Calibration of Johnson-Williams and PMS.ASSP probes in a wind tunnel

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ABSTRACT

Wet wind tunnel tests have provided calibrations and intercomparisons of the LAMP's cloud liquid water content probes (three Johnson–Williams sensor heads and one PMS ASSP). The tunnel liquid water content was deduced with a rotating cyclinder technique.

The results show that the Johnson–Williams dynamic response is different according to the sensor head and control units that are used. The tests with the ASSP give an evaluation of the maximum airspeed beyond which the measurements are unreliable.

1. Introduction

Within the framework of microphysical studies of clouds, the determination of the liquid water content is one of the fundamental in situ measurements carried out from instrumented aircraft.

Among the most widely and easily used sensors is the Johnson–Williams hot-wire device (Neel, 1973), which has been commercially available since the 1950s. More recently, there has appeared an initial version (ASSP, Gayet, 1976) of a series of laser spectrometers developed by Particle Measuring Systems (Boulder, CO). This probe directly provides the cloud droplet spectrum from which the liquid water content can be evaluated by integration.

Due to the difficulty of carrying out direct and systematic dynamic calibrations of these two types of probe, the Atmospheric Environment Service organized a series of calibrations and comparisons of these microphysical sensors in the wet wind tunnel of the National Research Council of Canada (NRC) in Ottawa (Strapp and Schemenauer, 1982), from 20 October to 7 November 1980. (The list of laboratories involved in this experiment is given in the Appendix.)

On 27 and 28 October, the Laboratoire Associé de Météorologie Physique (LAMP) tested three Johnson–Williams sensor heads and an axially-scattering spectrometer probe (ASSP). The object of this paper is to describe the results and to deduce the limits of these probes.

2. Characteristics of the wind tunnel and measurement procedures

a. Characteristics of the wind tunnel

The closed wind tunnel used by NRCs Low Temperature Laboratory can produce a maximum speed of about 150 m s^{-1} in the 30 cm × 30 cm × 45 cm measuring section. The refrigeration systems and the heat exchanger make it possible to operate down to temperatures of −40°C with an accuracy of ±0.5°C.

The nozzles set up in the plenum chamber can produce a maximum liquid water content of 2 g m^{-3} at 100 m s^{-1}. The droplet median volume diameter can vary from 10 to 35 μm by setting airflow rates in the nozzles according to a chart of parameters (air pressure, water flow, airspeed . . .) determined by NRC staff from oil slide calibrations. The median volume diameter set in the wind tunnel will be called "displayed" median volume diameter in the paper. The value of the liquid water content produced by the nozzles was estimated by the rotating cylinder method: the weight of ice deposited on the cylinders during a specified period of time determines the corresponding liquid water content. Stallabrass (1978) has made an exhaustive criticism of this technique. He showed that the errors introduced in the estimation of the liquid water content (increase in the radius of the deposit, specific mass of the frost, roughness of the surface, etc.) are of the order of 5% in the temperature and speed ranges used during the present experiment.

b. Measuring and processing procedures

Table 1 summarizes the various tests conducted with the Johnson–Williams and the ASSP probes. Basically, the sensors were tested for two distinct airspeeds, 51 and 103 m s^{-1}, and within a static temperature range extending from +6° to −15°C. All the tests were carried out with a displayed median volume diameter of 20 μm, with the exception of tests 6 and 15, for which that diameter was 30 μm, and test 16, for which the median volume diameter was variable (between 10 and 35 μm).

For tests pertaining to Johnson–Williams, two sensor heads were set up simultaneously in the tunnel. One was recorded by using the LAMPs control unit and

TABLE 1. Summary of the various tests performed in the NRC wind tunnel: test number, type and sensor head number, airspeed, static temperature, median volume diameter.

Probe type	Test	Sensor head	Airspeed ($m\ s^{-1}$)	Static temperature (°C)	Median volume diameter (μm)
Johnson–Williams	1	LAMP 226 AES 275	51	5.7	20
	2	LAMP 226 AES 275	103	4.7	20
	3	LAMP 226 AES 275	51	−4.8	20
	4	LAMP 226 AES 275	103	−6.3	20
	5	LAMP 226 AES 275	103	−6.8	20
	6	LAMP 226 AES 275	103	−6.8	30
	7	LAMP 226 AES 275	51	−13.3	20
	8	LAMP 226 AES 275	103	−15.3	20
	9	LAMP 221 LAMP 226	51	−6.3	20
	10	LAMP 221 LAMP 226	103	−5.3	20
	11	LAMP 227 LAMP 226	103	−3.3	20
ASSP	12		51	3.7	20
	13		103	−0.3	20
	14		103	−0.3	20
	15		51	3.7	30
	16		51	3.7	10 to 35
	17		103	−0.3	20

the other with the AES's control unit. Tests 1 to 8 correspond to LAMPs sensor head 226 and AES's sensor head 275. Tests 9 to 11 were performed to calibrate LAMP's sensor heads 221, 227 and 226, the latter being recorded via AES's control unit. Tests 12 to 17 dealt with the calibration of the ASSP (see Table 1). For each test, the probes were exposed to nozzle sprays corresponding to a series of 5–10 liquid water content values (between 0.2 and 2.0 g m^{-3}), during a period of about 30 seconds per liquid water content value and under stabilized conditions. The information provided by the two control units (LAMP and AES) were recorded on a magnetic tape at a frequency of 2 Hz for Johnson–Williams tests, and 10 Hz for the ASSP tests. For the two types of probe and for each measurement point, the values were averaged over a period for which the variance of the liquid water content was minimal (best stability conditions of the measurement point). For the Johnson–Williams, the offset correction was determined before the water was injected.

3. Results obtained with the Johnson–Williams probes

a. Tests carried out at 103 m s^{-1}

The results obtained with the two sensor heads mounted simultaneously in the sampling section are summarized in Table 2. These results are now discussed in detail and are illustrated by figures that represent the values of the liquid water content measured by the two sensor heads as a function of the displayed reference values in the wind tunnel.

(i) For a temperature of −15°C (test 8, Fig. 1), the two probes show significant underestimation when the liquid water content is greater than 1.5 g m^{-3}. This underestimation is due to the icing of the upstream support of the compensation wire, which thereby affects the measurement. For liquid water contents lower than 1.5 g m^{-3}, LAMPs sensor head 226 gives satisfactory measurements. On the other hand, sensor head 275, which underestimates the liquid water content by about 20%, is probably more sensitive to icing. The character of this icing signature is not necessarily repeatable, and these tests cannot be considered effective calibrations. Strapp and Schemenauer (1982) have reported on the frequency of icing problems with sensor heads tested at the NRC tunnel.

(ii) When the median volume diameter is 30 μm (test 6, Fig. 2), the two probes show an underestimation (25 to 30%) that increases with increasing liquid water content. This deviation is thought to be due to the splitting-up of large drops (>30 μm) on the measurement wire before evaporation. These results confirm

TABLE 2. Results of the tests of the Johnson–Williams probes at 103 m s^{-1}: test number, static temperature (T), median volume diameter (d), sensor head number, slope of the regression line (S) and standard deviation (σ).

Test	T (°C)	d (μm)	Control unit					
			LAMP			AES		
			Sensor head	S	σ (g m^{-3})	Sensor head	S	σ (g m^{-3})
2	4.7	20	226	0.95	0.06	275	0.85	0.05
4	−6.3	20	226	1.01	0.10	275	0.88	0.06
5	−6.8	20	226	1.15	0.01	275	0.99	0.03
6	−6.8	30	226	0.67	0.11	275	0.52	0.11
8	−15.3	20	226	—	—	275	—	—
10	−5.3	20	221	1.29	0.07	226	0.95	0.04
11	−3.3	20	227	1.15	0.04	226	0.86	0.05

those of Spyers-Duran (1968) and Personne et al. (1982) established on the basis of airborne measurements.

(iii) Although tests 4 and 5 (Figs. 3a and 3b) were carried out under identical conditions of speed (103 m s^{-1}), temperature (−6.5°C), and median volume diameter (20 μm), the slope of the regression lines corresponding to the two probes is greater for test 5 than for test 4 (1.15 versus 1.01 for sensor head 226 and 0.99 versus 0.88 for sensor head 275). This may be due to non-reproducibility of the wind tunnel conditions, which would indicate variations of up to 15% in this case. Strapp and Schemenauer (1982) pointed out, on the basis of the processing of all the icing cylinder measurements carried out in the NRC wind tunnel in 1980, that, in general, the reproducibility of the liquid water content during careful icing cylinder measurements is excellent (less than 3%). However, larger variations during actual instrument calibrations could have occurred, due to the large number of manual settings required for hundreds of individual spray conditions, and due to ice buildup on the tunnel walls during runs below 0°C. The latter effect has subsequently been observed to produce relatively large variations (<20%) in icing cylinder measurements at high liquid water content conditions at 100 m s^{-1}, suggesting that the tunnel should be deiced frequently to insure confidence in tunnel accuracy (Strapp, personal communication, 1985). This case illustrates the value in simultaneous tests of similar instruments to assist in identification of the occasional anomalies in tunnel conditions. It should be noted that many other tests with simultaneous instrument calibrations have shown that the Johnson–Williams probe can itself provide non-reproducable results. The reproducibility of the tunnel in this case is verified by the consistency of the second probe results.

(iv) When the temperature is warmer than −15°C and the median volume diameter is less than 30 μm, sensor heads 226, 227 and 275 (tests 2, 4, 5 and 11) give satisfactory results (less than 15% error). A systematic deviation is observed, however, between the responses of the two control units (LAMP and AES), no matter which sensor head is used. For example, the

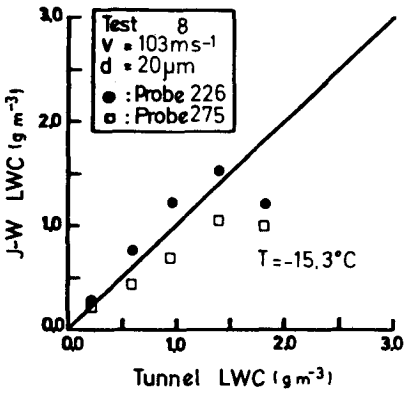

FIG. 1. Johnson–Williams liquid water content vs wind tunnel liquid water content. Values plotted are ~30 s averages. The test number, the airspeed, the wind tunnel median volume diameter, the static temperature and sensor head numbers are also indicated with the 1:1 line. Test 8. This figure shows the Johnson–Williams underestimation due to the icing of the probe for LWC > 1.5 g m^{-3}.

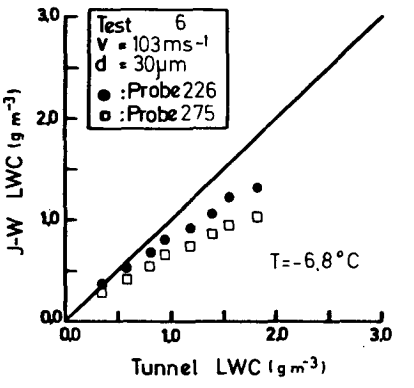

FIG. 2. Test 6. The figure shows the underestimation of the two probes for median volume diameter of 30 μm.

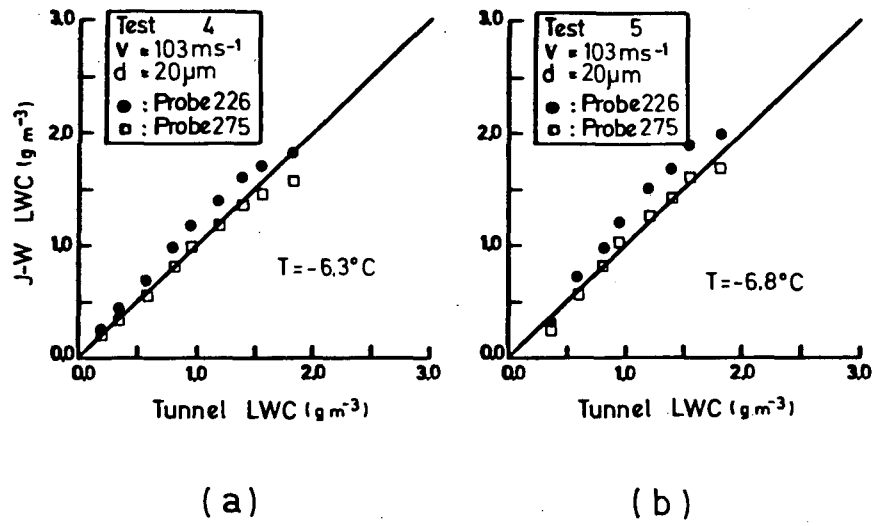

FIG. 3. Despite identical wind tunnel conditions, the responses of the two probes are different between (a) test 4 and (b) test 5. Note also the saturation of the probe responses for LWC > 1.5 g m^{-3}.

results of sensor head 226 recorded via the AES's control unit (tests 10 and 11) show a regression line slope of about 0.9, whereas the same sensor head recorded via the LAMP's control unit (tests 4 and 5), gives a greater regression line slope ($S \sim 1.1$). This suggests a different response from the amplification or compensation systems of the two control units when the same sensor head is used. Sensor head 221 overestimates the liquid water content by a wide margin (30%). This may be due to differences in the construction of the probes or to the characteristics of calibration resistances. In this case, the "dummy head" calibration procedure[1] that is in standard use is inadequate. (See also Strapp and Schemenauer, 1982.)

(v) All the probes tested at 103 m s^{-1} have a dynamic response that is more or less linear to liquid water contents of at least 1.5 g m^{-3} (see Figs. 3a and 3b for example). Beyond that value, the response shows possible saturation, although the number of points is small. This nonlinear zone was observed in electronic measurements under laboratory conditions by Pinty and Rousset (1982), when the probe was connected to the control unit by cables 5 m long (aircraft cabling). They also show that the response is linear in the 0–2 g m^{-3} range with short cables.

b. Tests carried out at 51 m s^{-1}

Table 3 summarizes the results. An examination of these results shows that only sensor head 275, used for temperatures less than −5°C, gives satisfactory results. The other sensor heads show a significant overestimation of the liquid water content (as high as 75%). Figure 4 illustrates this overestimation.

Figure 5 shows the values of the slopes (S) pertaining to each sensor head as a function of temperature. For sensor head 226, the slope is 1.28 when the temperature is around 6°C; it then increases to 1.75 for −13°C. When used with AES's control unit and for a temperature of −6°C, sensor head 226 shows a smaller de-

[1] This procedure consists in simulating two liquid water content values (0 and 2 g m^{-3}) by means of standard resistances.

TABLE 3. Results of the tests of the Johnson–Williams probes at 51 m s^{-1}: test number, static temperature (T), median volume diameter (d), sensor head number, slope of the regression line (S) and standard deviation (σ).

Test	T (°C)	d (µm)	Control unit					
			LAMP			AES		
			Sensor head	S	σ (g m^{-3})	Sensor head	S	σ (g m^{-3})
1	5.7	20	226	1.28	0.00	275	0.96	0.02
3	−4.8	20	226	1.51	0.01	275	0.98	0.01
7	−13.3	20	226	1.75	0.08	275	1.18	0.05
9	−6.3	20	221	1.75	0.13	226	1.26	0.09

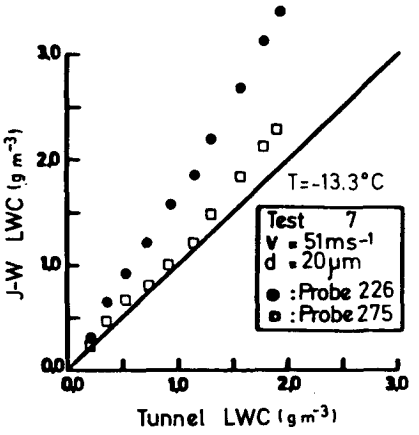

FIG. 4. Test 7. Overestimation of the probes for an airspeed of 51 m s^{-1} and a temperature of −13.3°C.

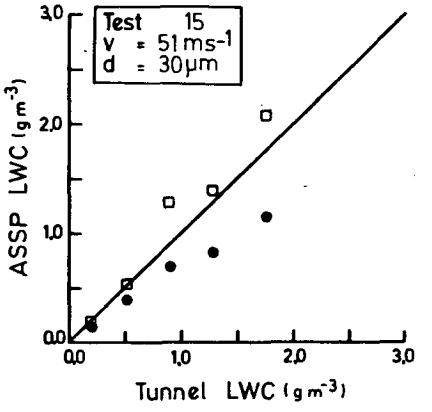

FIG. 6. Test 15. ASSP liquid water content vs wind tunnel liquid water content. Values plotted are ~30 s averages; ● symbols correspond to uncorrected values; □ symbols correspond to corrected values.

viation: 1.26 versus 1.51 with LAMP's control unit. At a temperature of −13.3°C, sensor head 275 shows a tendency similar to that of sensor head 226. This tendency is similar to effects seen in icing cylinder measurements with badly iced tunnel walls, indicating that iced tunnel walls may have produced this apparent nonlinearity in both probes. Sensor head 221 shows a significant overestimation ($S \sim 1.75$), when used at −6°C.

The above results were supported by processing of the microphysical measurements (sensor head 226 and FSSP) carried out during the 1979 and 1981 experiments of the Precipitation Enhancement Project (PEP). Comparisons of the liquid water content values obtained by means of the above two probes have revealed an overestimation of the Johnson–Williams for a speed of 60 m s^{-1} (the cruising speed of the Piper Aztec) during the 1981 PEP experiment (Gayet and Genest, 1981). On the other hand, at 100 m s^{-1} (DC7 aircraft; 1979 PEP experiment) and after correction for errors of coincidence on the FSSP measurements (Personne et al., 1982), the comparisons turned out to be satisfactory.

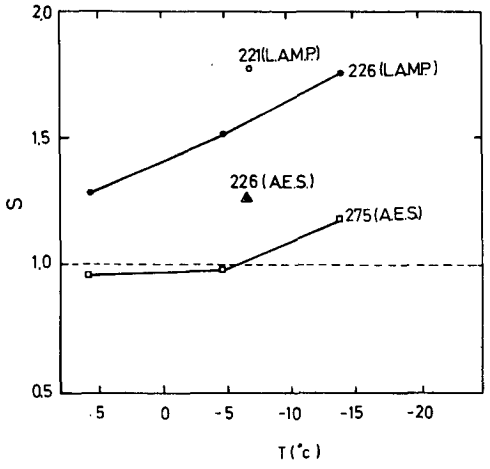

FIG. 5. Values of the slopes of regression lines (S) as a function of static temperature (T) for different sensor heads. Results of the tests performed at 51 m s^{-1} are shown. The symbols in parentheses indicate the control unit with which the sensor head has been recorded.

4. Results obtained with the PMS ASSP

a. Tests carried out at 51 m s^{-1}

An example of results obtained with the ASSP at 51 m s^{-1} is reported in Fig. 6. This figure displays the liquid water content values obtained after integration of the droplet spectra as a function of the displayed reference values in the wind tunnel.

The results are summarized in Table 4. The values of the displayed (LWC) and measured (LWC_m) liquid water content, and the concentration of droplets (CONC) are listed for both before and after correction of the measurements (to be discussed).

1) LIQUID WATER CONTENT AND DROPLET CONCENTRATION

Table 4 shows that whatever the displayed median volume diameter ($10 \leqslant d \leqslant 30$ µm), the values of the liquid water content deduced from the ASSP spectra (before correction) are lower than the ones displayed in the wind tunnel (for 1.78 g m^{-3} and 20 µm, a difference of 50% was observed). Such differences can be explained first by problems of coincidence[2] described by Personne et al. (1982), and second by the presence of droplets of diameter greater than 45 µm (upper limit

[2] When the number of particles sampled by the probe is large (high concentration and/or high speed), the logic time (τ) required by the ASSP electron circuits to process the information becomes comparable to the mean interval between the arrival of two particles in the sample volume.

TABLE 4. Results of the tests concerning the ASSP probe carried out at 51 m s^{-1}: test number, static temperature (T), wind tunnel median volume diameter (d), measured median volume diameter (d_m), wind tunnel water content (LWC), measured liquid water content (LWC_m) and droplet concentration (CONC), before and after correction.

Test	T (°C)	d (μm)	d_m (μm)	LWC (g m^{-3})	LWC_m (g m^{-3})	CONC (cm^{-3})	LWC_m (g m^{-3})	CONC (cm^{-3})
					Before correction		After correction	
			27.7	1.78	0.87	147	1.21	204
			26.6	1.31	0.64	145	0.88	199
12	4	20	23.9	0.92	0.53	153	0.73	210
			21.0	0.53	0.37	158	0.48	205
			17.9	0.20	0.17	172	0.19	172
			27.6	1.78	1.19	204	2.09	357
			27.1	1.31	0.85	184	1.38	297
15	4	30	26.5	0.92	0.73	203	1.29	357
			24.9	0.53	0.40	165	0.53	220
			23.3	0.20	0.15	128	0.15	131
		10	19.4		0.43	152	0.59	209
		12	19.8		0.46	163	0.65	233
		15	20.9		0.55	183	0.86	288
16	4	20	22.7	0.92	0.65	203	1.15	357
		25	24.6		0.66	203	1.16	357
		30	26.4		0.79	232	1.39	357

of ASSP measurements). In this respect, Strapp and Schemenauer (1982) show that measurements with a recent version of ASSP[3] indicate only a small quantity of water (~10%) was present in drops of diameter greater than 30 μm.

When coincidence problems arise, a statistical correction method (Personne et al., 1982) makes it possible, in certain cases, to improve significantly the ASSP measurements of liquid water content and concentration. This method assumes that the particles are uniformly distributed in space and crosses the sampling volume with exponentially distributed time intervals. The correction formula[4] can be shown as follows:

$$N_m = N_0 \exp(-AV\tau N_0), \quad (1)$$

with N_m and N_0 the measured and true concentrations, respectively; A the total sampling area; V the speed; and τ the length of time needed to process the information.

More precisely, Personne et al. (1982) pointed out that the total sampling area (A) depends on the droplet spectra, in such a way that larger droplets result in a larger sample area. Nevertheless, the measured droplet spectra being similar (see Table 4: d_m ranges from 19 to 27 μm), we assume, as a first approximation, that the total sampling area A is constant for all the tests performed in the wind tunnel. Assuming, moreover, that the coincidence errors do not entail an improper sizing of the particles, we have:

$$N_m/N_0 = LWC_m/LWC, \quad (2)$$

where LWC_m and LWC are the measured and reference water contents (values of the wind tunnel in the present case). It is then possible to determine the coefficient $\alpha = AV\tau$ which leads to the best fit (linear regression) of the experimental values of Table 4.

Figure 7 shows the variation of N_m as a function of N_0 from Eq. (1) when α is assigned the value determined with the regression method described above ($\alpha = 0.0018$ cm^3). The curve has a maximum that corresponds to the maximum measurable concentration ($1/\alpha e \sim 210$ cm^{-3}), i.e., a real concentration of 570 cm^{-3} ($1/\alpha$). The corrected values of the liquid water content have been indicated in Fig. 6, as well as in Table 4 with the new values of the droplet concentration.

The method of statistical correction brings an improvement to the evaluation of the liquid water con-

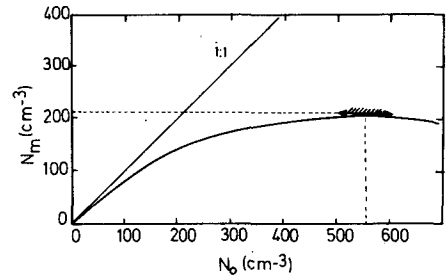

FIG. 7. Plot of the ASSP measured droplet concentration (N_m) as a function of the true droplet concentration (N_0), $N_m = N_0 \exp(-\alpha N_0)$, $\alpha = 0.00018$ cm^3 (see text).

[3] The ASSP version used by LAMP was purchased in 1974.

[4] This expression pertains to ASSPs with a retriggerable delay and reset sequence, as the LAMP ASSP. Some probes have been modified to make the delay and reset sequence nonretriggerable, which decreases the statistical correction in high concentrations and results in a different correction expression than (1).

tent. However, over the whole set of measurements, the relative errors remain significant (30%, on the average) as is shown in Fig. 8, where they are indicated as a function of the wind tunnel water content. These errors are of the same order as those evaluated by Baumgardner (1983): 34%, on the basis of a series of intercomparisons among several sensors (ASSP, FSSP, Johnson–Williams, King Probe, and impactors).

2) MEDIAN VOLUME DIAMETER

An examination of Table 4 shows scattered values of the measured median volume diameter despite constant displayed median volume diameters (tests 12 and 15).

Nevertheless, the results of test 16, conducted with a fixed liquid water content (0.92 g m^{-3}), indicate that the measured median volume diameter increases with the displayed median volume diameter but in a smaller proportion (from 19.4 to 26.4 μm against 10 to 30 μm). Two reasons may explain the differences.

- The oiled slide method (Golitzine, 1950) used to measure the size of the spray droplets, needs a reevaluation. Indeed, several workers (Gates, 1983; Makkonen and Stallabrass, 1984) have recently argued that this method overestimates the droplet size by at least a factor of 1.5.
- The absolute accuracy of the ASSP measurements is suspect. It can be affected by coincidence errors, the nonhomogeneities of the laser beam and the speed of the particles, when that speed is high ($\sim$100 m s^{-1}). A laboratory study (Rousset and Pinty, 1982) has shown that, when there is coincidence among several particles, the largest ones tend to impose their characteristics, and this situation causes an excessively low count of the smallest drops and, therefore, an overestimation of the median volume diameter. The nonhomogeneities of the laser beam, at the level of the sampling surface, lead, in general, to an overestimation of the number of small drops. A high speed ($\sim$100 m s^{-1}) results in a systematic underestimation of the diameter ($\sim$2 μm) because of the signal attenuation in the electronic device (upper limit on the band width) (Cerni, 1983).

These effects induce a spectral broadening that can reach 4 μm in standard deviation (Baumgardner, 1983). The accuracy of the mode of the measured spectrum depends essentially upon the calibration of the probe by means of calibrated glass beads (Pinnick et al., 1981). This adjustment procedure introduces an uncertainty of the order of 10% for diameters lower than 15 μm because of the large variations of the scattering function for the smallest particles.

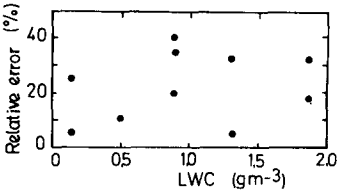

FIG. 8. ASSP liquid water content accuracies (after corrections) as a function of wind tunnel liquid water content. Results of tests performed at 51 m s^{-1} are shown.

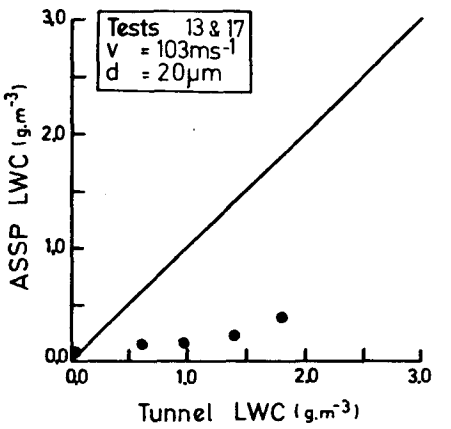

FIG. 9. Tests 13 and 17. This figure shows the large underestimation of the ASSP when used at 103 m s^{-1}.

Furthermore, for tests conducted with large liquid water content and large median volume diameter, droplets larger than the upper limit of the ASSP (i.e., $D > 45$ μm) may occur in the spray and significantly contribute to a larger median volume diameter than actually measured.

b. Tests carried out at 103 m s^{-1}

Figure 9 displays an example of results performed with the ASSP at 103 m s^{-1}. Table 5 summarizes the results. This table shows that the values of the liquid water content deduced from the spectra of the ASSP are very much lower than those displayed in the wind tunnel (more than 100% relative error). The method of statistical correction described above gives the value

TABLE 5. Results of the tests of the ASSP probe at 103 m s^{-1}: test number, static temperature (T), wind tunnel median volume diameter (d), measured median volume diameter (d_m), wind tunnel liquid water content (LWC), measured liquid water content (LWC_m) and droplet concentration (CONC).

Test	T (°C)	d (μm)	d_m (μm)	LWC (g m^{-3})	LWC_m (g m^{-3})	CONC (cm^{-3})
13 and 17	0	20	25.6	1.82	0.39	67
			24.0	1.40	0.23	53
			21.0	0.96	0.16	56
			18.2	0.60	0.14	78
14	0	30	24.0	1.82	0.31	100
			24.2	1.40	0.29	109
			24.1	0.96	0.22	98
			23.7	0.60	0.18	95
			21.2	0.21	0.11	90

of α as 0.0042 cm^3. Assuming that the total sampling area A is the same for the two sets of tests, the ratio of the two coefficients should be

$$\alpha_{103}/\alpha_{51} = (A\tau \times 103)/(A\tau \times 51) = 2,$$

which is in accordance with the experimental ratio

$$0.0043/0.0018 = 2.3.$$

For $\alpha = 0.0043$ cm^3, the maximum measurable concentration is only 90 cm^{-3}, which is obtained for a real concentration of 240 cm^{-3}. However, the droplet concentrations encountered in the course of similar tests (Strapp and Schemenauer, 1982) are much higher (300–500 cm^{-3}), and the proposed method of statistical correction is not applicable with our version of the ASSP for a speed of 100 m s^{-1}. Therefore, the characteristics of the probe (sampling area, duration of the information processing) impose some restrictions for its use, in particular with regard to the maximum airspeed V_{max}, which can be evaluated on the basis of our experimental results as follows:

$$V_{max} = 1/N_0 A\tau \quad (3)$$

where N_0 is the real concentration, and $A\tau = 3.9 \times 10^{-5}$ cm^2 (experimental mean value).

Figure 10 gives an estimation of the values of the maximum airspeed beyond which the measurements cannot be used as a function of the true droplet concentration. It should be noted that this curve is valuable only for droplet spectra defined by a median volume diameter of about 20 μm (constant value of A). For droplet distributions having a smaller median volume diameter for the same true concentration (N_0), the airspeed limit will be greater than defined in Fig. 10 for the same true concentration (N_0). Further complementary tests would be necessary to give quantitative results. This problem could be remedied somewhat by electronic modifications to make the counting behavior non-retriggerable. The LAMP FSSP (a different version from the ASSP), which has the advantage of faster electronics, insures useful measurements up to 100 m s^{-1} (Personne et al., 1982).

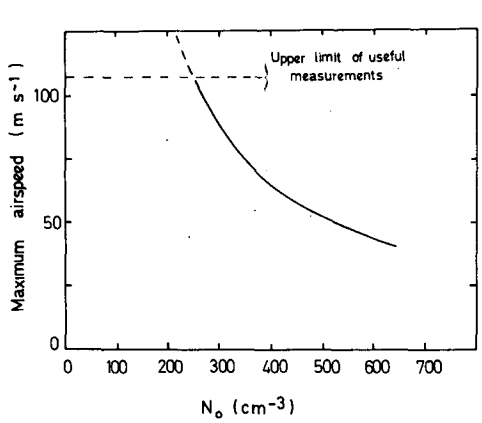

FIG. 10. Estimation of the values of the maximum airspeed beyond which the ASSP measurements cannot be used as a function of the true droplet concentration (N_0).

5. Discussion and conclusions

a. Characteristics of the wind tunnel

The analysis of the measurements by the Johnson–Williams and ASSP probes in the NRC wind tunnel has shown that the calibration of the liquid water content seem satisfactory when the displayed median volume diameter is 20 μm. The reproducibility of the tests is, in general, satisfactory, except for one case where differences up to 15% have been noticed. Nevertheless, some uncertainties are present in the median volume diameter. A reevaluation of this parameter using an absolute technique (holography for example) is needed.

b. Johnson–Williams

The dynamic response of the probe is a function of both the sensor head and the control units. At an airspeed of 103 m s^{-1}, sensor heads 226, 227 and 275 give satisfactory results (~15%) for temperatures warmer than −15°C. For colder temperatures, the measurements deteriorate rapidly because of probable icing build-up on the compensation wire. For all the sensor heads, the dynamic response is linear in the 0 to 1.5 g m^{-3} range; beyond that value, saturation is probable.

Tests at an airspeed of 51 m s^{-1} have shown that the response of the probe is dependent on temperature to a varying extent depending on the sensor head being used. Generally, the liquid water content is overestimated when the temperature is low.

Several sources of error may explain this behavior.

1) "DUMMY HEAD" CALIBRATION METHOD

In this method, the sensor head is replaced by a set of calibrated resistances (dummy head) that simulate two values of the liquid water content (0 and 2 g m^{-3}). However, if the dummy head is not suitably ventilated, the resulting rise in temperature may cause a variation between 20 and 30% in the higher reference value (2 g m^{-3}) since the dissipated power can reach 15 to 20 W (Pinty and Rousset, 1982; Baumgardner, 1983).

2) CONNECTION ERRORS

These errors may become important since a variation of 7.8 mΩ in the measurement resistance (i.e., 16% in relative value) corresponds to a variation in liquid water content of 2 g m^{-3} at 50 m s^{-1}, (i.e., a sensitivity of 3.9 mΩ g^{-1} m^3) (Pinty and Rousset, 1982). In the measurement of such a low resistive value the length of the linking cables and the quality of the various connec-

tions become important factors. The resulting parasitic resistances lead to a reduction of the sensitivity on the measurement.

3) COMPENSATION

In theory, the compensation wire is designed to compensate for drifting of the zero due to changes in altitude and temperature. In fact, our results show that this system is not reliable, in particular at 51 m s^{-1}. Its design and the location of the compensation wire (turbulent zone) are probably at fault.

4) CONCLUSIONS

The measurements of liquid water content provided by the Johnson–Williams probe can be estimated with 15% accuracy under certain conditions of use ($T \geq -15°C$, LWC < 1.5 g m^{-3}, $d < 30$ μm, $V \sim 100$ m s^{1}), if the calibrations have been done with care.

It is also apparent that the "dummy head" calibration method, used until now, is inadequate. The accuracy could be improved by the use of a real calibration technique involving a micro-wind tunnel producing calibrated and reproducible values of the liquid water content at a speed of up to 100 m s^{-1}.

c. *ASSP*

The measurements obtained at an airspeed of 51 m s^{-1} imply that the use of a statistical correction method will bring the accuracy of the measurement of the liquid water content up to about 30% error. This value is compatible with the results of Baumgardner (1983). This estimate assumes that the calibration of the probe is satisfactory and that the optics of the device (laser, lenses, photodetectors) are perfectly aligned.

The measurements at an airspeed of 103 m s^{-1} and for a droplet concentration greater than about 200 cm^{-3} are unusable because the mean time interval between particles was comparable or even smaller than the time delay required by the electronic circuity to process the data. The time delay can be considerably reduced by modifying the electronics so that the signal is processed faster (factor 3), or the optics can be modified so that the sampling area is reduced.

In conclusion, the paper shows that tests of probes conducted in a calibrated wind tunnel are very useful to get microphysical measurements as accurate as possible, and should encourage others to perform similar calibrations.

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APPENDIX

List of Laboratories That Participated in the NRC Wind Tunnel Experiment in 1980

National Research Council (NRC)	Canada
Atmospheric Environment Service (AES)	Canada
National Center for Atmospheric Research (NCAR)	United States
University of Wyoming (U. WY.)	United States
University of Washington (U. WASH.)	United States
University of North Dakota (UND)	United States
South Dakota School of Mines & Technology (SDSMT)	United States
Colorado International Corporation (CIC)	United States
British Meteorological Office (BMO)	United Kingdom
Royal Aeronautical Establishment (RAE)	United Kingdom
Laboratoire Associé de Météorologie Physique (LAMP)	France

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