The Influence of Cloud Nucleus Population on the Microstructure and Stability of Convective Clouds

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Abstract

Measurements of the concentration of cloud droplets and of the supersaturation spectrum of the cloud nucleus population in the air below cloud base showed a strong correlation between these properties. It is concluded that variations in the cloud nucleus content of the air are primarily responsible for variations of cloud droplet concentrations and colloidal stability.

1. Introduction

Rain from clouds which do not reach the freezing level, usually called warm rain, is generally agreed to form by coalescence of cloud droplets. It is commonly observed that warm clouds differ widely in efficiency as rain producers; in maritime air, cumuli usually rain soon after reaching a depth of some 6,000 ft, whereas well inland clouds often reach much greater depths without raining. It has been suggested that this difference in behaviour is due to the fact that the droplets in a cloud should be relatively large for the coalescense process to proceed efficiently and that the supersaturation spectrum of those condensation nuclei which grow into cloud droplets ("cloud nuclei") was the chief factor determining the size of the droplets formed in cloud condensation (SQUIRES 1952). In the absence of a method of measuring the spectrum of these cloud nuclei, indirect support for this hypothesis was gained from measurements of droplet spectra in cumuli. It has been shown that the droplet concentration is systematically less in maritime than in continental cumuli (SQUIRES 1956; BATTAN and REITAN 1957), and that the average and maximum drop sizes found in maritime cumuli, are considerably greater than those found in continental cumuli (SQUIRES 1958a). Evidence has been presented to show that these differences cannot be explained by a difference in typical updraught velocity or average lifetime of cloud parcels (SQUIRES 1958b), or in the concentration of giant sea salt nuclei (SQUIRES and TWOMEY 1958).

Techniques capable of measuring the spectrum of cloud nuclei have recently been described by WIELAND (1956) and TWOMEY (1959a). Twomey (loc. cit.) has shown that the cloud nucleus spectra in maritime and continental air, sampled at ground level, were systematically different, the latter being much richer in these nuclei. Typical nucleus spectra and representative updraught speeds were used (TWOMEY 1959b) to compute the number of nuclei which would become activated and grow into cloud droplets in both maritime and continental cumuli; the results are summarized below and compared with the average concentrations observed by SQUIRES (1958a).

The discrepancy between the observed droplet concentrations and the values computed from the nucleus spectra is not very serious: at ground level, the air may have been richer in nuclei than at cloud base level; the observations of nucleus spectra and of cloud droplet concentrations were made quite independently

Table 1. Comparison between average droplet concentrations observed in maritime and continental cumuli and those computed from mean cloud nucleus spectra, for various assumed updraught velocities.

Updraught velocity assumed in computing droplet concentration (m sec^{-1})		Air Mass	
		Maritime	Continental
Computed	0.1	36	290
	1	60	520
	10	100	930
Observed	—	45	228

and not even at the same place or time; finally it is possible that processes may operate within clouds to eliminate some droplets after they have been formed. The results of Table I appear to leave little doubt that the contrast between cloud nucleus spectra in maritime and continental air is the major factor causing the contrast in cloud droplet concentrations. According to the argument presented above, differences in cloud nucleus spectra are ultimately responsible for differences in mean and maximum droplet sizes and in colloidal stability.

Measurements of cloud droplets and cloud nucleus spectra have now been carried out simultaneously, the air sample for spectrum determination being taken in the free air below cloud base.

2. Sampling

A series of flights were made near Parkes, New South Wales, during the spring of 1958. This area, some 300 km inland from Sydney, lies near the northern edge of the westerlies at that time of the year. The wind direction varies from north to north-west ahead of the cold fronts to south to south-west behind them. The prefrontal northerly air typically has had a land trajectory of some 2,000 km, having crossed the coast of Queensland as a south-east to east (trade) wind several days previously and gradually turned southward after penetrating up to 1,000 km inland. The air behind the fronts comes from the Southern Ocean, crossing the intervening 600—800 km in about a day. Thus the air masses sampled at Parkes ranged from fairly continental to slightly modified maritime. Two flights were made from Sydney later in the year, one in continental air from the west, and one in a maritime stream from the south-east.

The techniques for measuring cloud droplets and cloud nuclei both have been described elsewhere (SQUIRES and GILLESPIE 1952; SQUIRES 1958a; TWOMEY 1959a). During each flight droplet samples were taken in one or more non-raining cumuli, usually at several levels, with the aim of deriving an average value for the droplet concentration. Samples of air from below the cloud base were taken in plastic (P.V.C.) bags with a volume of about $^1/_4$ cubic metre; the nucleus content of the air samples was measured on the ground immediately after each flight.

In the DC-3 aircraft used, it was not feasible to circle within the updraught feeding a cumulus, so that there was no assurance that any air sample was representative of the air in which the cloud formed; it is well known that the updraught may differ considerably from the surrounding air in humidity mixing ratio, and hence the cloud nucleus content may also have been different. The following procedure was therefore adopted; during the climb to cloud levels, temperature and humidity measurements were made, plotted on an aerological diagram and the adiabatic condensation levels computed. Usually the air near ground level was found to have an adiabatic condensation level below the observed height of cloud base, while air near cloud base level had a condensation level above cloud base. At some intermediate height the computed condensation level coincided with the observed cloud base; the air sample was taken at this height, on the grounds that the mean properties of this air were most likely to correspond with those of the updraught when it reached cloud base.

3. Determination of Cloud Nucleus Spectra

The production of continuous small supersaturations by diffusion between surfaces of pure water and dilute aqueous HCl, and the measurement by a photographic technique of the droplet concentration in the cloud produced when an air sample is admitted to a water-HCl diffusion chamber, has been discussed in detail elsewhere (TWOMEY 1959a). During the observations under discussion, cloud nucleus measurements were made by passing a portion of an air sample into each of a set of five diffusion

chambers containing HCl solutions selected to give a range of supersaturation from 0.08 % to 8 %. Each chamber was thoroughly flushed with filtered nucleus-free air before accepting the sample air; the procedure used was known to permit no pollution of the diffusion chambers by room air. Following the introduction of sample air, clouds formed in the diffusion chamber and several photographs were taken of each cloud. From the photographs, the number of droplets formed per unit volume in each chamber was determined and plotted as a function of supersaturation. A curve was then drawn through the representative points; this curve was taken as the nucleus spectrum. A small correction (usually of order +10 %) was made to allow for the decrease in number of nuclei during the period for which they had been stored. This correction was only a minor one and the final results would be little changed by its omission.

4. Computation of Cloud Droplet Concentration from Cloud Nucleus Spectra

Given the nucleus spectrum, it would be possible to predict directly the concentration of cloud droplets, if the maximum supersaturation attained in the cloud was known. Since it is not possible to measure the supersaturation, it is necessary to compute its maximum value.

This value is influenced not only by the rate of cooling of the air but also by the number and nature (critical supersaturations) of the nuclei present. It has been shown (TWOMEY 1959b) that the expression

$$S_m^{k+2} = \frac{1.6 \times 10^{-3}\, V^{3/2}}{c k B^{3/2} k^{1/2}} \qquad (1)$$

gives, with fair accuracy, the maximum supersaturation S_m(°C) attained when air at 800 mb, 10° C, containing nuclei distributed logarithmically so that there are cS^k nuclei per cm³ active at supersaturations up to and including S, ascends at V cm sec^{-1}. The computed cloud droplet concentration is then found from the nucleus spectrum; it is simply the number of nuclei active at supersaturation S_m.

When the observed nucleus spectra were approximately linear when plotted on a logarithmic scale, the straight line log N= log c+k log S furnishing the best approximation was drawn, and the corresponding values of c and k were inserted in equation (1) to obtain the maximum supersaturation; the computed number of cloud droplets was then obtained by reference to the nucleus spectrum.

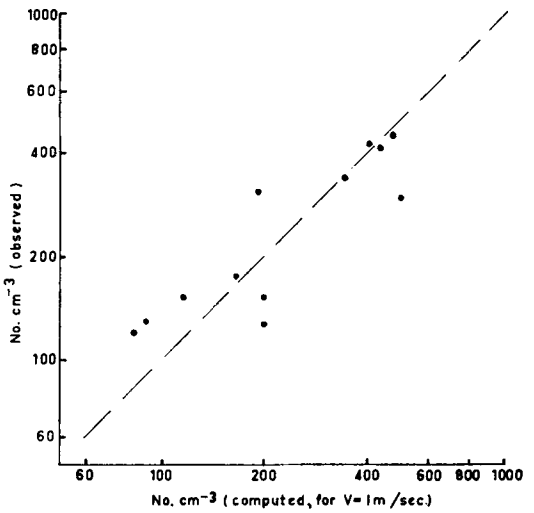

Fig. 1. Measured cloud droplet concentrations (cm^{-3}) plotted against those computed from the observed cloud nucleus spectra, assuming a value of 1 m sec^{-1} for the updraught velocity in the critical region near cloud base where the supersaturation passes through its maximum value. The dashed line represents exact agreement between observed and computed values.

Some of the samples gave spectra which deviated considerably from the logarithmic; S-shaped curves (designated type B curves in an earlier paper) were found on several occasions. In such cases, the number of nuclei may increase by a factor of ten over a relatively small range of supersaturation, and the computation of cloud droplet concentration may not be reliable, since small errors in the maximum supersaturation could entail large errors in computed cloud droplet concentration. Observations from which spectra of this kind resulted (three out of a total of fifteen) were not included in the final analysis.

5. Comparison between Observed and Computed Droplet Concentration

In Figure 1 the mean of observed cloud droplet concentrations are plotted against the droplet concentration computed from the nucleus spectrum (assuming an updraught of 1 m/sec). It is apparent that the agreement between the observed and computed values is excellent. This supports the contention that the systematic differences observed with respect

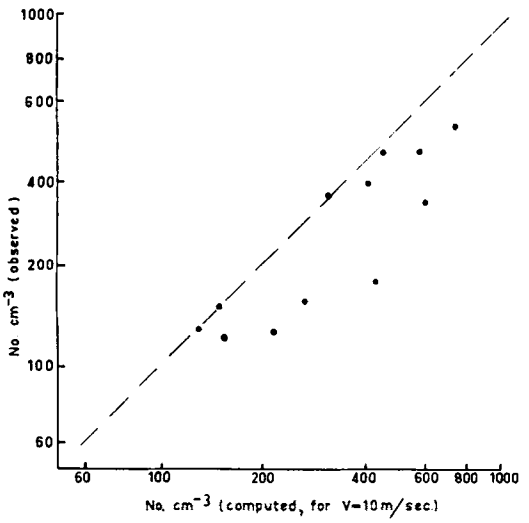

Fig. 2. Measured versus computed droplet concentrations for an assumed updraught velocity of 10 m/sec. The dashed line represents exact agreement between observed and computed values.

to cloud droplet concentration and spectra are primarily caused by variations in cloudnucleus population.

The use of a value other than 1 m/sec for the updraught velocity would give a set of different values for S_m and hence for the computed droplet concentration. However, the computed droplet concentration, being proportional to $V^{3k/2k+4}$ (where k was usually about $^1/_5$ and never exceeded $^4/_5$), was not strongly influenced by updraught velocity. Thus the good agreement shown in Figure 1 was not critically dependent on the choice of 1 m/sec for the updraught velocity. When the data was computed for an updraught of 10 m/sec, all but one of the computed droplet concentrations were now greater than the corresponding observed values, and the correlation between the observed and computed values was not as good (Fig. 2).

6. Conclusions

The degree of agreement shown in Figure 1 between the observed cloud droplet concentrations and those predicted from the measured cloud nucleus spectra seem satisfactory in view of the uncertainties involved. There is no assurance that the nucleus populations of the free air samples were strictly representative of those in the updraught in which the cloud formed. If the samples had been taken within the updraught at cloud base level, and if the updraught velocity could have been measured in each case, it seems probable that the agreement between observed and computed values would have been even better.

It may be concluded that the observed variations of droplet concentration in cumuli can be explained by variations in the cloud nucleus population. Continental clouds exhibit large droplet concentrations because continents are major sources of cloud nuclei. As a result of the greater numbers, the droplets are smaller than in maritime clouds, and it seems likely that this, in turn, explains why continental clouds are much less efficient in producing warm rain.

7. Acknowledgements.

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