Comparative Measurements of Cloud Liquid Water Using Heated Wire and Cloud Replicating Devices

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ABSTRACT

Liquid water concentrations in cumulus clouds have been measured from an aircraft using the Johnson-Williams hot wire device. From simultaneous continuous cloud replicator records, liquid water contents have been computed from the observed drop size distributions. Comparisons between data from the hot wire and replicator devices indicate that both instruments are fairly accurate in measuring liquid water contents at least up to 3.5 gm m^{-3}, with the closest agreement when the median volume diameter of the cloud droplets was under 30 μm.

1. Introduction

Liquid water concentration in natural clouds is of considerable importance in cloud physics. Better understanding of its magnitude and spatial distribution is needed for more precise calculations on the rate of growth of precipitation particles.

A great variety of devices for measuring liquid water is currently in use; however, so far lack of good calibration techniques has limited their usefulness. In this study a comparison is made of data obtained from the hot wire liquid water measuring device and the Cloud Physics Laboratory's continuous cloud particle replicator operated simultaneously during four cloud penetrations.

From such a comparison we hope to learn more about the behavior and reliability of these liquid water measuring devices.

2. Description of sampling methods

a. Continuous cloud particle replicator.[1] This instrument, developed in the Cloud Physics Laboratory (Spyers-Duran and Braham, 1967), was used as the primary measurement tool in this study. It provides a continuous record of the drop size distributions in space within the cloud. Using the drop spectra, liquid water is then computed from

$$\mathrm{LWC}=\tfrac{4}{3}\pi\rho\sum n_i r_i^3,$$

where n_i is the number of drops per unit volume in the r_i size class, r the drop radius, and ρ density of water. Drop concentration is given by $N=\sum n_i$.

b. Hot wire device. Our unit, manufactured by Johnson-Williams,[2] was designed for aircraft use and provides a continuous direct reading record of the liquid cloud particles. The principles behind the use of a heated wire for water content measurements have been discussed by Neel (1955). In our unit a wire (0.5 mm diameter), heated by an electric current, provides the sensor resistance in a bridge circuit. This bridge is balanced for clear air conditions. In clouds the impinging water drops cool the wire and decrease its resistance. This is used as a measure of the liquid water content; it is, however, dependent upon how effectively the variously sized water droplets cool the wire. The calibration supplied with the instrument gives an output linearly proportional to the liquid water content.

Owens (1957) found from a series of wind tunnel tests that the manufacturer's calibration for the hot wire was within ±5% in six cases, using drop spectra having volume median diameters of 18–20 μm and liquid water contents up to 7 gm m^{-3}. In a single test using a spectrum with a volume median diameter of 31 μm and a liquid water content of about 2 gm m^{-3}, the hot wire had an efficiency of about 77%. The present study provides additional evidence about this point.

3. Flight measurements

An instrumented Beechcraft D-18 was used for the cloud penetration and for data collections. All measurements were recorded continuously on a multi-channel oscillograph recorder. Four cloud passes have been selected for this study. Selection was made on the basis of

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[1] A word of caution is in order for those readers who have not had experience with continuous particle replicators. Data collection with these devices is subject to a number of errors and difficulties some of which can be overcome by calibration, and others which can be circumvented by one experienced in the use of this equipment. In addition, particle counting and sizing must be done by hand, one drop at a time. Readers may consult the references for detailed discussion of these matters.

[2] Johnson-Williams, Inc., 2300 Leghorn Avenue, Mountain View, Calif.

TABLE 1. Data on cloud penetrations.

Date and flight no.	Location	Cloud pass no.	Cloud base Height (m,MSL)	Cloud base Temp. (°C)	Cloud top Height (m,MSL)	Cloud top Temp. (°C)	Aircraft penetration Height (m,MSL)	Aircraft penetration Temp. (°C)
10 June 1964 604	southeast Missouri	C-1	1371	19.0	5182	−3.6	4725	−1.3
9 August 1966 705	north central Minnesota	F-1	1402	8.3	3685	−5.2	3292	−4.4
31 July 1965 663	north central Minnesota	B-1	1493	12.3	3841	−2.5	3048	0.5
31 July 1965 663	north central Minnesota	B-3	1493	12.3	3841	−2.5	2439	3.8

quality of data from replicator and simultaneous operation of the hot wire liquid water content measuring device. The restriction of this study to four cloud passes results primarily from the rather laborious task of evaluation of the replicator data. It is believed that this sample is adequate to give a good comparison of the instruments; however, it is not sufficient to study the microphysics of the four clouds. All passes were in cumuli showing no evidence of ice particles. All were sampled near the freezing level. Details of the cloud penetrations selected for this analysis are given in Table 1.

Data from the four cloud passes, Figs. 1, 2, 3 and 4, are given in the form of spatial distributions along the flight paths. Time is given in seconds from the start of the flights; data from the hot wire are "instantaneous" values as recorded on the oscillograph. Liquid water and drop concentrations from the replicator drop spectra were averaged over every 0.25 sec (flights 604 and 705) or 0.20 sec (flight 663) and are plotted as 1-sec running means.

Fig. 1 represents a penetration into a vigorous cumulus congestus cloud of southeast Missouri. Flight altitude was 4725 m MSL. Visual and measured parameters showed this cloud to consist of one broad updraft and two smaller ones separated by weak downdrafts.

The similarity of the two liquid water traces is most remarkable. However, the hot wire data trace gives clear indication of an instrument lag of about 1 sec. As a result, the hot wire tends to undersample in regions of increasing water, oversample in regions of decreasing water, and to delay peaks and troughs in the water profile. This can lead to serious errors in interpretation of cloud microstructure, e.g., near the 2252nd second, the replicator showed few cloud drops for a space of almost 0.75 sec, with the calculated liquid water content of 0.02 gm m^{-3}. At this time the hot wire gave an instantaneous reading >1.5 gm m^{-3} and a lagged trough value of about 0.6 gm m^{-3}. The difference between the replicator and the hot wire values after the 2240th second is probably due to icing on and around the replicator sampling slit, since the de-icer elements were inoperative on this flight.

The drop concentration and volume median diameters $\tilde{D}_v$ are plotted in the upper half of Fig. 1. In general, the trace of drop concentrations follows that for liquid water. Higher drop concentrations (up to 1230 cm^{-3})

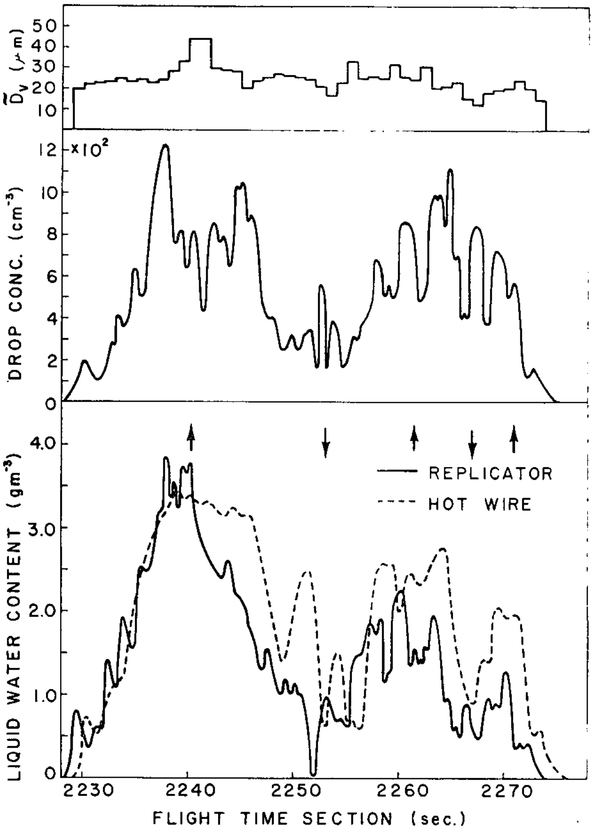

FIG. 1. Comparison between liquid water content measurements from the Johnson-Williams hot wire device and liquid water content deduced from the replicator droplet spectrum. Drop concentration and histogram of the volume median diameter $\tilde{D}_v$ (μm) along the flight pass are also given in the form of spatial distribution. The arrows indicate up- or downdraft regions through the cloud pass, flight no. 604, cloud C-1.

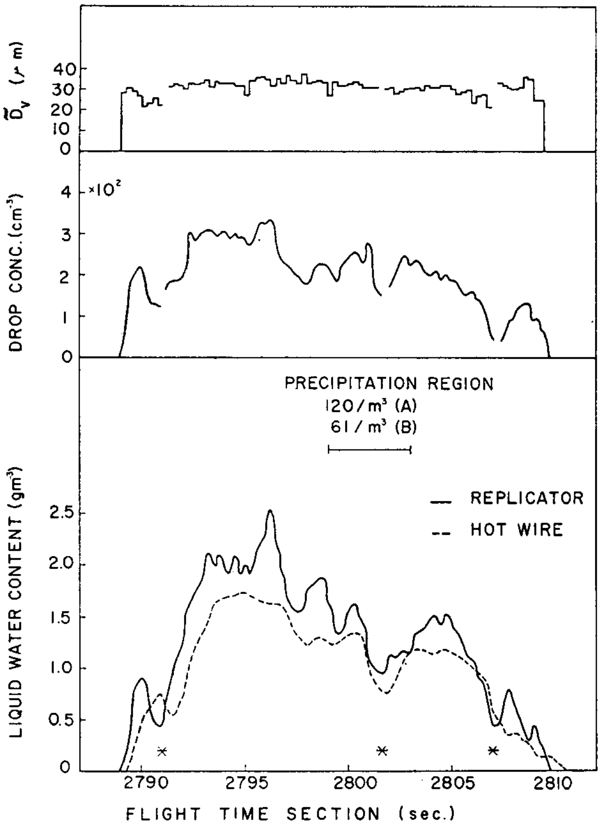

FIG. 2. Same as Fig. 1 except for flight no. 705, cloud F-1. Region of precipitation is indicated by bar, with concentration (m^{-3}) shown for drop size diameter ranges of A (270–470 µm) and B (470–640 µm). Asterisks indicate three smaller cloud turrets surrounding main turret.

tended to coincide with larger water contents and to be associated with cloud updrafts. The downdraft regions had lower drop concentrations and lower water contents. There also seems to be a tendency for the volume median diameter to be larger in the updraft regions than in the downdraft regions.

Fig. 2 shows data from passage through a convective turret which grew out of a stratocumulus base. The flight level was 3292 m MSL. The main cloud turret was surrounded by three smaller ones separated at flight level by a few feet of clear air. These are indicated by an asterisk on Fig. 2, at times 2791, 2802 and 2807 sec. These zero values do not survive the averaging processes used on the replicator data, and the instrument lag of the hot wire device. The liquid water from the hot wire device is in reasonably good agreement with the values computed from the drop spectra. The maximum value measured by the hot wire devices was 1.8 gm m^{-3}, while the replicator indicated a peak of 2.4 gm m^{-3}. Drop concentration followed the liquid water content trace with maximum values of 300 cm^{-3}.

A precipitation particle sampler (Brown, 1961) was in operation throughout this pass. This device uses a metal foil for its collecting surface. It has a lower size threshold for drops about 290 µm diameter. The record from the foil sampler shows drops larger than 300 µm during the 4-sec interval, 2799-2803 sec. This region is one of slight minimum in drop concentration and cloud liquid water, but the contribution of large drops to liquid water content is negligible (0.01 gm m^{-3}). Volume median diameter through the pass is 30.7 µm.

Figs. 3 and 4 show data from two successive passes through a single convective turret growing out of a stratocumulus layer. The flight altitudes were 3048 and 2439 m MSL. Looking first at the data from the 3048-m level, we note that the water content traces have the same general pattern. Highest drop concentrations (690 cm^{-3}) were found at the core of an updraft region where both the replicator and hot wire indicate over 3.4 gm m^{-3} with the volume median diameter at 28 µm. The foil sampler registered large precipitation particles in two places; again their contribution to the liquid water content was negligible (0.003 and 0.004 gm m^{-3}).

Fig. 4 shows only a portion of the pass at 2439 m. Both data traces show the same pattern. Highest droplet concentrations were found at an updraft region (500 cm^{-3}). Again there was very little contribution to the cloud water content (0.004 gm m^{-3}) from the drops in the precipitation region. Volume median diameter of the cloud droplets indicated uniformity with a value of around 23.3 µm.

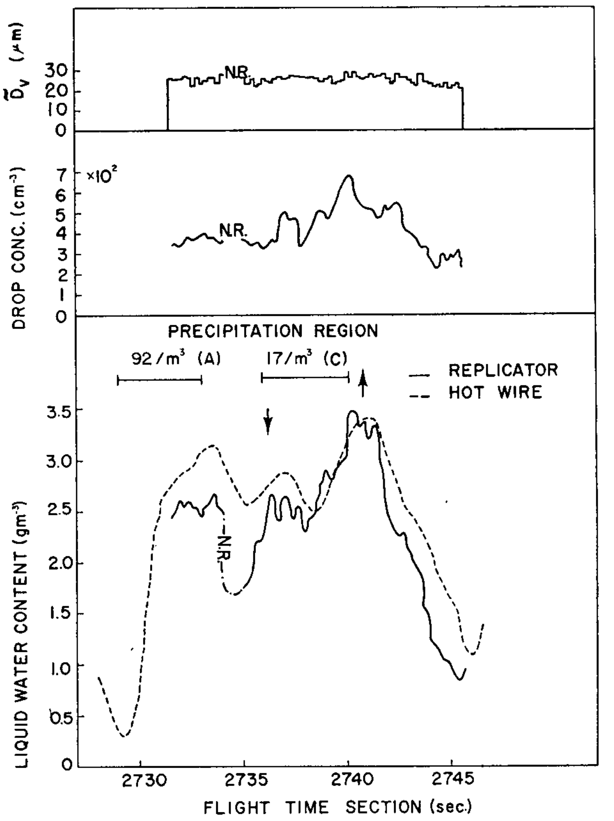

FIG. 3. Same as Fig. 1 except for flight no. 663, cloud B-1. Regions of precipitation are indicated by bars, with concentration (m^{-3}) shown for drop size diameter ranges of A (290–470 µm) and C (640–840 µm).

4. Effect of drop size on comparative measurements

The ratio of cloud water content, as measured by the replicator, to that measured by the hot wire, is shown in Fig. 5 to be a function of the volume median diameter. Data points represent 1-sec means taken from Figs. 2, 3 and 4, plus Fig. 1 up to 2240 sec. At the bottom of this figure is shown the average droplet spectrum for the groups of circled points (diameters between 21.5–23.0 μm and 32.5–34.7 μm).

It is fairly clear that this ratio increases with increasing volume median diameter, but the reason is not clear. We would expect the heated wire instrument to undersample the relatively infrequent large drops. We also would expect large drops to be flattened somewhat in the replicating process and to produce replicas somewhat larger than the size of the drop. On the basis of work done by MacCready and Todd (1964) we would not expect this to be important for drops smaller than the thickness of the film, about 70 μm for our replicator. It is our opinion that the flattening effect does not seriously distort the computed water contents. Both of these effects tend to tilt the trend of the data in the manner observed. Taken as a group we find that 35% of the 1-sec means are within ±10% of the unity value, 69% within ±20%, and 81% of all points are within ±30% of the unity value.

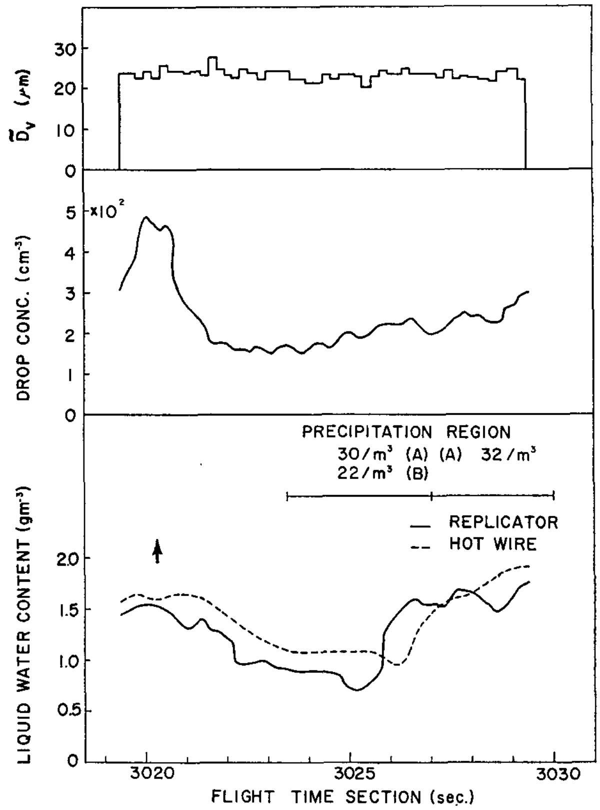

Fig. 4. Same as Fig. 1 except for flight no. 633, cloud B-3. Regions of precipitation are indicated by bars with concentrations (m⁻³) shown for drop size diameter ranges of A (290–470 μm) and B (470–640 μm).

5. Conclusions

Comparison between the magnitude and pattern of the hot wire and replicator devices appears to establish

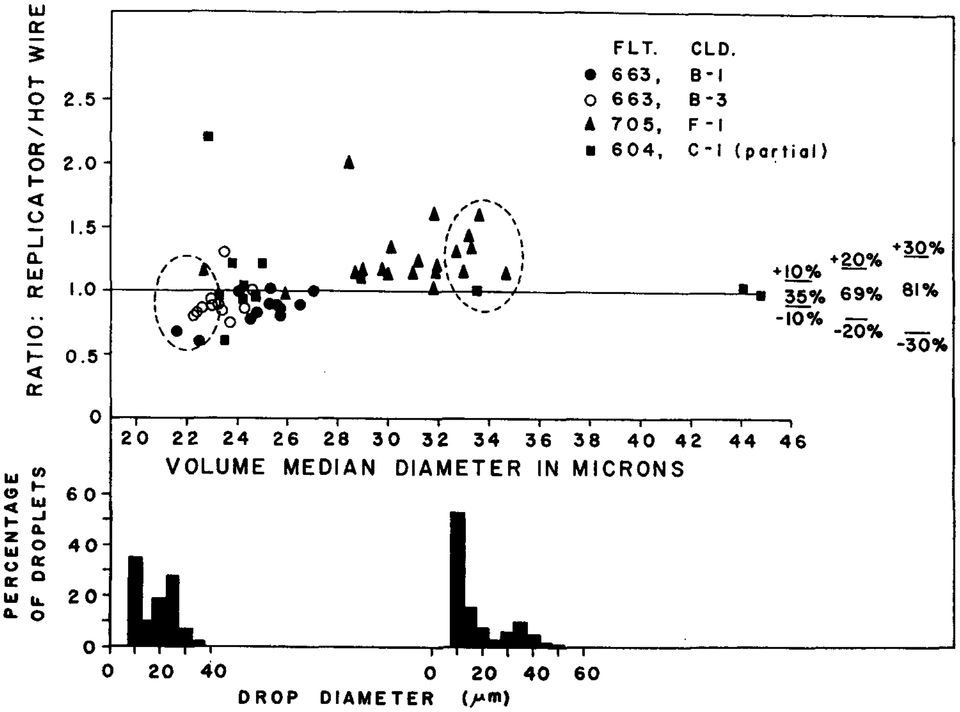

Fig. 5. Scatter diagram illustrating the ratio between replicator and hot wire liquid water content to the volume median drop diameter. Shown also are the drop size distributions obtained from the points between 21.5–23.0 and 32.5–35.0 μm.

that both instruments are fairly accurate for measuring liquid water content, at least up to 3.5 gm m^{-3}, when operated under conditions reported herein. The ratios of 1-sec mean values measured by the two instruments show somewhat greater scatter for volume median diameters $> \sim 28$ μm. The result is not unexpected from previously reported wind tunnel calibrations.

The presented data establish that the hot wire device has an instrument response time of approximately 1 sec, which can be seen when positions of troughs and peaks are compared. Because of this lag, the rapid liquid water content fluctuations are integrated as they occur in convective clouds Gross errors can arise from the instrument response, as we found regions on the replicator where there were no drops and the hot wire still indicated as much as 1.5 gm m^{-3} at the same time.

In the few cases studied, the droplet concentrations from the replicator data indicated that maximum values usually coincided with updraft regions. The lead foil sampler indicated that the first appearance of precipitation particles is associated with downdraft regions.

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