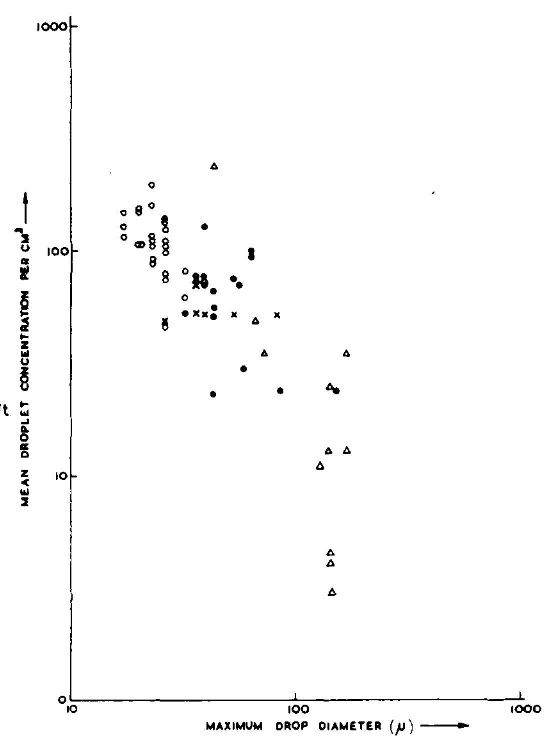

Fig. 5. Scatter diagram relating the maximum droplet diameter found in traverse of a cloud to the mean droplet concentration. Open circles, continental cumuli; full circles, maritime cumuli; triangles, the Hawaiian orographic cloud; crosses, transitional cumuli; crossed circle, layer of dark status.

through which the maximum droplet diameter decreases and the droplet concentration increases. The data used in Fig. 5 incorporate only the observations taken with a soot layer, since the earlier observations with magnesium oxide do not give a quantitative measure of droplet diameters. However, because of the association between droplet concentration and spectrum type, which is shown by Figs. 1—5, it is possible to discuss differences in microstructure in terms of droplet concentrations. This has the fundamental advantage of simplicity, and the incidental advantage that it makes it possible to use the observations made with a magnesium oxide layer, so that a considerably greater total volume of data is available. These earlier observations give only a qualitative measure of droplet sizes but they agree in a general way with those which have been measured since on soot, and in particular, show the same strong association between low droplet concentrations on the one hand, and broad spectra, and large average and maximum droplet diameters on the other.

In Fig. 6, observations in five types of clouds have been summarized. Each histogram shows the percentage of all samples in which the droplet concentrations fell within the specified ranges. The more extensive data of Fig. 6 clearly confirm the evidence of Fig. 5, and the impression given by the examples shown in Figs. 1—4.

The Hawaiian orographic cloud was always wholly warmer than freezing. In the other four groups, data have been included from clouds which had tops colder than freezing, but in no case was the temperature at the level of the cloud top lower than — 3° C, nor was

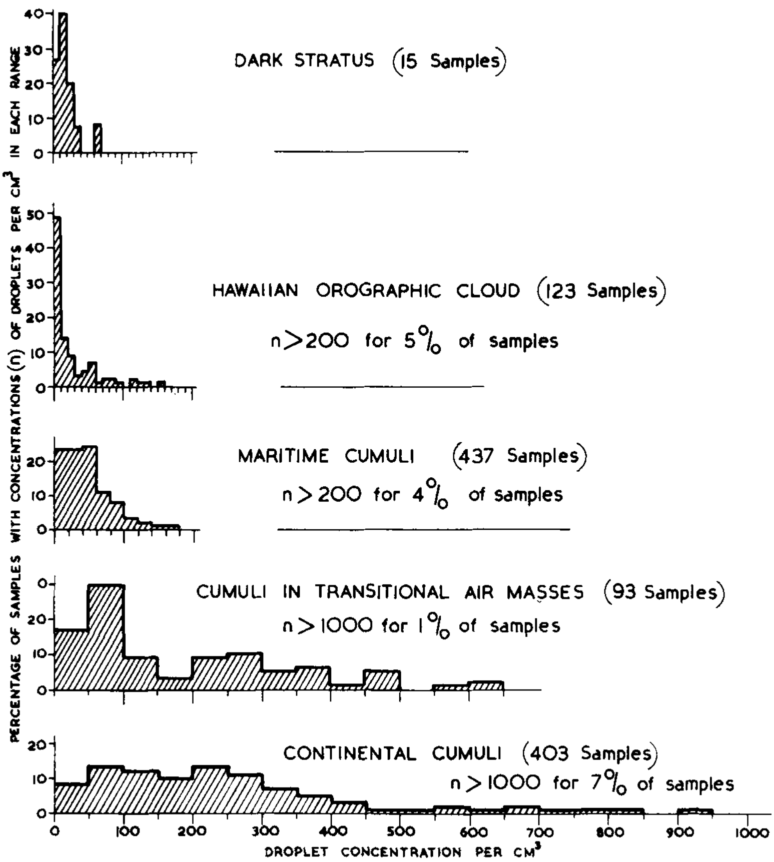

Fig. 6. Histograms of the percentages of samples taken in each of five cloud types for which the droplet concentrations fell in the ranges indicated by the graduations on the horizontal axes. The scale of concentrations is common to the five histograms.

any sign of ice seen in the clouds during the traverses. Only about one in five of the maritime, transitional, and continental cumuli reached above the freezing level and, even in these cases, about 80 % of the observations in the cloud were taken below freezing level. It may be remarked, however, that cumuli which did contain ice, and which have been excluded here, showed no systematic difference in microstructure from warm cumuli.

It will be seen from Figs. 5 and 6 that, although continental cumuli on the whole show high droplet concentrations, a proportion of the samples in these clouds gave concentrations in the range commonly found in maritime cumuli. This is partly due to the fact that dry zones occur in many clouds, in which both the liquid water content and the droplet concentration fall much below their average values. But it partly reflects the fact that continental cumuli do not invariably have high droplet concentrations. On a few days, the median concentration found in them fell below 100 droplets per cm^3.

The cumuli in transitional air masses were sometimes similar to maritime cumuli in microstructure; at other times they had median concentrations of several hundred droplets per cm^3. As a group, they differ from the continental cumuli only in that they show a greater proportion of samples with the low droplet concentrations which characterize maritime cumuli. There is however no clear association between droplet concentrations in cumuli on the one hand, and on the other, the time an air mass has spent, or the distance it has travelled, over land.

4. Colloidal structure and stability

These differences in microstructure can be related in a simple way to known differences in colloidal stability. It is only in recent years that the possibility of warm rain has been generally accepted, and practically all the documented cases of such rain describe cases where warm rain fell over the sea or nearby coastal regions (ALPERT, 1955). Observations off the coasts of Australia and off Hawaii indicate that, in a maritime air mass, warm cumuli which are 6,000 ft deep or more usually rain within half an hour, if they are not already raining when first observed. Over inland Australia, it is rare for cumuli as shallow as this to rain; more commonly, they build to considerable depths, and usually reach well above the freezing level before precipitating. There is some evidence in the literature to confirm these observations. BYERS (1956), summarizing the results of extensive observations on cumuli in the mid-west of the United States and over the Caribbean Sea, states that, for a 50 % chance of precipitating, clouds in the latter area must reach a height, in winter, of 10,000 ft; in the former, of 25,000 ft. BRAHAM et al. (1951) give data concerning the occurence of radar echoes (on 3 cm) in summertime cumuli in New Mexico. As presented, the cloud depths are not directly given, but it is possible to deduce lower bounds for the depth ranges for each group of clouds. BYERS and HALL (1955) give similar data for a 10-cm radar for wintertime cumuli over the Caribbean Sea. From their data, by assuming that the cloud base averaged 2,500 ft above the sea, the cloud depths can be deduced; this assumed height of cloud base would rarely be in error by more than 1,000 ft. The two sets of results are summarized in Table 1.

It is evident from this table that the summertime cumuli of New Mexico are much less efficient in releasing rain than tropical maritime cumuli of similar depths. This is so, despite

Table 1. Cloud depths related to the frequency occurrence of radar echoes.

Caribbean Sea (warm clouds) (after Byers and Hall)		New Mexico (after Braham et al)	
Cloud depth (ft)	Per cent of clouds with echoes	Cloud depth (ft)	Per cent of clouds with echoes
3,500—4,000	2		
4,000—4,500	4		
4,500—5,000	11		
5,000—5,500	13		
5,500—6,000	23	> 5,000—8,000	0
6,000—6,500	28		
6,500—7,000	53		
7,000—7,500	47		
7,500—8,000	73		
8,000—8,500	74		
8,500—9,000	83	> 8,000—11,000	18
9 000 and up	100	> 11,000—14,000	30

the fact that the New Mexican clouds often reach well above freezing level, so that when they do produce rain, it could be as a result of the Bergeron-Findeisen process.

Thus it appears that, in general, warm continental cumuli are colloidally stable. As shown in Section 3 above, they are usually characterized by high droplet concentrations, narrow spectra, and small droplet sizes. However, both of these generalizations are subject to exceptions. It has been pointed out that, occasionally, continental cumuli possess a more or less maritime type of microstructure. The world-wide summary of ALPERT (loc. cit.) shows that warm rain has sometimes been observed far inland. One such case has been observed; a warm cumulus, 5,000 ft deep, was seen to be raining lightly near Broken Hill, some 500 miles west of Sydney, on 13 March 1956. It was here also, on this same day, that the lowest droplet concentrations so far found in continental cumuli were measured. This observation suggests that the occasional instances of colloidal instability in continental cumuli may be associated with the occurrence of a maritime type of microstructure.

The Hawaiian orographic cloud, on most occasions when it was observed, decreased regularly in depth from about 4,000 ft at the coast to about 2,000 ft at its upslope or western edge. Nevertheless, this cloud usually produced quite significant rainfall. The amount of rain decreased steadily inland, but was still appreciable near the western edge of the cloud on some occasions.

Observers have occasionally reported seeing virga fall from "dark stratus" of a depth of 1,000 ft or less. One such case was observed off the east coast of Hawaii on 7 November 1954. A patchy layer of stratus about 500 ft thick based at 6,000 ft (14° C) was producing light rain which was first noticed when the climbing aircraft passed through the rain about 1,500 ft below the cloud.

From these examples, it appears therefore that high droplet concentrations and small average and maximum drop sizes are associated with marked colloidal stability, clouds of considerable depth failing to rain, as in the case of many continental cumuli. Low droplet concentrations, broad spectra, and large average and maximum drop size would seem to be associated with colloidal instability and the release of "warm rain", even from cloud of quite moderate depth.

5. Conclusion

Observations of cloud droplet spectra in a number of different kinds of clouds have shown that marked and systematic differences in microstructure exist, and that as between these differing cloud types, the droplet concentration in a cloud can be used as an index of the type of droplet spectrum, low concentrations being associated with broad spectra and large maximum and average droplet sizes.

Futher, it is shown that these variations in microstructure run parallel with variations in colloidal stability. In agreement with the theoretical expectation concerning the formation of raindrops by coalescence which was mentioned in the Introduction, it appears that a spectrum characterized by relatively large average and maximum droplet sizes is favourable to the operation of the coalescence process.

6. Acknowledgements

The author wishes to thank Mr. K. A. Davidson and Mr. E. Harting for their valuable work on the calibration of the method of measuring droplet sizes, and for their help in making the observations. The measurements were made in aircraft provided and flown by the Royal Australian Air Force.

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