Calibrations of Johnson-Williams Liquid Water Content Meters in a High-Speed Icing Tunnel[1]

J. WALTER STRAPP AND ROBERT S. SCHEMENAUER

Atmospheric Environment Service, Downsview, Ontario, Canada, M3H 5T4

27 March 1981 and 2 September 1981

ABSTRACT

Wind tunnel tests have provided calibrations and intercomparisons of 14 Johnson-Williams (J-W) cloud liquid water content (LWC) measuring devices with 23 sensor heads from 10 research organizations. The absolute tunnel LWC was deduced using a rotating icing cylinder technique accurate to ~5%.

A significant fraction of the systems arrived at the tunnel with nonfunctional shell or strut heaters, which can degrade measurements below 0°C. Several sensor heads exhibited airspeed dependencies. Switching heads sometimes produced calibration changes. At −15°C an instrument problem was discovered associated with icing of the compensating wire posts, which resulted in mild to severe measurement errors in 75% of the sensor heads at 103 m s^{-1}.

Calibrations at −5°C revealed that J-W measurements usually varied linearly with tunnel LWC, but sometimes with a slope differing from unity, implying that the system dummy head did not always define the correct conversion from J-W output voltage to grams per cubic meter. No more than six of the 13 systems tested at −5°C agreed to within 20% of the tunnel LWC with each of their sensor heads, but at least 10 of 13 did so with one sensor head. At −15°C similar results were obtained, but most systems suffered from the aforementioned icing problem, resulting in unreliable small-scale measurements.

1. Introduction

The determination of cloud liquid water content (LWC) is one of the more fundamental measurements made by cloud physics aircraft. A variety of instruments have been devised to measure cloud LWC but since the mid 1950's a heated wire probe originally manufactured by Johnson-Williams Ltd., Palo Alto, California, has been by far the most widely used. This probe (J-W LWC meter) is presently produced by Cloud Technology of Palo Alto, California.

Despite the fact that hundreds of J-W LWC meters have been produced, there is an almost complete absence of good calibrations of the probe in the literature. Owens (1957)[2] placed a J-W LWC meter plus a paper-tape and a chemical reagent LWC meter into a wet wind tunnel at the University of Chicago. Unfortunately, due to the highly variable droplet spray characteristics, the J-W LWC meter was in fact used to calibrate the tunnel and the other two instruments. Some important observations of the operating characteristics of the J-W LWC meter were made, as well as a confirmation of its potential value in cloud physics, but no absolute calibration of the probe was possible. A decade later (Spyers-Duran, 1968; Knollenberg, 1972) the basic "calibration" of J-W LWC meters and other LWC measuring instruments was still carried out by intercomparing one with another. In the subsequent decade several instruments (Merceret and Schricker, 1975; King *et al.* 1978) were proposed as alternatives to the J-W LWC meter. These new instruments would operate at a constant temperature rather than a constant current. Despite the considerable promise shown by the new instruments, particularly the one described by King *et al.* which does not require a wet tunnel calibration, neither has advanced beyond the prototype stage and neither is likely to completely replace the J-W LWC meter in the immediate future.

In October and November of 1980, the Cloud Physics Research Division of the Atmospheric Environment Service (AES) organized a 3-week test and calibration of J-W LWC meters in an icing tunnel operated by the Low Temperature Laboratory of the National Research Council (NRC) of Canada. The reasons for the tests were numerous: the absence of good wet wind tunnel calibrations in the literature; the need for compatible aircraft measurements in the 1981 CCOPE experiment; a requirement to assess the comparability of past aircraft measurements; access to, and previous experience with, a very well calibrated and documented wet wind tunnel. A variety of different LWC measuring instruments were evaluated and calibrated: J-W, CSIRO, Ruskin and PMS ASSP (see Table 2 for definitions). Only the results from the J-W probes will be presented in this note. It is anticipated that a discussion of the other probes will appear in a subsequent report.

[1] The Atmospheric Environment Service does not approve, recommend or endorse any proprietary product mentioned in this publication. No reference shall be made to the AES or this publication in any advertising or sales promotion which would indicate or imply that the AES approves or does not approve, recommends, or endorses any proprietary product mentioned herein.

[2] Owens, G. V., 1957: Wind tunnel calibrations of three instruments designed for measurements of the liquid water content of clouds. Tech. Note 10, Cloud Physics Laboratory, University of Chicago, 15 pp. Library of Congress PB-134558.

0021-8952/82/010098-11$06.75

The following organizations had probes in Ottawa during the icing tunnel tests:

Atmospheric Environment Service	Canada
British Meteorological Office	Great Britain
Royal Aeronautical Establishment	Great Britain
Université de Clermont II	France
National Center for Atmospheric Research	United States
University of Wyoming	United States
South Dakota School of Mines and Technology	United States
Colorado International Corporation	United States
Colorado River Municipal Water District	United States

In the discussion in this note, individual probes will not be identified by organization. Specific details of the calibrations of any probe should be obtained from the research groups at each organization listed above.

2. Tunnel characteristics and operating procedure

The principles of operation of the J-W LWC meter have been described by other authors (e.g., Merceret and Schricker, 1975) and will not be repeated here. The J-W LWC meter can be tailored somewhat to meet the operating conditions on a user's aircraft but most operate over two LWC ranges between 0 and 6 g m^{-3} and at air speeds from 50 to 150 m s^{-1}. Earlier work (Spyers-Duran, 1968) indicates that the collection efficiency of the sensor wire decreases for droplets ≥30 μm diameter and that therefore the instrument response is optimal in clouds containing only small droplets. The above points outline the basic tunnel conditions that should be available in order to properly calibrate a J-W LWC meter.

The high-speed icing tunnel used in these tests has been operated since the early 1960's by the Low Temperature Laboratory, Division of Mechanical Engineering, of the National Research Council of Canada in Ottawa. The closed circuit tunnel is powered by a 600 hp DC motor originally capable of producing Mach 0.9 in the 30 cm × 30 cm × 45 cm long measuring section. With the present upstream section, the maximum speed is ~150 m s^{-1}. The refrigeration system and heat exchanger can provide operating temperatures as low as −40°C with an accuracy of ±0.5°C. The tunnel is completely sealed and capable of being operated at static pressures covering the range from sea level to 300 mb. However, for the tests reported on here the tunnel was always operated at ambient pressure due to time restrictions. It should be noted that some of the probe icing problems discussed below would be less severe at lower pressures. Effects seen at −15°C and ~1000 mb would be closer to wintertime conditions and would be more serious than those encountered at ~500 mb in summer cumuli.

TABLE 1. Droplet spectrum concentration, mean volume diameter (MVD), mode, liquid water content (LWC), and LWC ≥ 30 μm recorded by a PMS ASSP at a tunnel airspeed of 78 m s^{-1}.

Tunnel LWC (g m^{-3})	PMS ASSP Droplet spectrum data (3–45 μm) 78 m s^{-1}: Concentration (cm^{-3})	MVD (μm)	Mode (μm)	LWC (g m^{-3})	LWC ≥ 30 μm (%)
0.2	300	10	6	0.2	4
1.0	600	14	9	0.9	11
1.9	600	17	12	1.4	12

The spray nozzles used in the tunnel produce LWC's in the measuring section from 0 to 2 g m^{-3} at 100 m s^{-1} and 0 to 4 g m^{-3} at 50 m s^{-1}. The median volume diameter of the droplets is variable from ~10 to ~30 μm. Table 1 contains droplet spectra data for tunnel runs at 78 m s^{-1} from a PMS ASSP probe which was tested under identical conditions to the J-W probes. This particular probe suffered from a sampling problem (coincidence errors) which resulted in uncertainties of ~25% in the ASSP concentration and LWC. Only a small percentage of the droplet LWC is distributed at sizes ≥30 μm where the J-W sensor wire collection efficiency decreases. Note that the values in Table 1 are not unlike data collected in continental clouds.

Of paramount importance for these tests was an accurate measurement of the tunnel LWC. The primary method of calibrating the tunnel LWC for twenty years has been the single rotating cylinder. The weight of ice accreted onto the cylinder in a fixed period of time determines the tunnel LWC very accurately. Stallabrass (1978)[3] has critically assessed the uncertainties in this technique. He looked at the errors introduced in the calculation of LWC due to: cylinder growth; ice density; specification of the droplet median volume diameter; use of a median volume diameter instead of a droplet distribution; droplet trajectory data; surface roughness of the ice; and splashing of droplets. He found the individual errors to be relatively small with some cancellation between various sources of error. Stallabrass also compared measured LWC's using the rotating cylinder to measurements using the iced blade (another historical technique) and found differences of only 1–2% at speeds of 75–125 m s^{-1} and temperatures of −5 and −20°C.

The estimated error in the measurement of tunnel LWC is ~ ± 5% over the range of temperatures and

[3] Stallabrass, J. R., 1978: An appraisal of the single rotating cylinder method of liquid water content measurement. National Research Council Can. Rep. LTR-LT-92, November 1978, 26 pp. [Available from Low Temperature Laboratory, Division of Mech. Eng., NRC Canada, Ottawa K1A 0R6.]

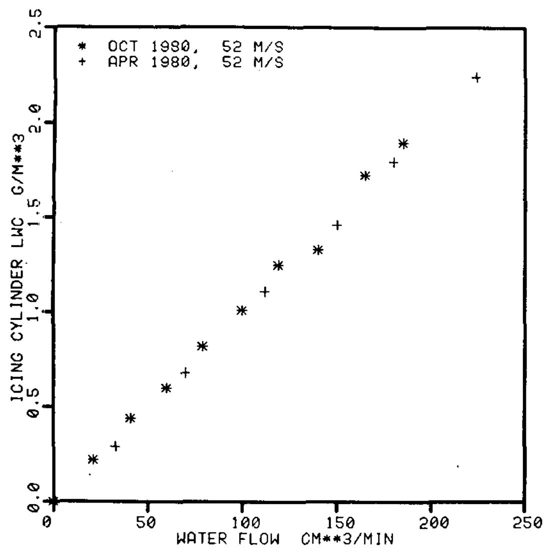


FIG. 1. Comparison of tunnel calibrations for April and October 1980 tests using rotating icing cylinder measurements, illustrating the LWC reproducibility in the tunnel.

air speeds used in the present test. Individual measurements are very repeatable. This is illustrated by comparing the icing cylinder measurements at 52 m s^{-1} from April 1980 tests to those of October 1980 tests. Fig. 1 contains the icing cylinder derived LWC plotted as a function of the water flow at the spray bars for April and October 1980 tests. Note that very little change was observed in the tunnel calibration in this 6-month period. The October calibration seems to be ~3% higher than the April calibration, possibly due to the change of ~1 cm in the location of the cylinder in the tunnel. This was necessary because new mounting plates were made for the October tests, displacing the J-W sensor head position in the tunnel somewhat from its April position. These results strongly indicate that the reproducibility of LWC levels in the tunnel under careful operation is very high, and that uncertainties in LWC due to setting up the tunnel runs are small compared to the 5% error quoted for determining the LWC from the rotating cylinder measurements.

In a typical set of runs, the tunnel was operated at a fixed temperature (+5, −5 or −15°C) and a fixed airspeed (52, 77 or 103 m s^{-1}). The J-W was then exposed to a series of up to 10 spray intensities corresponding to a LWC range of 0.2–2 g m^{-3}. Most probes were tested like this at two temperatures and two airspeeds. Each spray condition was maintained for 30–60 s at a nearly constant LWC. The spray was turned off to determine the J-W zero value before proceeding to the next spray condition. Fig. 2 contains a chart record example of two of a series of nine LWC conditions, as an illustration of how the experiment proceeded. Note that the LWC levels were very constant once the operator had stabilized the flow meter, with a standard deviation of the 0.5 s interval averages of only ~3% of the mean value. Two probes could be positioned in the tunnel at any one time. One probe was mounted vertically from the top of the tunnel, the other was mounted horizontally from the side. The center of each probe sensor head was 1.5 cm from the center of the tunnel. Tunnel mapping with one of the probes provided information on the distribution of LWC across the tunnel cross section, revealing a very uniform LWC near the center of the tunnel. Each experiment with two J-W systems provided both a comparison of LWC's from the two probes with the tunnel LWC, as well as an intercomparison between the two probes under identical conditions. In some tests, a J-W was operated with another instrument, or in a special experiment (e.g., pitch and yaw or droplet mean volume diameter variations; heater power variability). The results of these tests will be summarized in a subsequent report.

All sensor heads were tightened very firmly by hand or with a tool before testing. Some investigators have found that improper tightening of the sensor head can lead to measurement errors, and are accordingly modifying their systems to improve the sensor-head ground.

Data were recorded in digital form onto 9-track magnetic tape at a frequency of 2 Hz with a resolution of 2 mV. In special experiments, the data acquisition frequency was increased to 20 Hz (20 mV resolution). A multichannel chart record provided a real-time plot of the J-W output voltages. The data were later analyzed with a minicomputer to provide the desired derived quantities. Dummy head full-scale and zero voltages were also recorded before the tests, and were used to define the gain factor employed in the voltage to grams per cubic meter con-

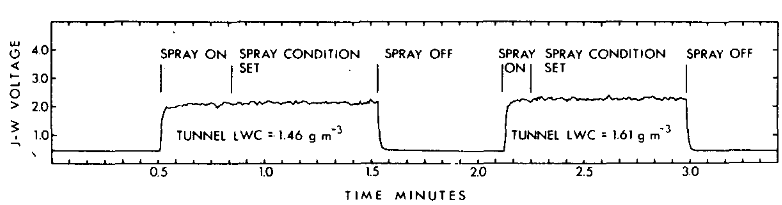


FIG. 2. Voltage record of a J-W probe for two of a sequence of nine LWC conditions tested at 104 m s^{-1}, −5°C.

version. The J-W was operated with a positive zero offset, so that zero drift could be monitored. Dummy head tests were also performed with this typical offset voltage. The chief parameter compared to the tunnel LWC was the 30 s average computed J-W LWC, compatible with the 30 s exposure time of the rotating cylinder. The 30 s averages were computed only for the time after the operator had reached a stable spray condition.

Some systems and sensor heads were not tested at all of the three airspeeds and three temperatures. Consequently, the data presented in the following sections are usually from a subset of the total number of control units and sensor heads.

TABLE 2. Overview of probes calibrated in the icing tunnel facility, October–November 1980.

Status \ Probe type	Johnson-Williams Control units	Johnson-Williams Sensor heads	CSIRO†	PMS ASSP‡	Ruskin[a]
Units brought to tunnel*	14	24	2	2	1
Units operational**	13	17[b]	≥1	1	1

* Total number of units taken to Ottawa and assumed operational.
** Units which did not have an obvious failure before or during testing.
† Described by King *et al.* (1978).
‡ Described by Pinnick and Auvermann (1979).
[a] Described by Ruskin (1967).
[b] Sensor heads which were mechanically functional (i.e., provided reasonable output and whose shell and strut heaters functioned). One sensor head did not provide acceptable output. Of the remaining 23 brought to the tunnel, 6 had a non-functional heater. Other sensor head problems (e.g. compensating wire post icing) are discussed in the text.

3. Probe calibrations

a. Sensor head problems

Table 2 shows that 24 of the 29 probes calibrated in the tunnel were J-W sensor heads. These sensor heads were used with 14 different J-W control units. The total number of combinations tested, at least in part, was 31. For the purposes of displaying and discussing the data, all control units will be identified by a letter from A to N, and all sensor heads by a number from 1 to 24. This allows a particular combination (e.g., D-4) to be discussed while preserving the anonymity of the organization that owns the probe.

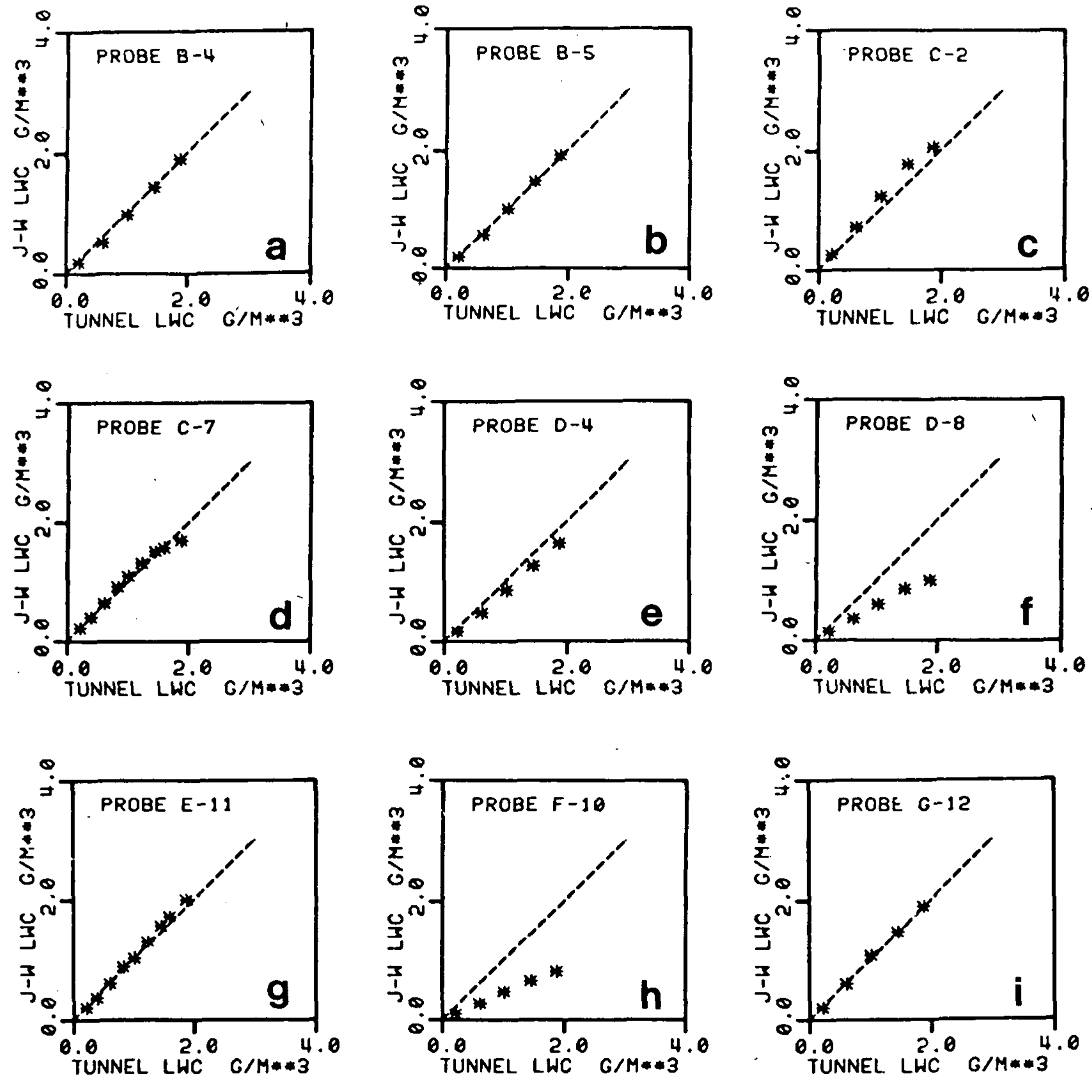
Of the 24 J-W sensor heads examined, 17 were free of obvious mechanical failures (e.g., heater failures). After calibrations at −15°C, it became evident that another common problem was a buildup of ice on the compensating wire posts, resulting in erroneous and erratic readings. Six of the 10 sensor heads tested at −15°C, 77 m s^{-1} exhibited definite signal deterioration due to this icing. At −15°C, 103 m s^{-1} this phenomenon was observed in 10 of the 14 probes tested. The sensor heads, which could not be tested below 0°C due to failed shell heaters, undoubtedly would have encountered the same problem without heater repair. Therefore, after only a cursory examination in the tunnel, it was evident that two-thirds or more of the sensor heads were not fully reliable over the range of conditions that could be experienced by a typical cloud physics aircraft.

The buildup of ice on the compensating wire post was observed and photographed after runs at −15°C. The indication of this problem in the instrument output was a large change in the zero offset when the spray was turned off. The zero remained low for a varying length of time, and then abruptly regained its original value, presumably as it shed collected ice. This icing phenomenon was never observed at −5°C under the range of exposure times (<1 min) and airspeeds (<103 m s^{-1}) tested, but could conceivably be a problem at temperatures warmer than −15°C if exposure times were longer or airspeeds were higher.

b. Liquid water measurements

In order to provide an indication of the quality of the J-W measurements collected by different cloud physics aircraft, the data from tunnel tests at an airspeed closest to the operating airspeed of each aircraft were examined at −5 and −15°C. These data are summarized graphically in Figs. 3a–3s (−5°C) and Figs. 4a–4o (−15°C). Most probes produced nearly linear measurements relative to the tunnel values at −5°C. Probes N-16 (Fig. 3s) and I-13 (Fig. 3l) display obvious signs of an upper "saturation" value, below which comparisons were linear. Some probes tend to indicate a slight nonlinearity. For example, the comparisons of probe M-3 (Figs. 3r and 4n) imply that its measurements > 2 g m^{-3} become increasingly unreliable. When relationships were linear, they do not necessarily have a slope near unity (e.g., F-10, Figs. 3h and 4f); in fact, most probes did show some displacement from tunnel values. The J-W output voltage was designed to be directly proportional to droplet LWC. The tunnel results at −5°C confirm this behavior in most probes. However, the difference in absolute value of the J-W and tunnel LWC imply that the dummy head does not necessarily define the proper gain factor relating output voltage to LWC.

At −15°C, many of the probes display a nonlinearity with the tunnel values, associated with the previously mentioned icing of the compensating wire post. In some cases (e.g., G-12, Figs. 3i and 4g) the icing influence seems to be so slight that the 30 s average J-W LWC seems to be unaffected and the only indication of icing is the dipping of the voltage on the chart record. In other cases (e.g., M-18, Fig. 4o) the influence of the ice buildup is severe and the 30 s average J-W measurement is erroneously



FIGS. 3.(a–s). J-W LWC measurements at −5°C as a function of calibrated tunnel LWC's at a representative airspeed for each aircraft. Values plotted are 30 s averages. Probe names are coded to preserve anonymity.

low. The tunnel tests at −15°C should not be used as calibrations, since this icing effect is not necessarily repeatable in quantitative terms. Furthermore, these results are for 30 s averages only, and cannot be transferred to other time intervals. Figs. 4a–4o, however, do illustrate the nature and degree of this problem.

A quantitative summary of the data from the J-W probes tested is given in Table 3. These data apply to tests performed at airspeeds appropriate to the particular aircraft on which the probe is commonly operated, and include more than one sensor head per control unit if data was available. The results are given at three LWC values, spanning the range tested, at both −5 and −15°C. The data at −5°C reveal that the probes compared more favorably with tunnel values at higher LWC. Approximately ½ and ¾ of the measurements at −5°C are within 20% of the tunnel values at 0.2 and 1.9 g m^{-3}, respectively. Surprisingly, at −15°C similar results were obtained, even though ice buildup on the compensating wire post is encountered. This is partially due to the fact that some probes which iced at −15°C measured high relative to the tunnel in non-iced conditions, and the icing depressed measurements to values closer to the tunnel values. The average correlation of J-W and tunnel LWC measurements, however, illustrates the icing problem, dropping from 0.993 at −5°C to 0.976 at −15°C. Thus, the results of Table 3 at −15°C are somewhat misleading. Although most 30 s average J-W values are evidently not largely affected at −15°C, the high-frequency signal deteriorates, resulting in unreliable small-scale J-W measurements.

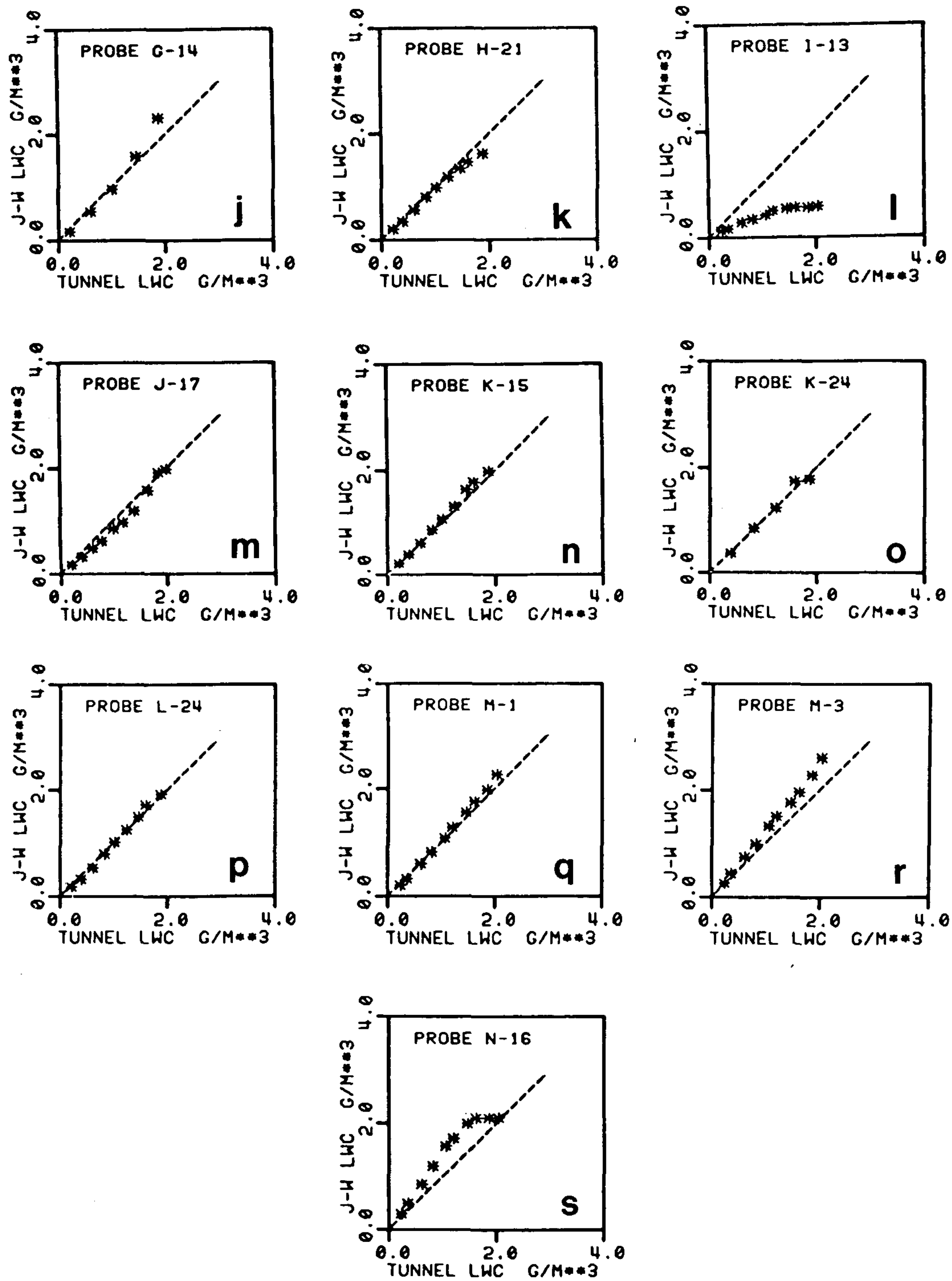
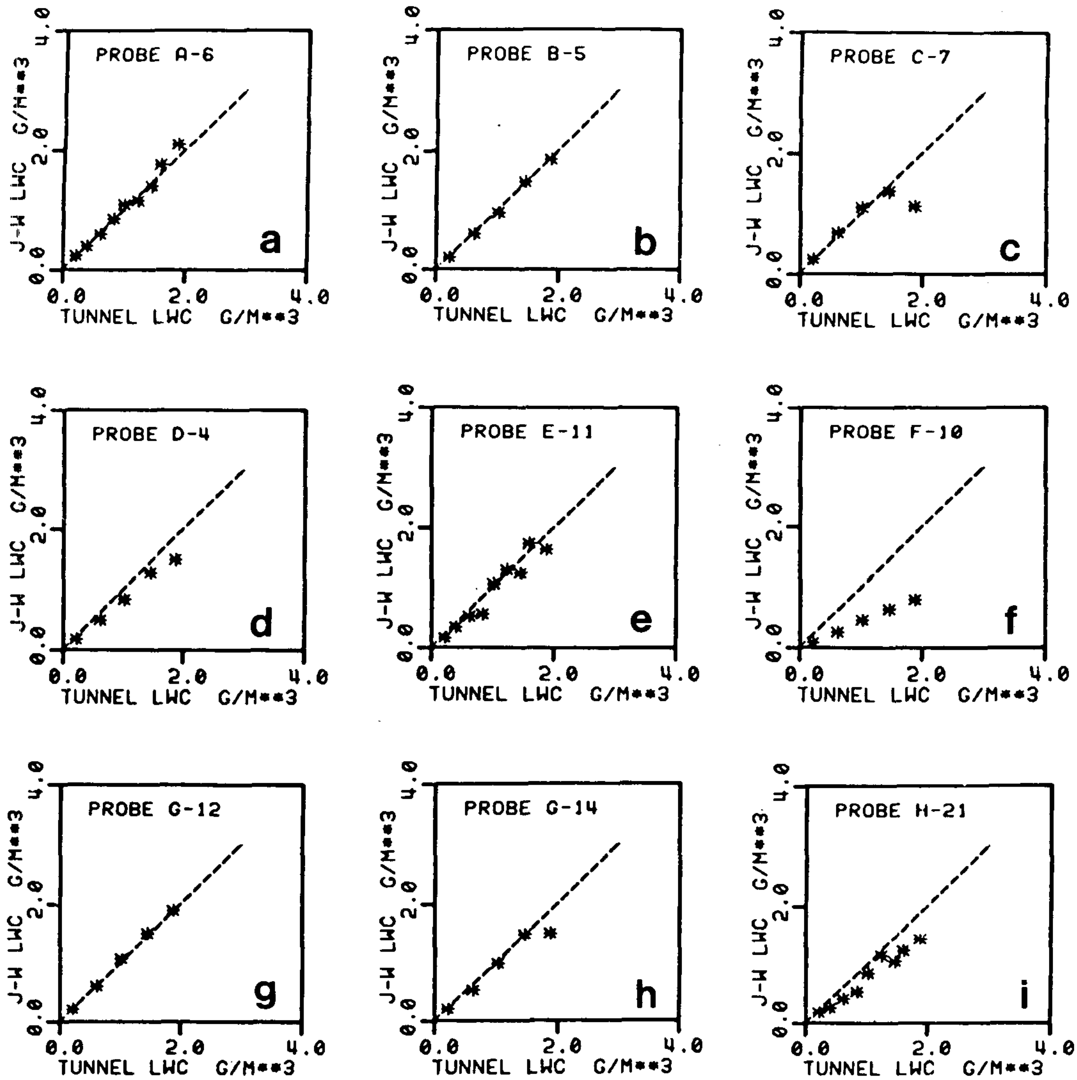


FIG. 3. (*Continued*)

c. Airspeed dependence

Airspeed dependence did not appear to be a major problem in most of the probes examined. Although tests were not performed on all probes, 22 control unit/sensor head combinations were calibrated at +5 or −5°C at two airspeeds differing by 26 or 52 m s^{-1}. Four of these 22 combinations displayed measurement differences with airspeed changes of >20% in the 0.2–2.0 g m^{-3} range. Fig. 5 displays measurements from a probe which exhibited such an airspeed dependence.



FIGS. 4.(a–o). J-W LWC measurements at −15°C as a function of calibrated tunnel LWC's at a representative airspeed for each aircraft. Values plotted are 30 s averages. Probe names are coded to preserve anonymity.

Changes in airspeed also were important in some cases in determining the advent of the ice buildup on the compensating wire post. The proportion of probes which encountered this problem at −15°C rose from ~10% at 52 m s^{-1} to ~60% at 77 m s^{-1} and ~75% at 103 m s^{-1} in the 0.2–2.0 g m^{-3} LWC range.

d. System dependence on change of sensor head

Most investigators, in the absence of a tunnel calibration, must assume that the J-W calibration is unchanged when interchanging sensor heads. The majority of the tunnel measurements support this claim, but some large differences were found between different heads used with a common control unit. Of the 14 systems which were tested in the tunnel at +5°C or −5°C, nine were tested with more than one sensor head. Three of these systems displayed a difference of >20% between measurements made with different heads. Fig. 6 contains measurements from one of these three systems.

Not all sensor heads encountered icing of the compensating wire post at −15°C, and an additional sensor head dependence relates to this icing problem (Section 3a).

e. Temperature dependence

Most probes were tested at more than one temperature. The data at the aircraft representative airspeed reveal that a 10°C temperature drop from +5 to −5°C did not result in J-W measurement changes of >20% in the 0.2–2 g m^{-3} range in any

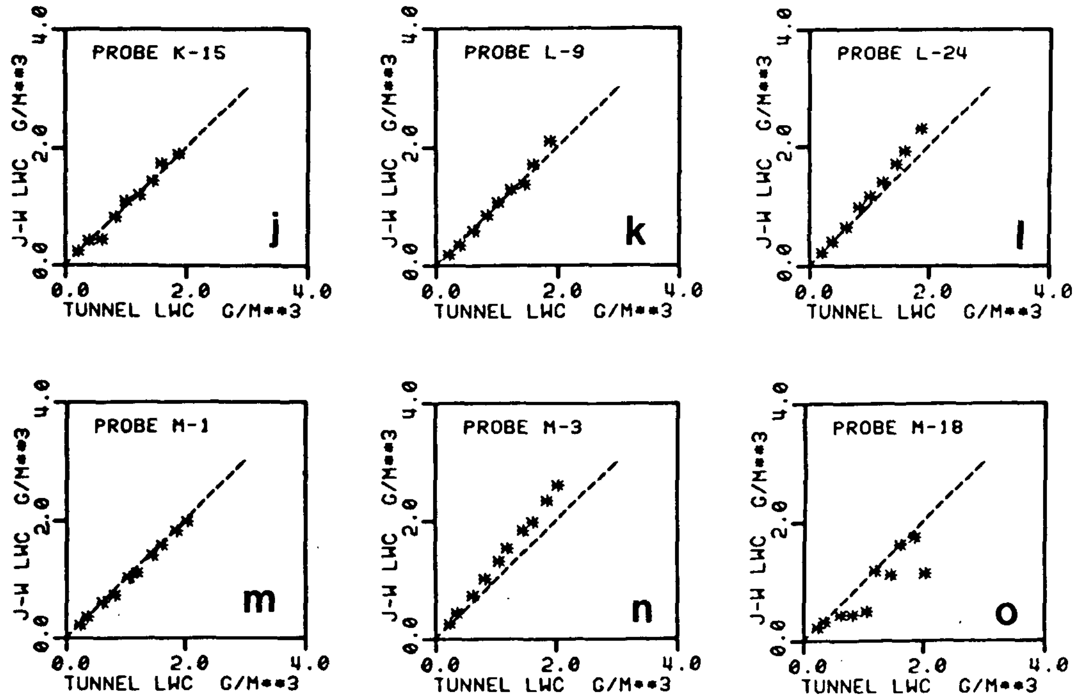


FIG. 4. (*Continued*)

of the 11 control unit/sensor combinations tested. Thus no large temperature dependence was found in the +5 to −5°C range. However, temperature strongly influenced the onset of ice buildup on the compensating wire post. No sensor heads exhibited this effect at −5°C, whereas >75% of the sensor heads showed at least some effect at −15°C (103 m s^{-1}).

4. Intercomparisons

The geometry of the tunnel sampling section permitted two J-W probes to be mounted simultaneously during the tests, and an effort was made to include two probes as often as possible. Consequently, a large data set of J-W intercomparisons was collected. Most intercomparisons were performed at more than one temperature and airspeed. These data give important detailed information of the relative agreement of probes in the 0.2–2 g m^{-3} LWC range. As an example of the comparisons, a summary of the intercomparison data at three airspeeds at −5°C is given in Table 4. Based on these data it would seem that the probability that two aircraft represented at the tunnel tests would not agree within 20% in J-W measurement under identical conditions is unacceptably large. A significant proportion of intercomparisons did not even agree to within ±50%.

TABLE 3. Overview of the J-W absolute LWC calibrations. Percentages of probes tested at −5° and −15°C at their representative airspeeds which agreed with tunnel LWC values of ~0.2, ~1.0, and ~1.9 g m^{-3} to within ±20%. At −5°C, data from 13 J-W control units and 18 sensor heads are shown. At −15°C, data from 11 control units and 15 sensor heads are shown. The average correlation coefficient of the J-W/tunnel comparisons also is shown. Data from obviously non-functional sensor heads are not included.

Liquid water content (g m^{-3})	% of probes measuring accurate LWC values	
	−5°C	−15°C
0.2	50%	73%
1.0	67	80
1.9	72	67
r	0.993	0.976

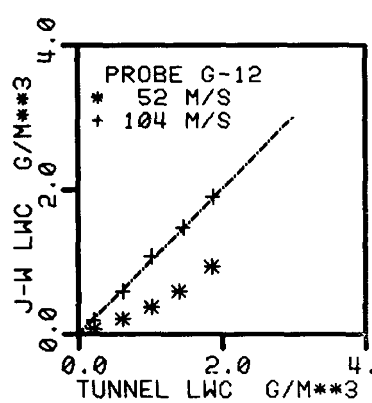


FIG. 5. Example of a J-W probe which exhibited an airspeed dependence.

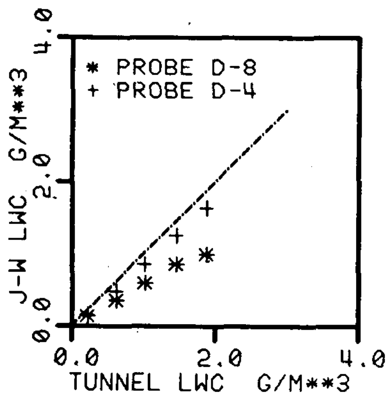


FIG. 6. Example of a J-W probe which exhibited measurement changes with a change in sensor head (−5°C).

Intercomparisons were also accomplished between the J-W and PMS ASSP, and the J-W and CSIRO "King" devices. These data will not be reported here.

5. System evaluations

Table 5 contains an itemized evaluation of each J-W aircraft system brought to the tunnel for calibration. Column 2 indicates that six of the 14 systems had at least one sensor head with a non-functional shell or strut heater on arrival, presumably unknown to its owner. This defect can cause erroneous data at below-freezing and above-freezing temperatures, as observed during these tests. Three systems displayed a large difference in measurement when changing sensor heads (column 3). Three more had at least one probe with a strong airspeed dependence (column 4). Based on these problems alone, nine of the 14 systems potentially could provide improper measurements if the most unfortunate set of sensor heads were used. Column 5 indicates that of the 12 systems tested at −15°C, 11 exhibited some signal deterioration with at least one sensor head at this temperature due to ice buildup on the compensating wire post. Therefore, at −15°C, almost all of the systems could be expected to have measurement errors with at least one sensor head. Applying the results of these tunnel tests, each system can now be used with the sensor head which provides the least errors, and thus the likelihood of poor measurements due to sensor head defects will significantly decrease.

Columns 6–9 contain a system evaluation of the measurement of LWC at −5°C and −15°C. At least 10 of the 13 systems tested at −5°C possessed at least 1 sensor head which measured LWC within 20% of the tunnel calibrations in the 0.2–2.0 g m^{-3} LWC range. However, no more than five and as few as four of the 13 systems did so with all their sensor heads. At −15°C, the results were poorer. For discussion here, a calibration at −15°C was considered "acceptable" if measurements were within 20% of tunnel values, and no signal deterioration was observed associated with compensating wire post icing.

TABLE 4. Summary of intercomparison data of J-W probes mounted simultaneously in the tunnel, for runs at 52, 78 or 104 m s^{-1}, and −5°C. Values shown are percentage of functional probes which agreed with each other to within ±20 and ±50% in 25 intercomparisons at each LWC.

Tunnel LWC (g m^{-3})	% of intercomparisons which agreed to within:	
	±20%	±50%
0.2	56%	88%
1.0	64	84
1.9	52	84

TABLE 5. Evaluations of the 14 J-W systems calibrated in the icing tunnel, October–November 1980.

	System faults					System measurement evaluation			
						−5°C		−15°C	
System	1	2	3	4	5	6	7	8	9
A		X	N/A		X	?	?		
B	X			X	X	*	?	*	
C	X				X	*		?	
D	X		X		X	*		?	
E		X	N/A		X	*	*		
F	X				X	?		?	
G	X	X	X	X	X	*			
H	X	X			X	*			
I	X		X		?			?	?
J			N/A		X	*	*		
K	X				X	*	*		
L	X					*	*	*	*
M	X	X			X	*			
N		X		X	?			?	?

* or X: Satisfied conditions below.
?: Insufficient tests to determine.
N/A: Not applicable.
1: More than 1 sensor head tested.
2: System with at least 1 sensor head with a non-functional shell or strut heater on arrival.
3: System with a sensor head dependence (>20% measured J-W difference at representative airspeed, +5 or −5°C, with a change in sensor head).
4: System with at least 1 sensor head with an airspeed dependence (>20% measured J-W difference at −5 or +5°C with a 26 or 52 m s^{-1} airspeed change).
5: System with at least 1 sensor head with compensating wire post icing at −15°C.
6: At −5°C, system providing J-W measurements with at least one sensor head at representative airspeed within 20% of tunnel LWC's.
7: As 6, but with all system sensor heads.
8: At −15°C, system providing J-W measurements with at least one sensor head at representative airspeed within 20% of tunnel LWC's.
9: As in 8 except with all system sensor heads.

At most seven and as few as two of the 14 systems have "acceptable" calibrations at −15°C with their best sensor head. At most three, and as few as one provide "acceptable" calibrations at −15°C with all their sensor heads. Combining the results at −5 and −15°C, *only one* of the 14 systems produces "acceptable" calibrations with each of its sensor heads at both −5 and −15°C. Even with the benefit of these tunnel tests to guide in choosing a system's best sensor head, at most five and as few as two of the 14 systems could satisfy an "acceptable" calibration at these temperatures.

6. Discussion

Wind-tunnel tests have determined individual calibrations in the 0.2–2 g m^{-3} range of 14 J-W liquid water measuring devices with 23 sensor heads at a variety of airspeeds and temperatures. As a consequence of these studies, new instrument problems were discovered, and the state of some J-W measuring systems was found to be quite poor. Six of 14 systems possessed a sensor head with a non-functional shell or strut heater, which can lead to erroneous measurements even above 0°C. This problem can be recognized without a wind-tunnel calibration, and regular inspection of sensor heads is advisable by each group. Sensor heads also were found to not necessarily be interchangeable, resulting in measurement differences >20% in several cases. Similarly, several sensor heads were found to have an airspeed dependence leading to >20% differences in measurements with airspeed changes of 26 and 52 m s^{-1}. Probably the most common problem was a buildup of ice on the compensating wire post at runs at −15°C and >77 m s^{-1}, resulting in a sometimes severe disruption of the expected signal. A symptom which was sometimes observed with this phenomenon was a large negative shift in the zero offset noticeable when the spray was turned off, which abruptly regained its original value after some time in dry air. Eleven of the 15 sensor heads tested at −15° and 103 m s^{-1} exhibited this problem. These sensor-head dependencies can be determined under controlled aircraft experiments, but are more easily and thoroughly examined in a facility like the NRC wind tunnel.

Reference LWC values were based on tunnel calibrations obtained using a rotating cylinder measurement accurate to ~5%. Since over 900 runs were performed in a 3-week period, the error in an individual measurement due to operator settings may have occasionally exceeded this value. Results of all the J-W sensor head calibrations at −5°C revealed that ≤75% of the probes agreed with the tunnel calibration to within 20% (see Table 3). Approximately 83% (10 out of 12) of the systems tested at −5°C possessed at least one sensor head which calibrated to within 20% of the tunnel. Although calibrations of 30 s average LWC values were not much different overall at −15 than −5°C, the higher frequency measurements were found to be affected in most sensor heads due to the previously mentioned icing problem, and some sensor heads exhibited severe underreading.

Often, when calibrations differed from tunnel measurements, they did so linearly, implying that the dummy head did not define the proper gain for converting output voltage to LWC. In these cases the tunnel comparisons provided a good estimate of the proper gain.

The tunnel tests have enabled J-W operators to assess the reliability of their systems, identify common problems, and calibrate their measurements under conditions close to operational. Data quality will no doubt improve, since each aircraft can now be operated with its best sensor head. For aircraft operating at cold temperatures (≤ −15°C), a solution to the compensating wire post icing problem is required. One should note that the age of the probe is not an indicator of how well it will perform. Both old and new probes can exhibit the problems discussed in this report or be free from them.

It is important to keep in mind the context in which the J-W calibrations were made in assessing the results of these tests. The scientific and technical staffs of the participating organizations were instructed to have their probes in good working order. Thus this group of probes could reasonably be expected to perform as well or better than a similar size set of J-W probes chosen at random from the very large number that have been produced over the years. All of the probes were owned and operated by research organizations actively involved in cloud physics/weather modification programs. Therefore, it was not encouraging to find that many systems suffered from problems, some maintenance-related, resulting in inaccurate LWC measurements. However, since a majority of the systems tested at −5°C possessed at least one sensor head with a good calibration, and one system was relatively problem-free in all tests with each of its sensor heads, it is evident that the J-W can be an accurate liquid water measuring device for the range of conditions tested. The J-W probe often provides "strategic" measurements for multimillion dollar weather modification experiments. These calibration results indicate that a periodic wind-tunnel calibration should become an essential part of the aircraft operations.

Acknowledgments. We would like to acknowledge the technical assistance of R. Poersch, D. Ker, R. Price and P. Hearty in the operation of these tests, and the years of careful work by J. Stallabrass and

P. Hearty in developing and calibrating the icing tunnel. We would also like to thank the Low Temperature Laboratory of the Division of Mechanical Engineering of the National Research Council of Canada, represented by Mr. E. Dudgeon and Mr. R. Ringer, for the opportunity to use their facilities.

REFERENCES

King, W. D., D. A. Parkin and R. J. Handsworth, 1978: A hot-wire liquid water device having fully calculable response characteristics. *J. Appl. Meteor.*, **17**, 1809–1813.

Knollenberg, R. G., 1972: Comparative liquid water content measurements of conventional instruments with an optical array spectrometer. *J. Appl. Meteor.*, **11**, 501–508.

Merceret, F. J., and T. L. Schricker, 1975: A new hot-wire liquid cloud water meter. *J. Appl. Meteor.*, **14**, 319–326.

Pinnick, R. G., and H. J. Auvermann, 1979: Response characteristics of Knollenberg light-scattering aerosol counters. *J. Aerosol Sci.*, **10**, 55–74.

Ruskin, R. E., 1967: Measurements of water-ice budget changes at −5°C in AgI-seeded tropical cumulus. *J. Appl. Meteor.*, **6**, 72–81.

Spyers-Duran, P. A., 1968: Comparative measurements of cloud liquid water using heated wire and cloud replicating devices. *J. Appl. Meteor.*, **7**, 674–678.