Liquid Water Content and the Adiabatic Model of Cumulus Development

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Abstract

The literature shows considerable disagreement concerning the liquid water contents found in cumuliform cloud and the relation of observed values to those deduced from the adiabatic model. The present paper describes some observations in which two methods of measuring liquid water have been used simultaneously and found to be in good general agreement. However, the two methods employed very different averaging periods, so that individual measurements were not strictly comparable. These results, and the observations of other workers, are discussed in relation to the general level of liquid water in cumuliform cloud and its variability in space.

1. Introduction

Some information concerning the structure and development of cumuliform cloud can be gained from a study of the spatial distribution of liquid water. While several observers agree that these clouds show a wealth of fine structure, there is no general agreement as to the general level and the overall pattern throughout the cloud. Both aspects – the fine structure and the general level and pattern – are relevant to theories of cumulus growth and interaction with the environment and to the theory of rain formation by the coalesence of droplets, a process which certainly occurs in warm clouds, and is likely to be important also in many clouds which reach far above the freezing level.

2. Discussion of previous measurements

Measurements of liquid water content have been made by a variety of means; the most important difference between them lies in the averaging time of the instruments. All the measurements give an average value over a narrow strip of cloud of finite length, but this length ranges from a few kilometres in some methods to about a metre in others.

(a) *The general level of the liquid water content*

The earliest measurements in considerable numbers were made in connection with icing research. LEWIS (1951) has summarized these measurements: the averaging distance employed varied from 3 km upwards; in 342 observations taken in cumulus and cumulo-nimbus, the maximum value found was 1.71 g m^{-3}, and the median, 0.34 g m^{-3}. BEST (1951) also discussed these measurements and concluded that the observed values were ordinarily less than those deduced from the adiabatic model of cumulus development. In order to explain this deficiency, following STOMMEL (1947), he postulated a lateral entrainment of dry air into the cloud.

ZAITSEV (1950) deduced the liquid water content from the size of a coloured spot made by depositing the collected water on filter paper. This method apparently averaged over a distance of about 100 m. Zaitsev's values are much higher than those found by most other observers. Indeed, in one of the two clouds for which he gives data, the measured value in the region of the central maximum exceeds the adiabatic liquid water content by a factor of about two; in the other, it is about equal to it.

DAY and MURGATROYD (1953) and DAY (1956 a) have measured the liquid water content of large cumuli with an icing meter and with heated cylinders. They gave the lag of the latter method as about 10 seconds and it may be assumed that their values represent averages over some 500 to 1,000 m. They quoted mean and maximum values for each traverse. In the measurements of Day and Murgatroyd the maximum value hardly ever reached 1 g m^{-3}, and the mean was usually less than 0.5 g m^{-3}. In Day's measurements, the maximum usually exceeded 1 g m^{-3}, and perhaps occasionally 2 g m^{-3}, but the instruments used were incapable of measuring values above about 1.8 g m^{-3}. The average value in this series hardly ever reached 1.0 g m^{-3}, and usually fell in the range 0.3 to 0.7 g m^{-3}. Comparing these mean values with the adiabatic model, it is found that the ratio of the mean observed to the calculated value, $\overline{w}/w_a$, never reaches 0.5; in the first series, its median value is about 0.08; in the second, about 0.2.

DAY (1956 b) has recently made further measurements using a refrigerated icing disc, in order to avoid the loss of water which can occur at moderately sub-freezing temperatures when w is large, as described by LUDLAM (1951). In this series Day found maximum values of water content (w_m) appreciably higher than in his earlier work; in cumuli it exceeded 1.0 g m^{-3} in a majority of cases. The maximum found was 4.2 g m^{-3}, and it seems that in some cases, w_m may have exceeded w_a. Mean values were not given – these were no doubt much smaller.

WEICKMANN and AUFM KAMPE (1953) deduced liquid water contents from measurements of the transmission of light. The values quoted by them are the highest in the literature, reaching over 6 g m^{-3} in cumulus congestus. About a quarter of their values exceed that found on the adiabatic model. However, their technique has been criticized by FRITZ (1954), who pointed out that with a given liquid water content, transmission could be greatly reduced if small droplets ($r \approx 1\ \mu$) were present in numbers reaching some thousands per cm^3. ELDRIDGE (1957) has recently made infra-red transmissometer measurements on Mt. Washington, and deduced that at times some tens of thousands of such droplets were present, per cm^3. DAY (1956 a) made measurements of visibility and drop size as well as liquid water content during his runs through cloud. He used a modified form of Trabert's formula due to BEST (1953), to compute a value of visibility from his measured values of drop size and liquid water. The values obtained were about three times the observed values. Thus it seems possible that the water content values deduced by Weickmann and Kampe were too high.

A series of measurements has been made by WARNER (1955) using an instrument in which the impacted cloud water changes the electrical resistance of a paper tape. This method yields an average over a distance of the order of 50 m. The absolute values are similar to those found by earlier observers, with the exception of ZAITSEV (loc. cit.) and WEICKMANN and KAMPE (loc. cit.) whose values are higher. Comparing the observed peak values for each traverse (w_p) with those calculated for the adiabatic model (w_a), it was found that the ratio w_p/w_a was always less than unity; on the average it was about 0.5 near cloud base, and decreased upwards until at a level some 2,000 m above base it had fallen to about 0.2.

Liquid water contents have been deduced from measurements of droplet sizes by SQUIRES using the imprints made on sooted glass slides. This method yields an average over a distance of about 1 m. The values found are in general agreement with those of Warner. The mean value of w/w_a was found to decrease from cloud base upwards, in the same manner as reported by WARNER (loc. cit.).

It is clear from this summary that there is no unanimity concerning the general level of the liquid water content. ZAITSEV (loc. cit.) and WEICKMANN and AUFM KAMPE (loc. cit.) found values which often exceed that expected on the adiabatic model, and commonly reached several g m^{-3}. According to other observers, the average values for a traverse only occasionally reached 1 g m^{-3}, irrespective of the size of the cloud, and in those cases where the observations could be compared with the adiabatic model, it seems that w was usually less than one quarter of w_a.

(b) *The fine structure*

A transmissometer record reproduced by WEICKMANN and AUFM KAMPE (loc. cit.) gives clear evidence of the occurrence of large fluctuations over short distances. It shows that great changes can occur in a distance of a few metres so that only an instrument with a time constant of much less than a second could delineate the fine structure, even if no more is attempted than to record all the fluctuations which are comparable with the average value. MALKUS et al. (1948) in testing an optical instrument designed to measure liquid water and cloud droplet sizes reached a similar conclusion.

Further supporting evidence of an indirect nature is afforded by observations made with a microwave refractometer in two cumuli by BUSSEY and BIRNBAUM (1953). Their record of refractive index shows major fluctuations occurring over distances of only a few metres. A common rapid fluctuation is equivalent to a change in water vapour content of 1 g m^{-3}, and it seems likely, on any hypothesis as to the origin of the inhomogeneities, that they would also appear to a marked extent in a sufficiently detailed record of the liquid water content.

The measurements of WARNER (loc. cit.) give a direct indication of the variability of liquid water, averaged over a distance of the order of 50 m. There were large fluctuations during nearly all traverses; these were often in the nature of downward excursions from a rather characteristic peak level, to which the record returned when the fluctuation had been passed. Records of this nature could perhaps be interpreted as indicating the existence of a number of cells. The downward fluctuations, however, were randomly distributed across the visible cloud, and showed no systematic preference for the peripheral regions. The edge of the cloud was often quite sharp; the liquid water content apparently rose from zero to its peak value within ten or twenty metres in some cases.

In the measurements made by SQUIRES (loc. cit.) the average value of the ratio w/w_a was about 0.2, but occasionally the full adiabatic liquid water content was encountered. Out of some 300 spot measurements, this happened only four times. Rather more frequently, well inside clouds, a zero value was found. These measurements, usually spaced some 200 m apart, showed marked variation from one observation to the next. Superimposed on the trends which appear in Warner's records, there appears to be a still finer structure of almost equal amplitude.

3. A comparison between two instruments

In order to try to resolve the question of the general levels of liquid water content, and to investigate further the fine structure of cloud, a comparison has been made of the instruments described by WARNER and NEWNHAM (1952) and SQUIRES and GILLESPIE (1952). These two methods, the general principles of which have been mentioned above, are fundamentally different in operation, and have very different averaging distances. It seemed therefore that if they were in agreement concerning the general level of liquid water content, it would be most unlikely that both should be wrong.

The comparisons were made by operating the two instruments simultaneously from one aircraft in two series of measurements: in the orographic cloud of Hawaii in 1954* and in cumuli in Eastern Australia in 1956. The results obtained on a series of runs through a cumulus cloud are shown in Fig. 1, which demonstrates the typical variability of liquid water found in cumulus with both instruments. It also shows that there is fair general agreement, although on a few occasions the two instruments are in very considerable disagreement. From what has been said above about the fine structure of clouds, and considering the difference in averaging distance of the two methods, this is not a matter for surprise. A scatter diagram showing the results of all the comparisons made on this day is shown in Fig. 2, which again shows the similarities and differences apparent from the individual records of Fig. 1. The mean water

* See Tellus, Project Shower, 9. (Editors note.)

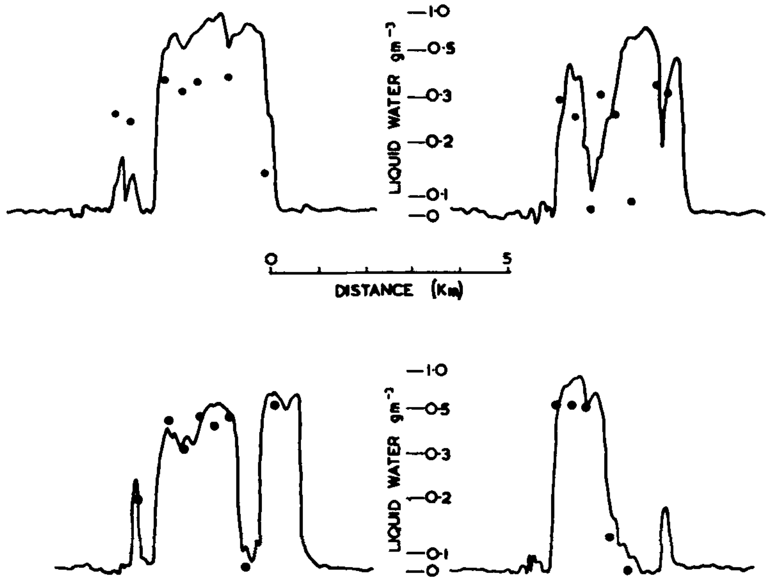

Fig. 1. Comparison of record of liquid water meter with values of liquid water deduced from droplet spectrum (circles) at various times during traverses through cumuli.

content deduced from droplet volumes in 155 samples in cumulus cloud in 1956 was 0.267 g m^{-3}; that obtained from the record of the water content meter at the times of sampling was 0.295 g m^{-3}, which is 1.11 times that deduced from the droplet volumes. The maximum values obtained on both instruments were near to 1 g m^{-3}. The modal drop diameter of the samples ranged from 7 to 26 microns with a mean of 17 microns. No

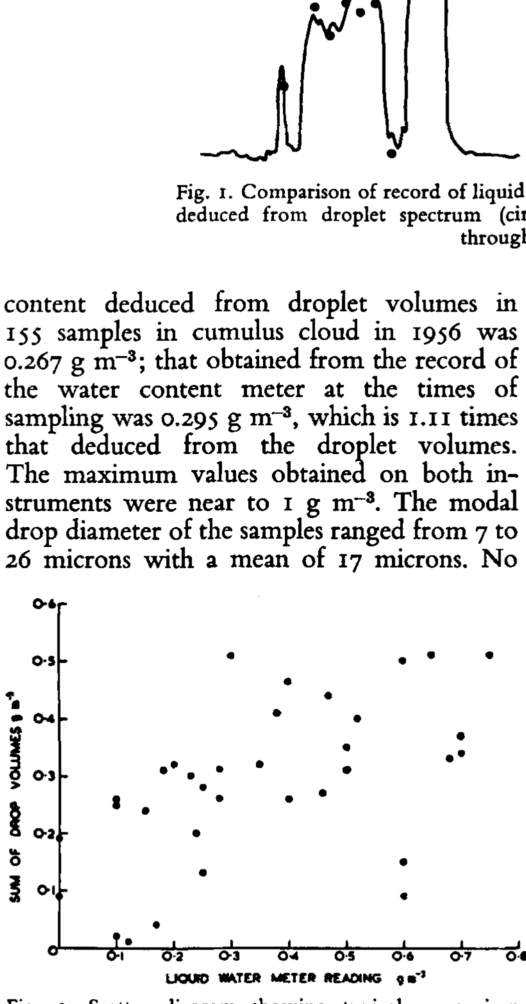

Fig. 2. Scatter diagram showing typical comparison between values of cloud water content deduced from liquid water meter and droplet spectrum (one day's observations).

significant correlation was found between the ratio of the measurements of the two instruments on a cloud sample and the modal droplet diameter of that sample, which suggests that the agreement is not a chance event depending upon some peculiar property of the droplet spectra.

Similar comparisons were made from the data of SQUIRES and WARNER (1957) relating to orographic cloud on the island of Hawaii. In this case, however, the degree of simultaneity of observations was not as great. The mean water content deduced from the droplet volumes in 92 samples was 0.349 g m^{-3}; that obtained from the record of the water content meter at the times of sampling was 0.280 g m^{-3} which is 0.80 times that deduced from the droplet volumes. The modal drop diameter of the samples ranged from 7 to 104 microns with a mean of 32 microns. The ratio of the water content measurements was again independent of modal drop diameter of the sample.

Since the two instruments obtain their values of liquid water through two totally different techniques and the calibration procedures were also completely different, it must be concluded that both calibrations are probably correct to within about ± 20 %. However, it is clear that with these instruments or any others used for measurement of liquid water content both cloud structure and instrumental averaging time must be borne closely in mind in interpreting the observations.

4. Conclusion

From these comparisons and the observations discussed in Section 2, it seems that cumuliform cloud consists typically of a large number of regions of relatively high and low liquid water content, the horizontal extent of which apparently ranges upwards from a few metres. It appears that the full adiabatic liquid water content in cumuli is realized, if at all, only in regions which are of negligible size in relation to the cloud as a whole. In most cases the liquid water in the main body of the cloud is less than a quarter of the adiabatic value, and often considerably less.

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