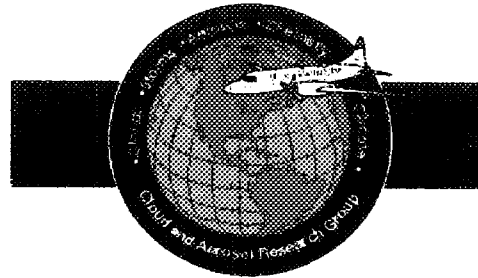


CLOUD AND AEROSOL RESEARCH GROUP



CALIBRATION OF LIQUID WATER PROBES FROM THE
UNIVERSITY OF WASHINGTON'S CV-580 AIRCRAFT AT
THE CANADIAN NRC WIND TUNNEL

by

Timothy Garrett and Peter V. Hobbs

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UNIVERSITY OF WASHINGTON
DEPARTMENT OF ATMOSPHERIC SCIENCES
SEATTLE, WASHINGTON
98195-1640

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1. INTRODUCTION

On April 20 - 21, 1999, three liquid water content (LWC) probes, used on the University of Washington's Convair-580 research aircraft, were tested at the Canadian National Research Council (NRC) wind tunnel in Ottawa, Canada. The probes were the Johnson-Williams (J-W), the Gerber Scientific Inc. PVM-100, and the Droplet Measurement Technologies (DMT) LWC-100. The purpose of these tests was to evaluate the performance of the probes under controlled conditions and to use the results to evaluate the data obtained with these instruments aboard the UW Convair-580 during the FIRE-ACE/SHEBA and KWAJEX field projects of 1998 and 1999, respectively.

2. OPERATING PRINCIPLES OF THE CLOUD LIQUID WATER PROBES

2.1. *Johnson-Williams*

The J-W liquid water probe uses a calibrated resistance wire to sense cloud LWC. As water droplets in a cloud strike the wire, they are evaporated, which changes the temperature of the wire. The consequent change in resistance of the wire varies linearly as the LWC of the cloud. The probe has a second resistance wire that does not intercept water droplets, since it is mounted with its axis parallel to the direction of the airstream. Changes in resistance in this second wire are due to variations in airspeed, altitude, and air temperature. By combining the response of the two wires, the instrument produces a voltage that is proportional to the LWC of the cloud.

2.2. Gerber Scientific Inc. PVM-100

The PVM -100 works on the principle that cloud particles diffract light, and that the angular intensity distribution of the diffracted light is sensitive to particle size. The probe contains two integrating sensors. The first inverts the angular distribution of light to obtain the third moment of the particle size spectrum (e.g., LWC), and the second performs an inversion to infer the second moment of the particle size spectrum (e.g., particle surface area (PSA)). The inverted signal is converted to LWC and PSA using calibration constants predetermined with a reference standard (Gerber et al., 1994).

2.3. Droplet Measurement Technologies LWC-100

The DMT LWC-100 depends on the principle that LWC can be calculated from measurements of the amount of heat released when water droplets are vaporized. A heated cylinder is exposed to the airstream and intercepts oncoming droplets. The electronics maintain this sensor at a constant temperature (~125 °C) and monitor the power required to maintain this temperature as droplets vaporize. This “wet” power is directly related to the amount of heat taken away by convection and vaporization. The convective heat losses are determined empirically and vary with airspeed, temperature and pressure. The liquid water content is linearly related to the difference between wet and convective (“dry”) power losses.

2.4. NRC Reference Standard

The reference method used at the NRC Icing Tunnel for LWC is the rotating icing cylinder. Stallabrass (1978) has estimated the errors in LWC values obtained with the rotating cylinder technique, and concluded that the most probable sources of error each lead to LWC estimate errors between about -5 and +5%, with some cancellation of errors. Stallabrass also compared rotating icing cylinder measurements to icing blade measurements of LWC. He found the rotating icing cylinder measurements to be 0.5% higher and 2.4% lower than the icing blade measurements for wind speeds of 75 and 125

m s⁻¹, with standard deviations of 3.8 and 5.6% respectively. Although Stallabrass stopped short of declaring an overall uncertainty in the rotating cylinder measurements, the implication of the error analysis and the comparisons with the blade technique suggest that the measurements of LWC with the rotating icing cylinder should be accurate to within a few percent.

An automated version of the rotating icing cylinder device used by Stallabrass (1978) was used as a standard in the present study. The apparatus automatically telescoped the rotating cylinder rapidly into the stream of water in the tunnel where it was exposed for a precise period of time. The ice accreted on the rod was weighed with a precision scale, and the LWC computed using an NRC computer algorithm based on the equations described by Stallabrass (1978).

3. CARG SOFTWARE ROUTINES

3.1. *Johnson-Williams*

The software used by the UW Cloud and Aerosol Research Group (CARG) for the J-W probe uses the following equation to convert instrument voltages to LWC:

$$LWC_{JW} = k \times (V - V_0) \quad (3.1)$$

where, V is the voltage in the cloud, V_0 is the voltage out of the cloud, and k is given by:

$$k = span \times \frac{tasset}{tas} \quad (3.2)$$

where, $span$ is the calibration constant, which currently has a value of:

$$span = 0.4 \quad (3.3)$$

and where tas is the true air speed, and $tasset$ the reference airspeed ($m\ s^{-1}$). The reference airspeed (in knots) is set by a dial on the front panel of the instrument. The CARG software assumes the reference value to be 140 knots ($71.5\ m\ s^{-1}$). During the tunnel calibrations at the NRC the reference value was set at 150 knots ($77.1\ m\ s^{-1}$); it is this value that is used in the analysis presented in this report.

3.2. Gerber Scientific Inc. PVM-100

The CARG software for the PVM-100 uses the following equation to convert instrument voltages to LWC values

$$LWC_{PVM} = V \times span \quad (3.4)$$

The PVM-100 was calibrated by the manufacturer on Sept. 28, 1998. The value of $span$ was determined to be 1.247. This value is currently used in the CARG software.

3.3. Droplet Measurement Technologies LWC-100

The DMT is a new instrument. Therefore, at the time of writing, a computer code has not been implemented for this instrument in the CARG software. Computer code exists for an earlier CSIRO King probe (King et al., 1978) that is no longer used. This will temporarily suffice as these two probes work on the same principles. However, there are some small design differences between the two probes and software changes will need to be implemented. In the following analysis, the “wet” power loss of the wire, P , is evaluated using the same technique as for the CSIRO King probe, with the exception that certain physical constants are changed. DMT has provided an algorithm (described in the DMT Operations Manual) for evaluating the “dry” power loss, P_d , which differs from the CSIRO King algorithm. We evaluate this new algorithm in the following analysis. However, the most precise estimate of P_d is obtained by directly measuring P_d when the

probe is in clear air and uniformly applying this value to cloudy air. It is this latter technique we use for calculating the “dry” power term in the LWC equation:

$$LWC = \frac{P - P_d}{ldv[L_v + c_p(T_v - T_a)]} \quad (3.4)$$

where, l is the length of the hot wire (2.02 cm), d the diameter of the hot wire (0.183 cm), v is the true airspeed, T_a the ambient temperature, L_v the latent heat of vaporization, and c_p is the specific heat of water at the temperature, T_v , at which water is evaporated from the wire. (Although the DMT manual suggests T_v is 100 °C, we use a value of 90 °C, as recommended by the manufacturers of the CSIRO King Probe. 90 °C is the probable film temperature of the evaporating water).

4. MEASUREMENT PROCEDURES

4.1. *Wind Tunnel Conditions*

The responses of the LWC probes were evaluated for fifteen predetermined cloud conditions. Seven of these conditions were made at tunnel speeds of 100 m s⁻¹, with LWC ranging from 0.079 to 1.741 g m⁻³ and a droplet median volume diameter (MVD) of ~22 μm. Another seven conditions were made at tunnel speeds of 80 m s⁻¹, with LWC ranging from 0.091 to 2.140 g m⁻³ and a droplet MVD of 22 μm. A final condition was at 100 m s⁻¹, with a LWC of 0.558 g m⁻³ and a droplet MVD of 15 μm. These conditions are approximately representative of cloud LWC and droplet sizes found in the atmosphere and for typical research aircraft speeds.

For each test run (in some cases, several runs were made for each set of conditions), the probes were exposed to cloudy air after the LWC had stabilized in the tunnel. The difference between the average LWC during this cloudy period and the LWC offset in a dry air flow is the measured LWC used in our analysis.

4.2. *Corrections for Tunnel Water Flow, Airspeed, and Probe Position*

Icing cylinder measurements of LWC in the NRC tunnel were performed at nominal water flows and airspeeds. During the wind tunnel tests, the true water flows and airspeeds differed slightly from the nominal values. Corrections were made to measured LWC based on the differences between true airspeeds and flows, and nominal airspeeds and flows. These corrections were typically less than 3% and were applied for each wind tunnel run.

Icing cylinder LWC are referenced to the center of the NRC wind tunnel. The positions of the test liquid water probes were usually slightly offset from the center. This is important since the distribution of cloud LWC varies across the width of the tunnel. Therefore, for each test condition an NRC King probe was used to map the LWC distribution across the tunnel. The ratio of the mapped LWC at the test instrument position to the mapped LWC at the tunnel center provided a third correction to test the LWC measurements. All three of the above corrections were applied to LWC measurements discussed below.

5. RESULTS

5.1. *Johnson-Williams (Head #179)*

On the morning of April 20, 1999, the UW J-W LWC probe with head #179 was tested in the NRC wind tunnel. The results of the tests for wind speeds of 80 m s^{-1} and 100 m s^{-1} are shown in Figs. 1 and 2.

From the results shown in Figs. 1 and 2 three things are clear. Firstly, the J-W significantly overestimated LWC, by a factor of 1.94 at 80 m s^{-1} and 1.77 at 100 m s^{-1} (encircled data points in Figs 1 and 2 are omitted from the linear fit). Secondly, the instrument responds linearly with LWC up to 1.2 g m^{-3} but not beyond that (as shown by the encircled data points). Thirdly, the response of the J-W depends on tunnel airspeed: (as indicated by the fact that the slope of the fit at 100 m s^{-1} is less than the slope of the fit at 80 m s^{-1}).

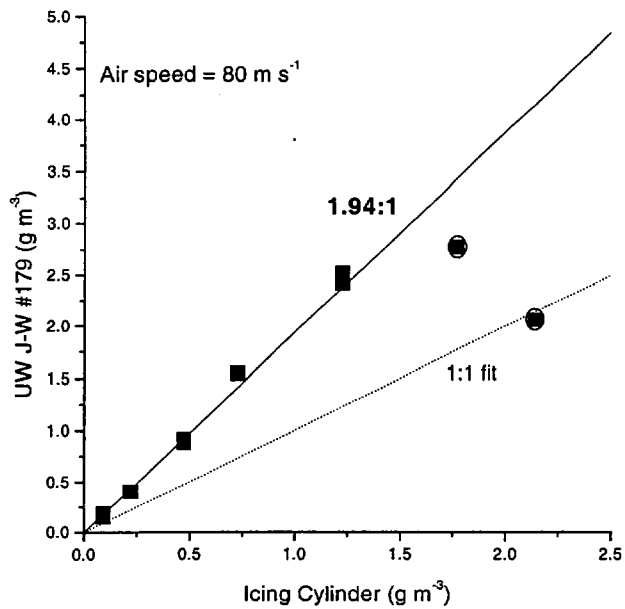


Figure 1: Comparison of liquid water content measurements with the UW Johnson-Williams LWC probe (head #179) and corresponding measurements from the NRC reference icing cylinder. The airspeed was 80 m s^{-1} . A fit to the data, that excludes the encircled data points, is shown by the solid black line. A 1:1 perfect-fit line is shown for reference.

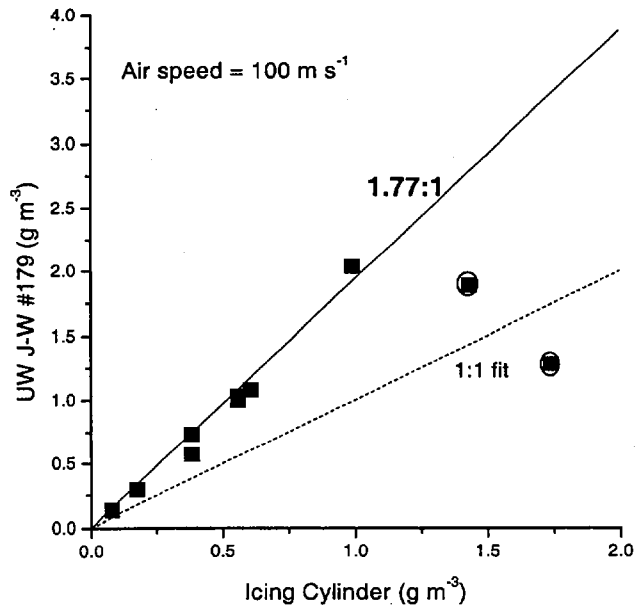


Figure 2: As for Fig.1 but for an airspeed of 100 m s^{-1} .

5.2. *Johnson-Williams Probe (Head #123)*

On the afternoon of April 20, 1999, the UW J-W probe with head #123 was tested in the wind tunnel. The results for the test runs are shown in Figs. 3 and 4.

For wind tunnel speeds of 80 m s^{-1} , the J-W probe varies linearly with LWC up to at least 2 g m^{-3} . However, the probe overestimates LWC by a factor of 2.23. At wind speeds of 100 m s^{-1} , the probe response varies linearly with LWC up to 1.5 g m^{-3} , beyond which the instrument response falls off. Below 1.5 g m^{-3} the probe overestimates LWC by a factor of 1.92. Therefore, the probe has a response that is a function of air speed.

5.3. *Droplet Measurement Technologies LWC-100*

The UW DMT probe was tested on the afternoon of April 20, 1999 (simultaneously with the UW J-W probe with head #123). The results of the tests are shown in Figs. 5 and 6. The DMT probe has a response to LWC that is linear up to at least 2 g m^{-3} and was independent of wind tunnel airspeed. The response was 12% lower than the icing cylinder standard at both 80 and 100 m s^{-1} .

The above results were obtained after subtracting a “dry” power term, calculated from out-of-cloud values, from a “wet” power term. It is possible to evaluate the “dry” power term in cloud, however it requires a precise estimation of the wire temperature. The manufacturers suggest an approximate hot-wire temperature of $125 \text{ }^\circ\text{C}$, but suggest that more precise values may be obtained by finding a hot-wire temperature that gives an in-cloud “dry” power equivalent to the out-of-cloud “dry” power. Through trial and error we found that best agreement was obtained for hot-wire temperatures of 130 and $126 \text{ }^\circ\text{C}$ at 80 and 100 m s^{-1} , respectively.

5.4. *Gerber Scientific Inc. PVM-100*

The UW PVM-100 LWC probe was tested in the NRC wind tunnel on the morning of April 21, 1999. The results are shown in Fig. 7. Since the PVM-100 infers

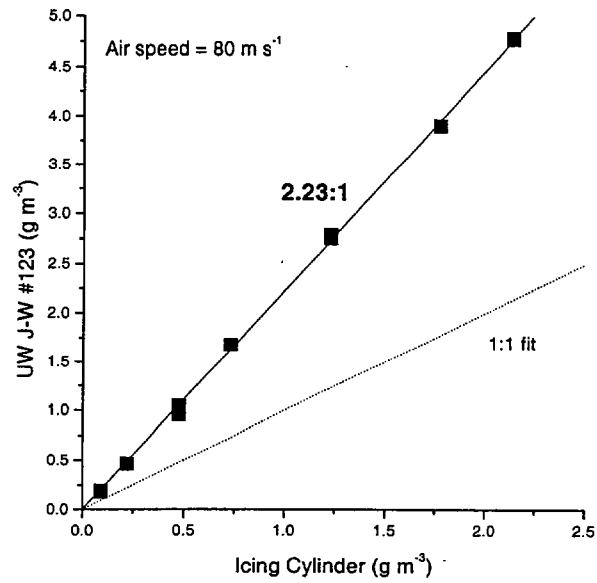


Figure 3: As for Fig. 1 but for UW J-W head #123.

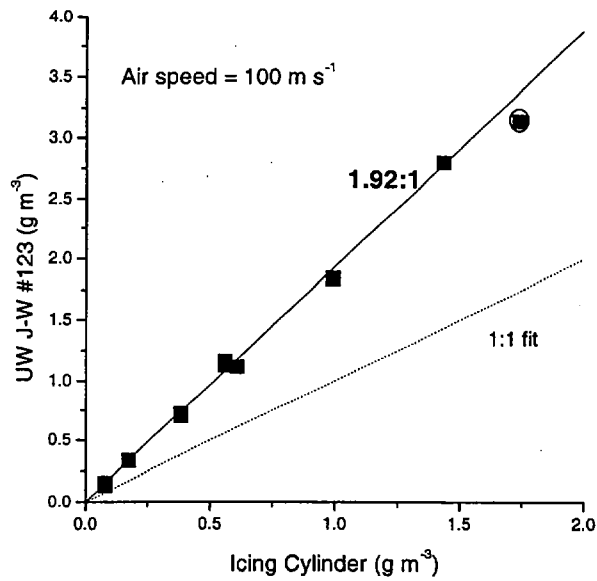


Figure 4: As for Figure 1, but for UW J-W head #123 and an air speed of 100 m s^{-1} .

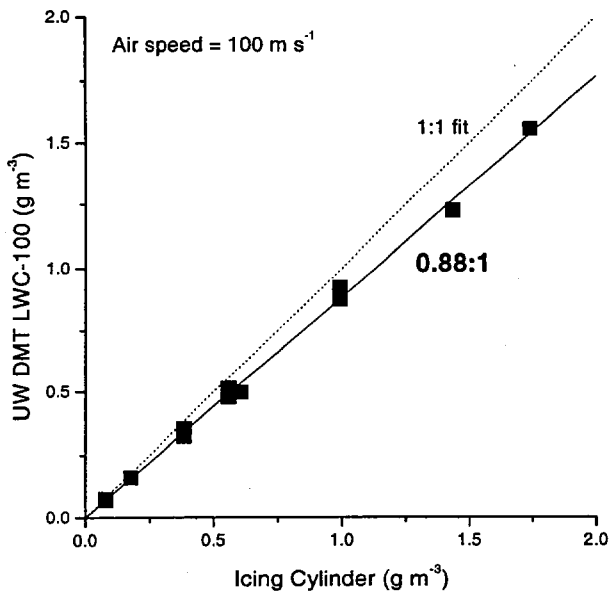


Figure 5: As for Fig.1 except for the UW DMT-100 probe.

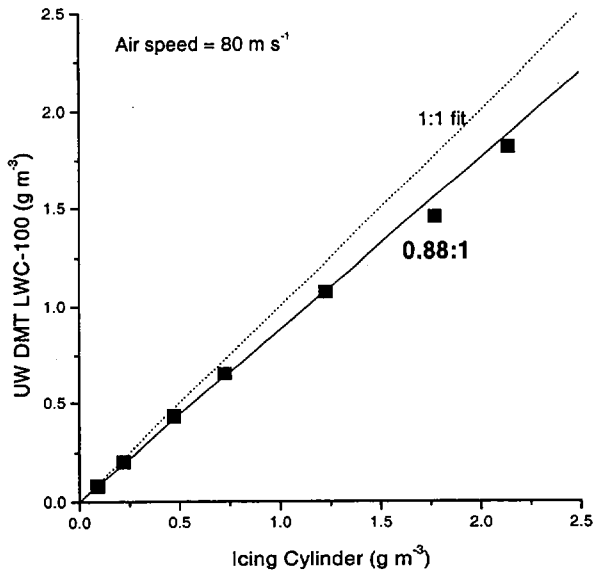


Figure 6: As for Fig. 1 except for the UW DMT-100 probe and an air speed of 100 m s^{-1} .

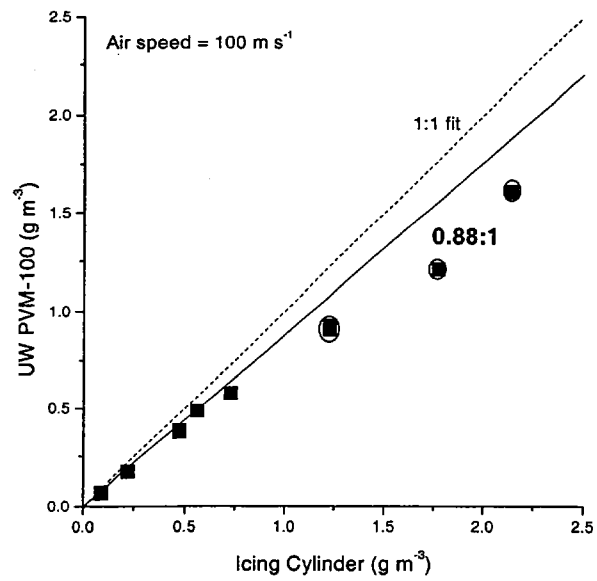


Figure 7: As for Fig. 1 except for the UW PVM-100A and at an airspeed of 100 m s⁻¹.

LWC from the bulk optical properties of a cloud, its response is independent of airspeed. Therefore, the probe was tested at one air speed only which was 100 m s^{-1} .

The PVM-100 response varied linearly up to $\sim 0.75 \text{ g m}^{-3}$, after which its response tailed off. Below 0.75 g m^{-3} the instrument response was 12% lower than the icing cylinder reference.

An experiment was conducted in the wind tunnel to evaluate the size response of the PVM-100. On the morning of April 21, 1998, the PVM-100 was exposed to sprays that had approximately constant LWC (Fig. 8) but for which the MVD of the spray droplets varied. The droplet volume size distribution of the sprays was measured with a Malvern laser-diffraction spectrometer probe (Swithenbank et al., 1977).

We evaluated the sensitivity of the PVM-100 to droplet MVD for three PVM-100 size response curves (Fig. 9). The first assumes the PVM-100 size response is unity for all sizes (even though the PVM-100 was designed to have a droplet size response similar to that of the FSSP-100). Droplets within the instrument's sample volume diffract light onto variable transmission filters. Based on theoretical considerations, the filter LWC response is linear between 5 and $40 \mu\text{m}$ diameter and gradually rolls off to 50% at $2 \mu\text{m}$ and $70 \mu\text{m}$ (Gerber, 1991). This is our second response curve. We also present a hypothetical response curve that assumes the PVM-100 response is linear between 0 and $20 \mu\text{m}$ diameter but tapers off for larger droplets.

By superimposing these three curves on the droplet distribution measured by the Malvern probe we can determine the fraction of the LWC in the droplet spray that is sensed by the PVM-100 (Fig. 10). Since the droplet spectrum of the spray is broad (significantly broader than in natural clouds), a fall off in the droplet size response indicates that the PVM-100 does not detect a significant proportion of the LWC in the spray. For each spray condition and response curve we evaluated the proportion of spray LWC that was not detected by the PVM-100 and corrected the PVM-100 data accordingly.

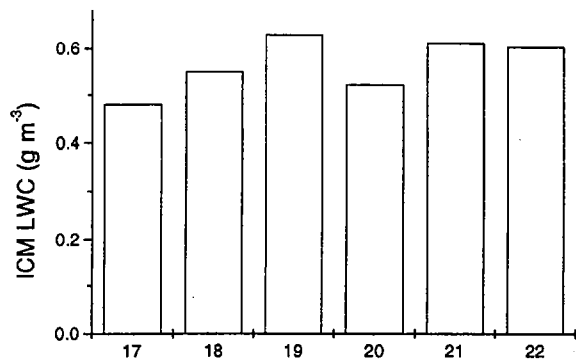


Figure 8. Icing cylinder liquid water contents during a test of the size response of the PVM-100.

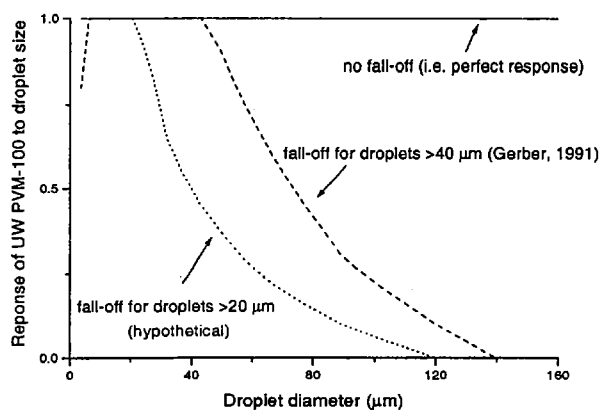


Figure 9. Three hypothetical curves for the response of the PVM-100 to LWC contained in droplets of a given diameter. A response of 0.5 at 40 μm diameter indicates the PVM-100 measured 50% of the LWC contained in 40 μm diameter droplets.

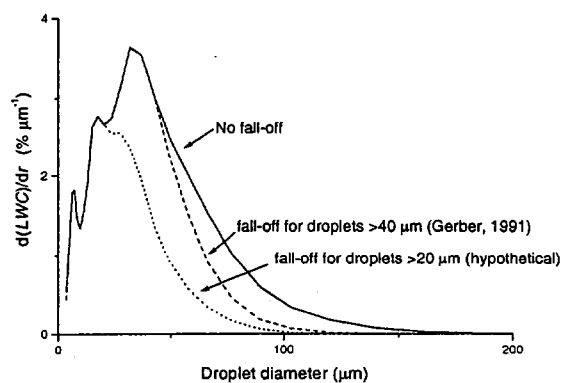


Figure 10. Superimposition of response curves in Fig. 9 on droplet volume spectrum measured by the Malvern laser diffraction spectrometer. The solid line represents the droplet volume distribution measured by the Malvern probe. The area beneath the dashed and dotted lines represent the portion of droplet volume measured by the PVM-100, shown here for two assumed size response curves of the PVM-100.

Shown in Fig. 11 is the ratio of the corrected PVM-100 LWC to the icing cylinder reference as a function of the MVD of the spray (as measured by the Malvern probe). If it is assumed that the PVM-100 response is linear over the entire droplet spectrum range (i.e., no correction is applied to the PVM-100 data), the PVM-100 progressively underestimates LWC as the MVD increases. For example, the icing cylinder and PVM-100 are in near agreement for a MVD of 10 μm , but the PVM-100 underestimates LWC by $\sim 40\%$ when the MVD is 32 μm and $\sim 60\%$ for an MVD of 57 μm .

Alternatively, if we correct the PVM-100 for the response curve determined by Gerber (1991) (where the tail begins at 40 μm), and this response curve is correct, the icing cylinder and corrected PVM-100 data should agree for all MVD values. In fact, correcting the data in this manner does not significantly improve the PVM-100 results; the PVM-100 still underestimates LWC by about 30 % for an MVD of 32 μm , and 40% when the MVD is 57 μm .

Finally, if we assume that the response of the PVM-100 falls off sharply for droplets with diameters greater than 20 μm , the PVM-100 is within 5% of the icing cylinder measurements for all MVD values. (Other response curves with a fall off beginning at larger or smaller droplet sizes do not produce such good agreement.)

These results indicate that the PVM-100 is not very sensitive to LWC contained in droplets larger than about 20 μm diameter. We can replot the results shown in Fig. 7 accordingly, correcting the PVM-100 measurements by assuming the instrument response falls off for droplets >20 μm (Fig. 12). With this correction, the PVM-100 is in nearly perfect agreement with the icing cylinder measurements for LWC up to ~ 0.75 g m^{-3} (slope = 0.965), although the sensitivity of the PVM-100 to large LWC remains somewhat diminished.

6. CONCLUSIONS AND RECOMMENDATIONS

- The UW Johnson-Williams LWC probe with head #123 varied linearly over a wider range of LWC than it did with head #179. At an airspeed of 80 m s^{-1} (the nominal

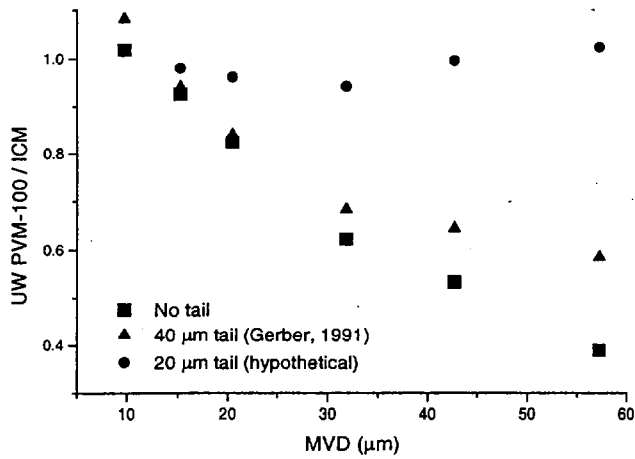


Figure 11. Ratio of the LWC measured by the PVM-100 to the LWC measured by the NRC icing cylinder LWC as a function of the median volume diameter (MVD) of the droplet distribution (measured by the Malvern laser-diffraction spectrometer) and the assumed response curve of the PVM-100.

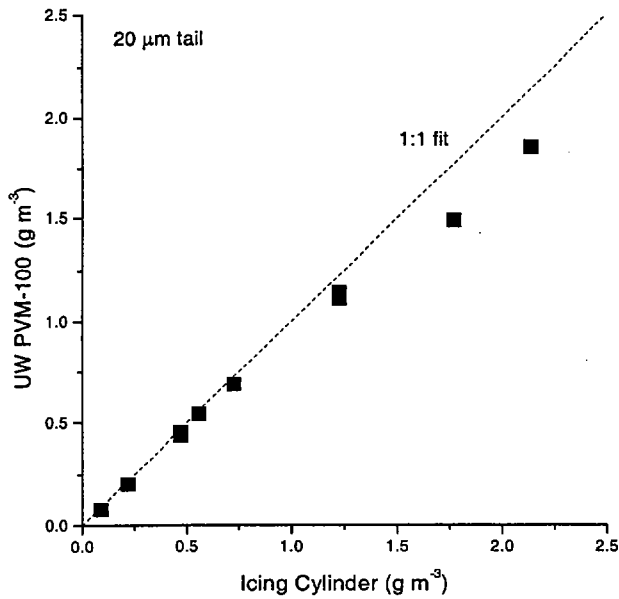


Figure 12. As for Fig. 7, except the PVM-100 measurements are corrected assuming a 20 μm tail (Fig. 9) in the PVM-100 response to large droplets.

speed of the UW CV-580) the LWC measured by head # 123 and head #179 are, respectively, 2.23 and 1.94 times greater than the icing cylinder reference. Both heads exhibited a response to LWC that is approximately 10% lower at aircraft speeds of 100 m s^{-1} . In view of these results, it is recommended that head #123 be used instead of head #179. In addition, the number 0.4 in Eq. 3.3 should be replaced by 0.18 if head #123 is used, and by 0.21 if head #179 is used. The J-W probe will slightly underestimate LWC if the aircraft speed is significantly greater than 80 m s^{-1} .

- The UW DMT LWC probe performed exceptionally well. Its response was independent of airspeed and varied linearly over the full range of LWC used in the wind tunnel tests ($0.1 - 2.2 \text{ g m}^{-3}$). Compared with the icing cylinder measurements, the UW DMT probe underestimated LWC by 12%. This discrepancy could be due to a systematic bias in the icing cylinder measurements, to a diminished response of the DMT probes to water droplets smaller than $10 \text{ }\mu\text{m}$ diameter (which accounted for approximately 10% of the total LWC), or to a diminished response to droplets larger than $30 \text{ }\mu\text{m}$ (which accounted for approximately 40% of the total LWC). An accurate estimate of the DMT probe “dry” power can be obtained in-cloud if a wire temperatures of $130 \text{ }^\circ\text{C}$ and $126 \text{ }^\circ\text{C}$ are assumed for airspeeds of 80 m s^{-1} and 100 m s^{-1} , respectively.
- The UW PVM-100 probe underestimated LWC by 12% in the 0 to 0.75 g m^{-3} range. An analysis of the response of the PVM-100 to large droplet sizes shows the PVM-100 has diminished response to droplets with diameter larger than $20 \text{ }\mu\text{m}$. At an MVD of $32 \text{ }\mu\text{m}$ the PVM-100 underestimated spray LWC by $\sim 40\%$, compared to the 18% underestimation at a MVD of $30 \text{ }\mu\text{m}$ reported by Gerber et al. (1994). If we apply a correction to the PVM-100 LWC data that takes into account a fall off in its response to droplets $>20 \text{ }\mu\text{m}$ diameter, the PVM-100 LWC is within 4% of icing

cylinder measurements for LWC $<0.75 \text{ g m}^{-3}$. For LWC $>0.75 \text{ g m}^{-3}$, the PVM-100 underestimates LWC by up to 30%.

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