The Water Content of Cumuliform Cloud

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Abstract

Measurements have been made of liquid water content throughout many cumuliform clouds. The amount of water present at any level was always less than the adiabatic value, and the ratio of these two quantities decreased with height above cloud base. This ratio was found to be independent of the horizontal extent of the cloud except in the case of very small clouds. The transition between clear air and dense cloud was frequently abrupt.

1. Introduction

Our state of knowledge of the physical properties of clouds is far from complete, and as a result, ideas about cloud formation and growth can at best only be tentative. Apart from isolated observations of liquid water content at unspecified points in cloud, the only detailed studies known to the author are those of ZAITSEV (1950) and WEICKMANN and AUFM KAMPE (1953). In neither of these cases was a continuous record of water content available at any one level in the cloud.

In most reported observations it has been noted that the value of the liquid water content at any level above the base of the cloud has been less than the amount that would be released by simple adiabatic lifting of the cloud air and condensation of the surplus water vapour. STOMMEL (1947, 1951) followed by AUSTIN and FLEISHER (1948), HOUGHTON and CRAMER (1951) and MALKUS (1949, 1952 a, 1952 b) put forward and elaborated a theory of entrainment of the environmental air into the cloud which could account for the observed deficiency in liquid water. In no case were suitable observations of cloud water content available to give quantitative support to the theory. MALKUS (1954) calculated updraft velocities in cloud from the observed temperatures on the basis of the theory and found them to be in good agreement with the observed values. A particular defect of the theory, namely its assumption of a steady state in a cumulus cloud, was commented upon by SCORER and LUDLAM (1953) in putting forward their alternative "bubble theory". Some support for this bubble theory is given by MALKUS and SCORER (1954) from an analysis of time-lapse motion picture studies of the development of cumulus towers. At present this theory can give only a qualitative guide to the variation of water content that might be expected throughout a cumulus cloud, and no attempt has been made to interpret existing observations in terms of the theory.

An instrument developed by WARNER and NEWNHAM (1952) has been used to measure liquid water content of cumuliform clouds at all levels. This investigation was made on maritime and landward clouds along the eastern Australian coast. The present investigation was restricted to cumulus or stratocumulus clouds, wholly or almost wholly warmer than freezing from 2,000 to 10,000 ft deep, and for the most part, to single clouds well isolated from their neighbours.

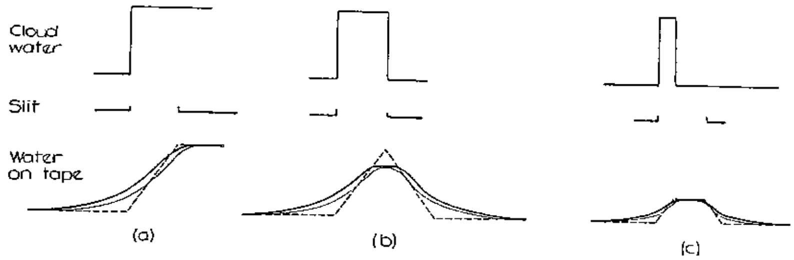

Fig. 1. Pictorial representation of effect of sudden changes of water on instrument for 10"/min tape speed, 140 knots air speed. (a) Sudden rise to steady value; (b) Peak 140 ft across; (c) Peak 50 ft across.
Legend: --- Effect of slit alone. —— Slit plus spreading of water on tape. —— Overall effect of slit plus spreading of water plus contact width.

2. Method of measurement

The method of measurement as described by Warner and Newnham (1952) consists essentially of continuously recording the electrical resistance of a paper tape moved past a narrow slit open to the airstream and moistened by the cloud droplets. The instrument used in the present series of measurements differs only slightly from that described earlier. It was housed, together with other meteorological instruments, in an aerofoil-shaped section suspended below and slightly forward of the leading edge of the starboard wing of a DC3 aircraft. One of the main differences in the present instrument was that the resistance of the tape was measured on the moistened side of the paper, resulting in lower resistance values being obtained. This change lessened the effect of water vapour on the readings and also gave a more rapid response to changes in liquid water content.

Further calibration of the instrument was undertaken, particularly with a view to determining its response time. A very simple method was used, since previous investigations had indicated that for a given amount of water deposited on the paper its method of application did not significantly effect the resistance. This method consisted of applying water to the paper through a wick which was fed through a capillary tube, and determining the rate of application by a measurement of the movement of a small air bubble introduced into the capillary. Measurements of resistance were made at different tape speeds and flow rates, and the calibration deduced from a calculation of the cloud water content that would result in a given amount of water being deposited on the paper under known conditions of slit size, air speed and tape speed. The calibration obtained in this manner agreed with that obtained previously using a spray in a small wind tunnel (under similar conditions of the instrument) and was very much simpler to perform.

The factors influencing the response time of the instrument are: the width of the slit and the rate of movement of the tape past it, any spreading of the water on the tape, the width of the measuring contacts, and the time constant of the recording ohmmeter. Since the slit is 0.1 inches wide the usual tape speed of 10 inches per minute results in any point on the tape taking 0.6 seconds to cross the slit. Thus a sharp-edged cloud would appear as one in which the water content rose from zero to maximum in 0.6 seconds of tape travel, corresponding to a distance in the cloud of 140 ft at the usual aircraft speed of 140 knots. When the water is deposited on the paper it is absorbed and tends to spread. The amount of spread varies with the amount of water deposited on the paper, but usually corresponds to a further 200-ft extension of the sharp-edged cloud postulated above. The width of the resistance measuring contacts makes any change of tape resistance commence to record earlier and finish recording later than it otherwise would, the total extension being equivalent to 60 ft for the conditions under discussion. For the case of a sharp peak of liquid water a similar argument leads to the likely form to be taken by the record. The overall effects are summarized pictorially for different cloud conditions in Fig. 1. The values suggested will vary with tape and aircraft speeds and will also change with the cloud water content itself.

The discussion above has ignored the time constant of the recording ohmmeter. This varies with the amplitude of the signal and slightly with the position of the pointer on the scale. For a signal equal to 5 per cent of full scale deflection, half amplitude is reached in 1 second and full response occurs after 10 seconds. Optimum response occurs with signals of about half full scale amplitude which record fully in 0.8 second. Owing to overshoot, larger signals take longer to reach their final value, a full scale deflection signal achieving a steady state in 5 seconds after a 5 per cent overshoot.

All these effects are clearly not additive and if fine structure of clouds is under investigation the limitations of the instrument need to be considered in detail, bearing in mind the nature of the variation being looked for. However, an overall time constant of the instrument can well be regarded as $^1/_2$ second.

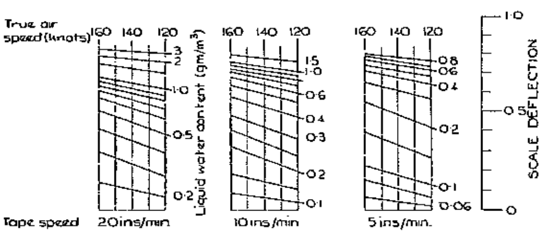

Fig. 2. Calibration of instrument at different aircraft speeds and tape speeds. (For collection efficiency 1.0).

For completeness it is as well to summarize the other important characteristics of the instrument.

(a) The overall accuracy of a water content measurement is about ± 20 per cent, though the comparative accuracy is much better.

(b) The calibration is non-linear, being shown in Fig. 2.

(c) The calibration is sensibly independent of temperature within the range 2° C to 28° C.

(d) The salinity of the cloud water does not affect the calibration at least over the range normally experienced.

(e) The collection efficiency of the instrument is 0.75 for 10 μ diameter drops, and for most clouds 80 per cent or more of the liquid water is collected. A figure of 0.8 has been taken in the results described below.

(f) For the drop size range experienced in clouds the calibration is unaffected by drop size once the drops have been collected.

(g) Readings taken in rain are unreliable owing to splashing and loss of most of the larger drops.

(h) Readings cannot be made at sub-zero temperatures owing to icing.

The flight procedure usually followed was to climb to about 1000 ft above the cloud tops to choose a suitable cloud, the choice being governed by the degree of isolation of the cloud from its neighbours and by a guess as to the probability that it would grow or decay only slightly during the half hour or so required for measurement. Most clouds did, in fact, change during the measurement, both growing and decaying cyclically, but even in cases of continuous slow dissipation the base was affected last and it was sometimes possible to obtain a satisfactory series of observations. Once a cloud was chosen, a series of traverses was made at appropriate height intervals (usually 500 or 1000 ft) starting a few hundred feet below the top and finishing just above cloud base. If during a traverse the liquid water readings exceeded about 0.75 of full scale deflection, where the scale is becoming very crowded owing to saturation of the paper, the traverse was normally repeated using a higher tape speed. Subsequently a climb was made to cloud top height to examine the cloud again, and a sounding was then made of the environmental air from above the cloud top to ground level, measuring temperature and humidity. Special flights at constant height in one cloud, or at a series of heights through many clouds, were also made.

3. Results

Measurements have been made in large numbers of clouds throughout the year, but owing to the limitations of the instrument no data are available on clouds extending markedly above freezing level, and most of the observations were made in summer. In general they were made in clouds that either had no rain in them, or in which the rain was light or restricted to a small part of the cloud. Data have been rejected when they were obtained in heavily raining clouds and when gross changes occurred in the cloud during the course of the observations. Observations have also been rejected when the variation of water content with height was found to be very erratic. This occurred mainly in measurements made in a complex cloud situation and frequently cor-

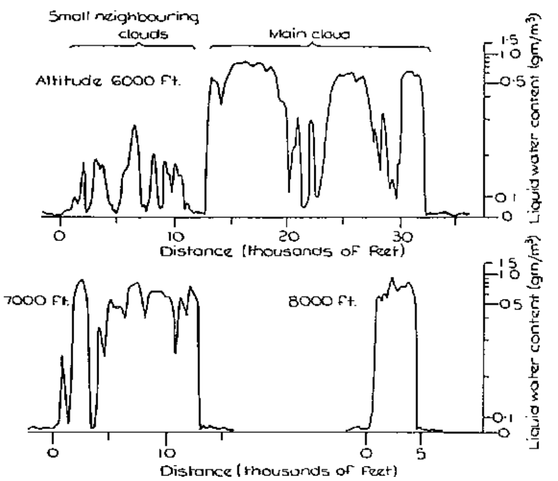

Fig. 3. Successive traverses through cumulus cloud at 6,000, 7,000 and 8,000 ft. Cloud base 3,000 ft, temperature 18·3° C; top 9,300 ft, 7·2° C.

responded to big changes in the appearance of the cloud.

(a) *Peak liquid water content*

The most obvious characteristic of the records of water content at a given height in one cloud was the variability during the traverse as is shown in Fig. 3. It became necessary to decide on the most significant feature of the record. Since the water content sometimes descended to zero well inside cloud, the cloud being defined by failure to see the ground or sky, it was thought inadvisable to use the average value throughout the traverse. It was found that the peak value, or possibly the mean of the series of peaks, was fairly reproducible from traverse to traverse at a fixed height

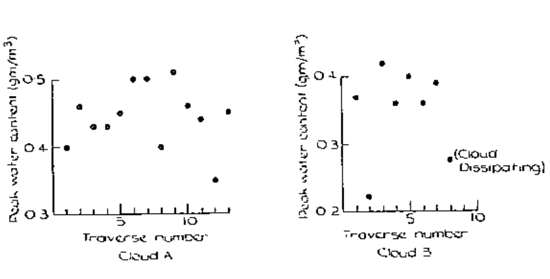

Fig. 4. Constancy of peak liquid water content at given height. Successive traverses through two different clouds, the total period of observation being about 30 minutes in each case.

	Cloud A	Cloud B
cloud base	2,500 ft	3,000 ft
height of traverses	5,900 ft	8,000 ft

and appeared to be a definite characteristic of the cloud. This is well indicated in Fig. 4 which shows, over a period of roughly 30 minutes, the peak values on successive crossings through two different clouds on different days. The recorded peak is not necessarily the maximum liquid water content since the instrument averages over a distance of a hundred or so feet, but it probably does not differ markedly from it in most cases.

(b) *Variation of water content during any traverse*

The water content may rise slowly from the edge of the cloud to its peak value, or it may increase very rapidly. In general, however, there is no steady rise from the edge towards the middle, and the peak value can often be reached very rapidly, the liquid water content

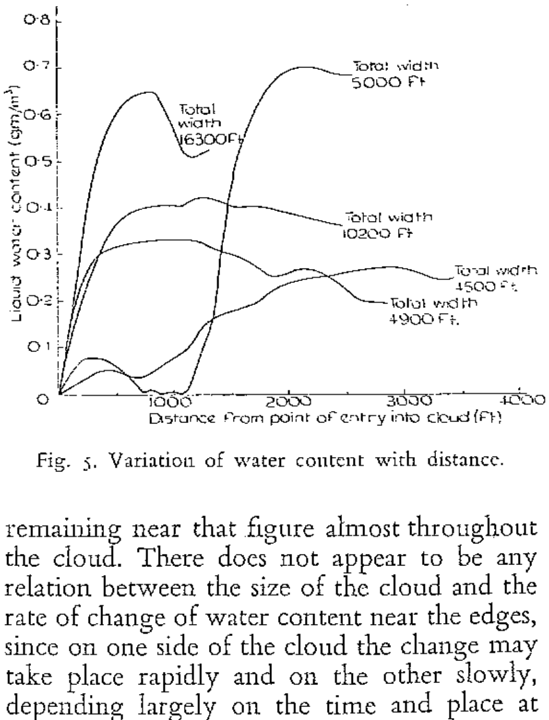

Fig. 5. Variation of water content with distance.

remaining near that figure almost throughout the cloud. There does not appear to be any relation between the size of the cloud and the rate of change of water content near the edges, since on one side of the cloud the change may take place rapidly and on the other slowly, depending largely on the time and place at which the aircraft enters the cloud. Some typical results showing the rate of change of water content near the point of entry into cloud are shown in Fig. 5. When it is remembered that the instrument's response time is such that a sharp-edged cloud would appear as one in which the liquid water increased gradually to its maximum over a distance of the order of 400 ft, it can be seen that in some

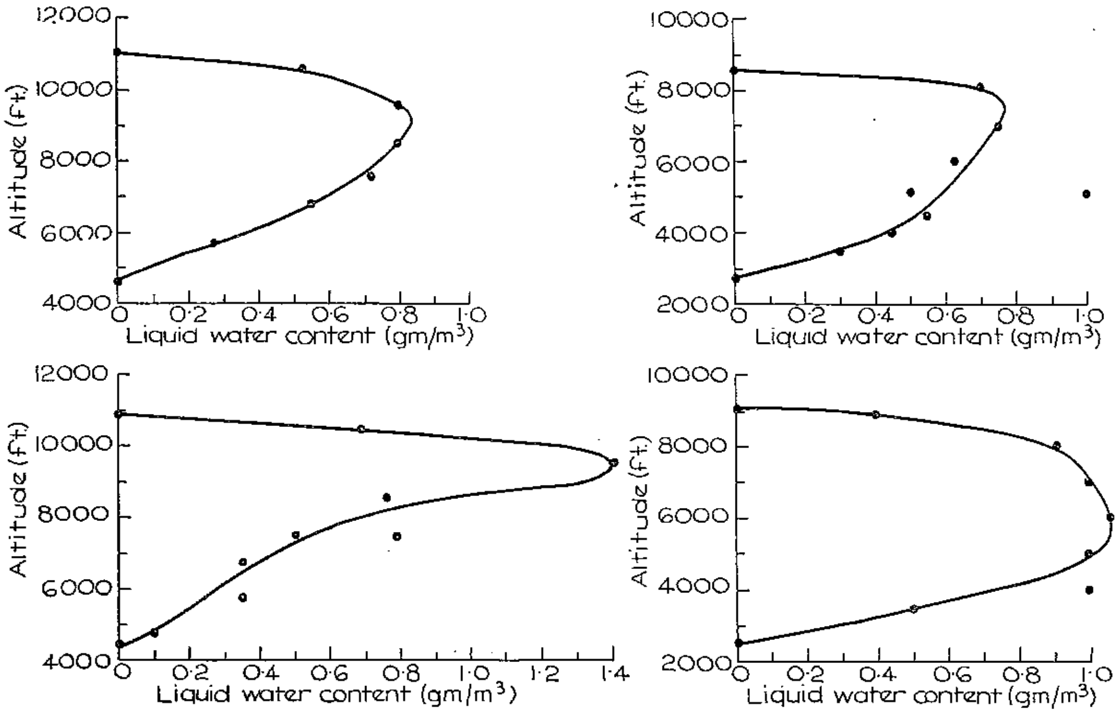

Fig. 6. Variation of peak water content with height.

cases the full transition between cloud and environment must occur over a few tens of feet.

(c) *Variation with height above cloud base*

When the peak value is plotted against height above cloud base it is generally found to increase fairly steadily until a point about 1000 ft below the top of the cloud, after which it falls rapidly to zero. Typical cases of this result are given in Fig. 6. The magnitude of the peak water content is always less than the adiabatic value appropriate to that level. If the ratio of the observed liquid water content W to the adiabatic value W_a is plotted as a function of height above cloud base, it is found in general to decrease from near unity at cloud base to a value approaching 0.2 at 5000 ft above the base. There is, however, a great variation from cloud to cloud, particularly near cloud base. In Fig. 7 the value of this ratio is plotted against height for about 25 clouds. A line is drawn through a series of points each of which represents the peak value of W/W_a on a traverse at a given height in one cloud to represent the conditions throughout the depth of that cloud. The values are taken only in that part of the cloud in which the observed water content is increasing with height. The top one or two thousand feet of cloud in which the water content is decreasing is not represented. The mean value of this ratio for all the clouds is plotted in Fig. 8.

(d) *Mean value of W/W_a throughout a cloud*

If in any cloud the average value of W/W_a is taken from near the base to the point where the water content begins to decrease, it is found to vary markedly from one cloud to the next. Fig. 9 shows a plot of this mean value against the range of W/W_a from the highest observed value, generally found near the base, to the lowest which occurs usually at the point of maximum liquid water content. From consideration of this figure and Fig. 7 it is seen that clouds tend to be either "wet" or "dry" throughout. A cloud which is on the average "wet" is not so because of the presence of an isolated very wet area. The biggest variation from cloud to cloud of W/W_a does, however, occur near the base of the cloud.

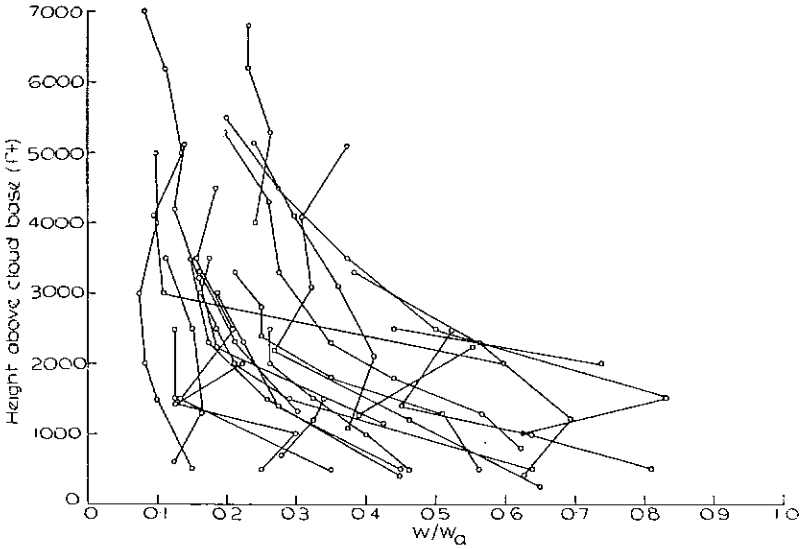

Fig. 7. Ratio of observed liquid water content to adiabatic value versus height above base.

(e) *Variation of W/W_a at a given height with cloud width*

A study was made of the variation of W/W_a at a given height above cloud base with the horizontal width of the cloud under observation. Only clouds greater than 2000 ft across were considered and the observations were grouped into 5000-ft width and 1000-ft height intervals. The result of this examination is shown in Fig. 10 from which it can be seen that there is no evidence that the cloud width affects the value of W/W_a at any given level. When observations were made on many clouds on the one day there was again little evidence that the cloud width affected W/W_a. This statement does not apply to small clouds, however: clouds less than about 1,500 ft across appear to be significantly drier than the bigger clouds at a given height above their bases, and their "wetness" increases with their horizontal extent.

(f) *Effect of environmental parameters on mean W/W_a*

An examination of the data available to the author failed to reveal any correlation between

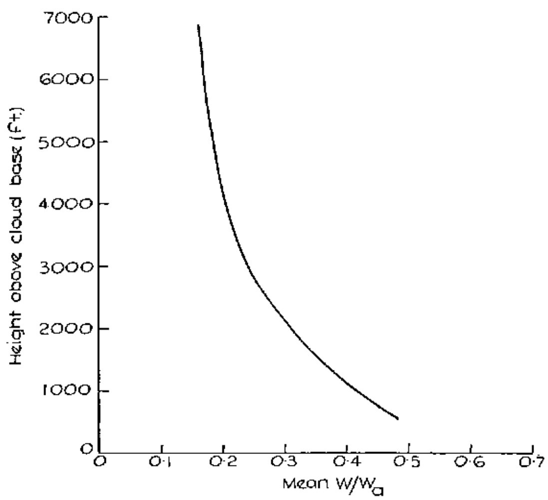

Fig. 8. Mean ratio W/W_a versus height above base.

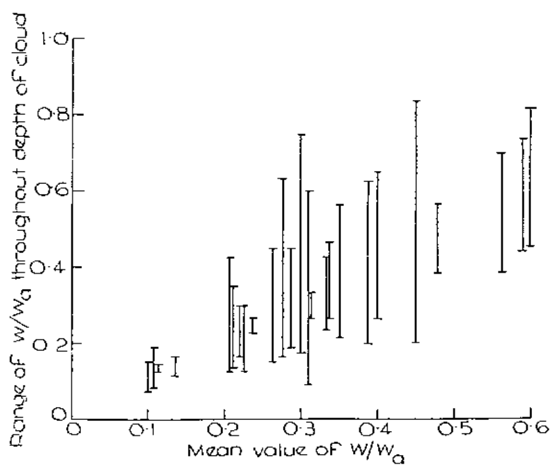

Fig. 9. Range of W/W_a versus mean value W/W_a.

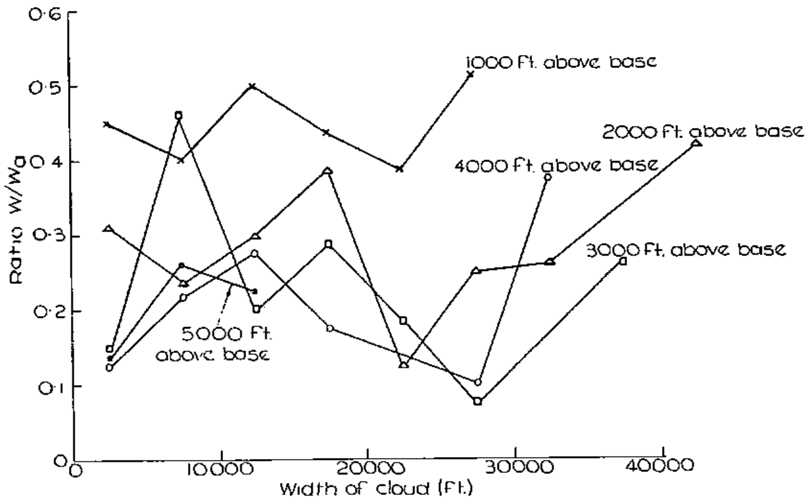

Fig. 10. Relationship between W/W_a and cloud width at given height above base.

the mean value of W/W_a throughout the cloud and either cloud base temperature or mean environmental lapse rate over the first 5,000 ft above ground.

Thus, to summarize the results that have been obtained it can be stated that:

(a) The peak water content considered is a characteristic of the cloud and does not vary with time except when the cloud is consistently dissipating.

(b) In many clouds the transition from clear air to dense cloud is abrupt.

(c) The value of W/W_a in general decreases with height above base but the value varies greatly from cloud to cloud. It is, however, always less than 1.

(d) Clouds tend to be either "wet" or "dry" throughout.

(e) The width of the cloud, provided it is greater than about 1500 ft, has no effect on W/W_a at a given level.

(f) The mean value of W/W_a throughout the cloud is not strongly correlated with either lapse rate or cloud base temperature.

4. Discussion of results

Perhaps the most significant features of the results are the facts that at no point above the base, even in the largest clouds examined, does the observed liquid water content approach the adiabatic value; that the deficiency in water is not a function of the horizontal dimension of the cloud except for very small clouds; and that the edges of clouds are frequently as wet as the centre.

Since in large measure the reliability of these observations depends on the accuracy of the calibration of the instrument, it is considered desirable to discuss this aspect a little further. As was mentioned in Section 2 of this paper, it is thought that the accuracy of measurement of water content is about ± 20 per cent. Several different laboratory calibration techniques all agreed within this accuracy, but unfortunately it has not been possible to calibrate the instrument in flight or at speeds approaching that of the aircraft. However, the fact that the observed liquid water content is sometimes found to approach the adiabatic value near cloud base suggests that the calibration is not seriously in error. Since both "wet" and "dry" clouds give results of the same general character it appears unlikely that saturation effects or splashing are of importance. This view is further supported by the lack of discontinuity between the figures for the lower drier areas of "wet" clouds and those for their upper regions.

The response time of the instrument will also affect the results to a degree dependent on the rate of variation of water content in the cloud under examination. Thus a cloud in which the water content fluctuated very rapidly might appear drier than one in which a steady somewhat lower peak value obtained. In this regard there did not appear to be any significant difference in the character of the records obtained in large and small clouds, except in the case of very small clouds 1,000 ft or less in width which always showed only a single peak. Visibility records obtained by WEICKMANN and AUFM KAMPE (1953) with an instrument having a very short time constant show small flucutations in distances of about 30 ft, but the bigger changes occur over a distance of more than 100 ft.

The magnitude of the error due to the time constant of the instrument is not known, but in view of these facts it is thought to be comparatively small. In any event it is considered unlikely that probable instrumental errors could affect the general nature of the results obtained.

The steady decrease of W/W_a above cloud base thus appears to be a real and normal phenomenon. Where it did not occur, as in some of the observations not reported, it was associated with a complex cloud situation in which two or more layers of cloud tended to mix, or with the raining out of the cloud during the course of the observations. Pronounced changes in the cloud under observation sometimes occurred and were associated with departures of the W/W_a versus height relationship from the general pattern.

In a cloud undergoing periodic growth and decay, such as those instanced in Section 2(a) and Fig. 4, the water content at a level well removed from the top and base of the cloud remains relatively constant and no increases up to the adiabatic value have been observed. Since in the case of Cloud A of Fig. 4, traverses were made roughly every $1^1/_2$ minutes, it is unlikely that any significant feature would have been missed. Thus, if the growth period is due to the rise of a fresh bubble of air from beneath, that bubble must be well mixed with its environment by the time it reaches the cloud and must continue to mix vigorously during its further ascent through cloud. This view is of course supported by the observation that clouds tend to be "wet" or "dry" throughout their whole vertical depth; there are not regions of excessive wetness well removed from the base. There could of course be very small wet regions to which the instrument would not fully respond. An idea of the effect of such small regions on the record can be gained from a consideration of the earlier discussion of the time constant of the instrument. This would suggest that at an initial liquid water content level of 1 g/m^3 a wetter region 140 ft across would record only 0.3 to 0.5 of its increased water content, assuming increases from 0.5 to 2 g/m^3 respectively. A larger wet region 500 ft across would record 0.8 or more of its increased water. While these estimates are undoubedly very rough they do suggest that if the full adiabatic value of liquid water is achieved in a cloud it can only be so over a very small region for the instrument not to record the increase. For example, in a cloud where the observed peak water content was 0.9 g/m^3 at a height of 4,000 ft above the base and the adiabatic value, assuming ascent from cloud base, was 2.6 g/m^3 a wet patch must be only about 30 ft across for the increase to be reduced to below 0.1 g/m^3 on the record and thus possibly to have passed unnoticed.

The facts, that the edges of a cloud can frequently be as wet as the middle and that the deficiency in water content is largely independent of cloud width, tend to suggest either that there is no significant horizontal mixing of the cloud air with the environment, or that the mixing is rapid compared with the rate of growth of the cloud and extends over its whole width. The author's observations in this regard are in conflict with those of ZAITSEV (1950) which were, however, restricted to isolated readings, and it is considered doubtful if the contours of liquid water shown in his figures can really be justified. While WEICKMANN and AUFM KAMPE (1953) did not measure water content directly, it is interesting to note that their transmissometer records are very similar in character to the author's own water content records and demonstrate clearly the sharp edge of a cloud and the absence of a central wet region. It should be noted, however, that their computed values of liquid water are markedly higher than those at present being reported. The presence of "holes" well inside cloud in which the liquid water is very low is a feature of many records obtained in both single and multicelled clouds. Sometimes these "holes" appear to extend vertically for a considerable distance since they repeat for two or three traverses spaced 500 ft or more apart. Their presence may correspond with downdrafts in the cloud, but the author's own accelerometer records are not sufficiently extensive to give adequate support to this idea.

It appears to the author that there is a need to investigate the nature of the air circulation in and around cloud, and that it is only through such an investigation that a better understanding of the process of cloud development and growth will occur. In this regard it is suggested that the technique described by WARNER and BOWEN (1953) may prove useful.

5. Acknowledgements

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