Cloud Liquid Water Measurements on the Armored T-28: Intercomparison between Johnson–Williams Cloud Water Meter and CSIRO (King) Liquid Water Probe

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ABSTRACT

Comparisons are made between liquid water concentration (LWC) readings obtained from a Johnson–Williams (J–W) cloud water meter and a King (Commonwealth Scientific and Industrial Research Organisation) liquid water probe, both mounted on the armored T-28 research aircraft during penetrations of springtime convective storms in Oklahoma and Colorado. The King probe readings are almost always higher, being up to twice those of the J–W instrument in clouds with narrower cloud droplet spectra. In clouds with broader droplet spectra, the ratio often climbs to three or greater. The King probe responds partially to drops larger than cloud droplet size, and also to some ice particles, so its reading can be higher than the cloud LWC present. However, this and earlier comparisons by others indicate that the primary reason for this discrepancy is that the J–W probe often underestimates the cloud LWC due to incomplete response to larger cloud droplets. Thus, published studies involving cloud LWC in convective storms based on readings of the T-28 J–W probe have often overestimated the effects of entrainment and precipitation scavenging on depletion of updraft liquid water, particularly in those areas characterized by clouds with broad droplet size spectra.

1. Introduction

The armored T-28 aircraft operated by the South Dakota School of Mines and Technology was instrumented with two microphysical measurement devices when it was first put into the field in 1969 as a cloud physics research platform: a foil impactor for monitoring the sizes and concentrations of precipitation-size hydrometeors (e.g., Sand and Schleusener 1974), and a Johnson–Williams (J–W) cloud water meter (e.g., Spyers-Duran 1968). Measurements derived from the T-28 J–W probe have been a primary source of in situ observations of cloud liquid water concentration (LWC) in convective environments in a variety of locations (see, e.g., Musil et al. 1973, 1976, 1986, 1991; Sand 1976; Knight et al. 1982; Heymsfield and Musil 1982; Heymsfield and Hjelmfelt 1984a; Waldvogel et al. 1987; Rasmussen and Heymsfield 1987; Kubesh et al. 1988; Musil and Smith 1989; Blackmore et al. 1989; Stith et al. 1990; Huston et al. 1991; Ramachandran et al. 1996; French et al. 1996; Bringi et al. 1997). There have been references in the literature to inadequate performance of J–W probes in general (Spyers-Duran 1968; Strapp and Schemenauer 1982; Personne et al. 1982; Baumgardner 1983; Gayet 1986), as well as the T-28 J–W probe in particular (Knight et al. 1982; Heymsfield and Hjelmfelt 1984a). The main performance deficiency for a properly operating J–W probe is underreporting of cloud LWC when the cloud droplet size distribution is broad. Here we review the performance of the J–W probe that flew on the T-28 from 1969 through 1997 and compare it to a more accurate sensor, a King liquid water probe, carried simultaneously with the J–W probe in recent flights.

2. Background

The J–W sensor belongs to the class of ‘‘hot-wire’’ liquid water probes. In this type of device, the power required to evaporate water wetting a hot sensing element is related to the rate at which water is being collected by the element. Specific details of J–W sensor operation are discussed in, for example, Spyers-Duran (1968).

The T-28 J–W system was included in a wind tunnel testing program described in Strapp and Schemenauer (1982). It was tested with three sensing heads, with two tested at multiple temperatures. Figure 1 shows the results of these tests, for tunnel airspeed in the range of typical T-28 storm penetration true airspeeds. The J–W probe readings range from 85% to 133% of the independently determined tunnel LWC. Over the droplet size range where the J–W is believed to provide accurate measurements of LWC, the T-28 J–W instrument performs in an unbiased manner. The absolute uncertainty

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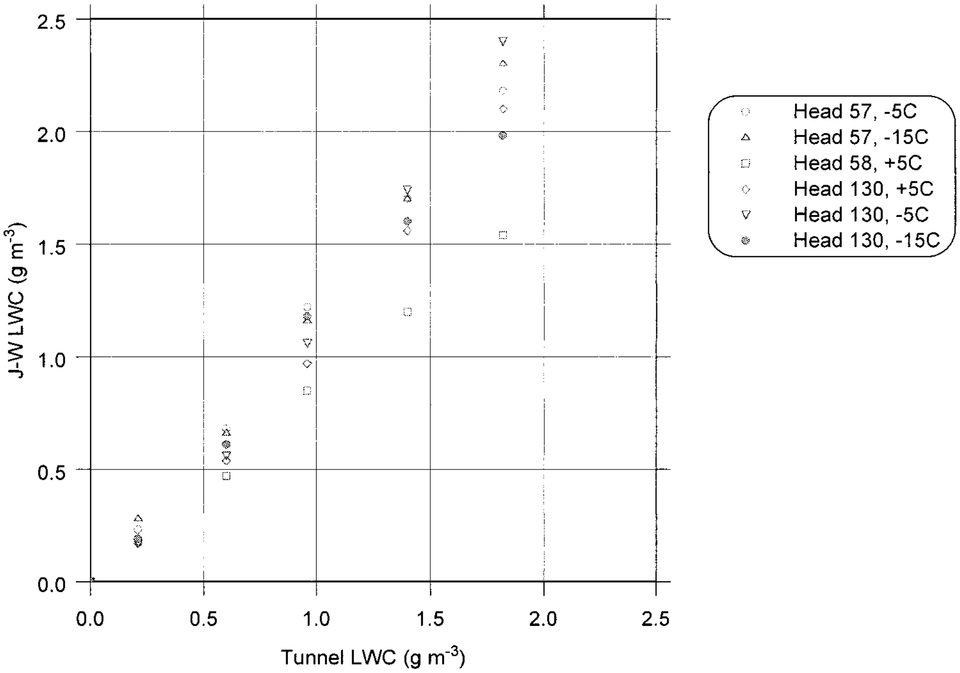

FIG. 1. Scatterplot of J–W LWC indication as a function of wind tunnel LWC for three heads from the T-28 J–W probe exposed to a range of temperatures and LWCs. Data were obtained during wind tunnel testing program described in Strapp and Schemenauer (1982).

in the system, allowing for use of any of three different heads, is roughly ±⅓ of the reading. Most T-28 storm penetrations are at true airspeeds between 90 and 100 m s^{-1}, and variation of probe response with airspeed is not a great concern in comparing measurements made on different penetrations.

This is the only time the T-28 J–W probe was tested in a well-characterized and controlled wind tunnel. To verify that there was no degradation in performance of the circuitry from year to year, the dummy head supplied with the unit was used every season to check the instrument's response to a signal of known strength. No drift with time in the response of the unit was noted. The T-28 has operated mostly in dry continental climates, so corrosion of the sensing head has not been a problem with the T-28 J–W probe.

The sensing wire has often been broken during T-28 field work, due to impacts from graupel particles or hailstones. A head is removed when damaged and a spare is substituted to make the aircraft ready for the next mission while the damaged head is repaired and made ready for a future substitution. In general, a head is left in place until it is damaged. It has not been unusual to use all three heads during one field project. Thus the uncertainty that applies to T-28 J–W probe measurements should account for varying heads, as does the accuracy figure of ± of reading.

Another method of assessing J–W probe performance is to compare its readings in updraft cores to an estimate of LWC based on adiabatic ascent of a cloud parcel from cloud base to aircraft altitude. In August 1981, near-adiabatic values of J–W LWC were reported in vigorous updrafts in large Montana storms (Musil et al. 1986). In August 1994, during passes in west Texas near cloud base where droplet size spectra ranged only over sizes small enough that complete J–W probe response could be expected, agreement within $\sim$20% was obtained. These observations are consistent with the results of the aforementioned wind tunnel tests. The data obtained during the 1995 flights discussed below were not suitable for comparison to adiabatic cloud LWC estimated from soundings.

The Commonwealth Scientific and Industrial Research Organisation or King LWC probe, another heated-element instrument, incorporates a number of desirable improvements over the J–W probe. These include a fully calculable response (the J–W probe must be calibrated empirically) and response to a broader range of cloud droplet sizes (King et al. 1978, 1981, 1985; Biter et al. 1987). However, the King probe also responds to water drops larger than the usual range of cloud droplet sizes, as well as to some ice particles. It may therefore overestimate the "cloud" LWC. The dry power consumption by the King probe needs to be calibrated as a function of true airspeed and ambient temperature for each specific mounting arrangement, then subtracted from total power consumption during in-cloud traverses to arrive at power consumption needed to evaporate water from the element. From the latter an estimate of LWC is derived. This dry power calibration over a range of conditions was done for the T-28 probe location shown in Fig. 2. The consistency of this dry power calculation over a range of temperatures and airspeeds demonstrates that the electronic gain in the signal processing circuitry was within design specifications.

Both J–W and King probes were, for the first time, flown together on the T-28 during May and June of 1995 in the second year of the Verification of the Origin of Tornadoes Experiment (VORTEX). The Research Aviation Facility at the National Center for Atmospheric Research loaned a King probe manufactured by Particle Measuring Systems, Inc., for use on the T-28 during these 1995 deployments. During six weeks of flying, the T-28 penetrated clouds with a variety of temperature, cloud water, and precipitation (liquid and frozen) conditions in central Oklahoma and in northeastern Colorado. The data from these flights provide an opportunity to compare the T-28 J–W and King LWC probe measurements in a variety of conditions.

The J–W probe on the T-28 was mounted under the right wing tip. The King probe was mounted on the flank of a pylon under the center portion of the same wing. The locations are shown in Fig. 2. Due to variations in the airflow over different portions of the wing, and the spatial separation of the probes, some differences in their readings can be expected because of actual differences in droplet concentrations sampled at the two locations. Norment (1988) analyzed the airflow-induced differences in the context of a similar mounting location on a different airframe, involving a Particle Measuring Systems, Inc. (PMS) Forward Scattering Spectrometer Probe (FSSP) rather than a King probe. He concluded that undermeasurement of LWC as great as 20%–30% may occur, and that roughly half of the airflow distortion responsible for the undercounting is due to the instrument itself. Airflow around the pylon on which the King Probe is mounted (shown in Fig. 2) may be characterized by distortions of a similar magnitude to that demonstrated for the FSSP mounting studied by Norment, leading to undermeasurement qualitatively similar to that estimated by Norment for the FSSP. It is likely that flow distortion of similar or lower magnitude occurs at the position of the J–W probe nearer the wing tip. The effect of these distortions on the ratio of LWCs will most likely be less than their effects on either reading individually.

King et al. (1981) estimate accuracy of ~5% for a properly operating King probe, while King et al. (1985) estimate 10% accuracy. Baumgardner (1983) estimates agreement between King and J–W probes should be within 30%, assuming both are responding completely to the entire spectrum of droplets present. The results presented here demonstrate that this agreement was not obtained on the T-28 when only smaller droplets were present, and that variability of J–W response with droplet size results in much greater disagreement when cloud droplet size distribution have larger medians.

3. Data

The J–W and King probe measurements from seven T-28 flights in various microphysical environments were examined in detail. A PMS FSSP, also carried on these flights, provided characteristics of the cloud droplet size distribution. During 1995, the FSSP was periodically calibrated in the field using latex beads of known sizes, and accurate estimates of its volume sampling rate were derived from measurements of the beam diameter, depth-of-field, and parameters of the signal processing circuitry (e.g., Baumgardner and Spowart 1990). Performance of the FSSP slowly deteriorated during June due to mechanical failure in the optical path. Using periodic calibrations, we did our best to compensate for changing optical characteristics of the probe. Integrated LWC based on the FSSP-measured droplet spectra ranged from about half to more than twice the King probe LWC, though the two generally agreed better than the J–W versus King values (see Table 1).

A PMS OAP 2D-P optical array probe was installed for the May 1995 Oklahoma flights. It is designed to image precipitation particles from approximately 200 μm to 6.4 mm in size. A Stratton Park Engineering Corporation (SPEC) High Volume Precipitation Spectrometer (HVPS) was installed for the June 1995 flights in northeastern Colorado. This probe images particles with approximately the same size resolution as the 2D-P, but with a much higher volume sampling rate. Data from these precipitation particle imaging probes were used to assess the presence of precipitation particles in the regions in which comparisons are made between J–W and King probe LWC.

In the sequence of flights analyzed in this paper, the de-icing heaters on the J–W probe were not functioning properly. This produced the undesirable effect of a variable baseline in the J–W measurements. The problem is more pronounced for penetrations in which the air temperature was further below 0°C. The compensating wire post and housing on the J–W probe iced to varying degrees in environments below 0°C, which caused an electrical bias in the system and/or disturbed airflow through the probe and restricted the sample volume. In general, it is possible during data analysis to adjust the J–W baseline manually. A correction is determined for each separate cloud penetration. Passes requiring large adjustments may have icing severe enough to cause additional problems, such as sample volume blockage or electronic gain changes, and therefore were not used in our analyses.

4. Results

Comparisons of J–W and King probe measurements were made for portions of the seven flights (30 cloud penetrations total). Among the 30 passes, there is about a half hour of data in which the King probe indicated more than 0.1 g m^{-3} of LWC. During these periods the

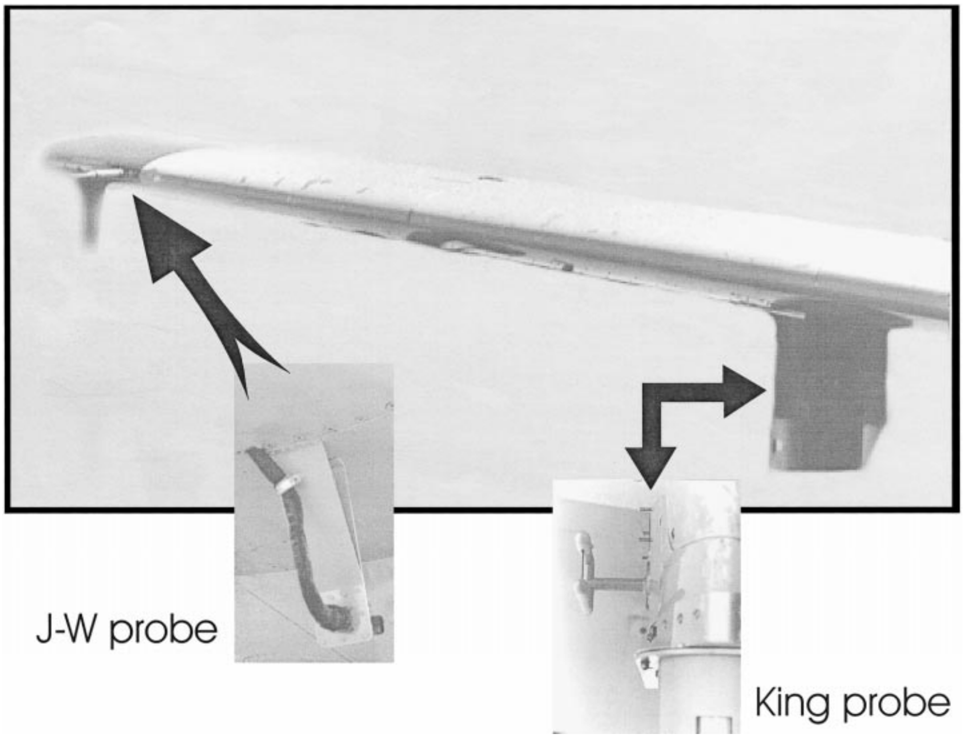

FIG. 2. The right wing of the armored T-28 is shown, with locations of the J–W probe and King probe indicated. Insets show details of the two probes. The distance between the two probes is 3.6 m.

J–W probe measured LWC less than the King probe 99% of the time. In general, the scatter of King versus J–W LWC values is linear and well-correlated. Unfortunately, the mean ratio of King to J–W LWC is not constant and ranges from 1.5 to 5.0 (see Table 1). While distributions of ratios of like quantities tend to be skewed and not symmetric about the mean for these LWC data, the medians of the LWC ratios are not significantly different than the mean ratios (the maximum difference being less than 0.2) and the distributions are reasonably symmetric for all but a few passes. Thus the mean ratio is used in Table 1 to characterize the relative responses of the probes. Other key information, such as temperature, the approximate concentration of particles larger than 200 μm, and mean LWC values from the different sensors, is summarized in Table 1.

In Fig. 3, the mean ratio of King to J–W LWC measurements for data from each cloud pass is plotted as a function of MVD (median volume diameter—the diameter of the droplet with median volume of the volume distribution derived from the FSSP). The mean ratio of King to J–W LWC appears to be positively correlated with MVD with an r^2 value of 0.55. (Note: The ratio of the peak King to peak J–W LWC measurements yielded essentially the same result.)

For MVD smaller than 15 μm, the King LWC averaged from 1.5 to 2 times the J–W LWC. This mean ratio of King to J–W LWC increased to 2.5 to 5.0 as MVD increased to 26–28 μm. This result is consistent with that of Personne et al. (1982), who also found the response of the J–W probe to decrease significantly for droplet sizes beyond 15 μm (see their Fig. 7). Strapp and Schemenauer (1982) found good agreement between most J–W probe readings and independently determined wind tunnel LWC when their tunnel MVD was less than 15 μm.

Our results are inconsistent with those reported by Personne et al. (1982), Strapp and Schemenauer (1982), and King et al. (1985) in that the results of those studies would lead one to expect a mean King LWC versus J–W LWC ratio very close to one for MVD < 15 μm. Our larger ratios for MVD < 15 μm might be explained by 1) the fact that in some passes, partial King probe response to particles is larger than the cloud droplet size range; 2) errors in FSSP size calibration in our study; and 3) unresolved absolute errors in LWC and MVD in previous or present studies. Despite this disagreement in the MVD < 15 μm size range, all prior studies and the present study are in agreement that one should expect the mean King LWC to J–W LWC ratio to increase linearly as MVD increases.

Spyers-Duran (1968) indicates that the J–W probe responds completely to cloud LWC when MVD is less than about 30 μm. This threshold is significantly higher than what our results and the 1982 reports, cited above, suggest. The droplet size distributions in Spyers-Duran (1968) are bimodal, different from our distributions which tended to be monomodal. We attribute the dif-

TABLE 1. Mean values of key quantities for each pass.

Date (1995)	Loc	Pass Dur(s)	Mean King/J–W LWC ratio	Mean T (°C)	*Shad OR/ HVPS Counts (# m^{-3})	Median vol diam (μm)	Mean J–W LWC (g m^{-3})	Mean King LWC (g m^{-3})	Mean FSSP LWC (g m^{-3})
4 May	OK	69	2.9	6.3	120	24	0.21	0.52	0.45
		49	2.1	12.0	30	17	0.18	0.38	0.34
5 May	OK	53	1.9	12.5	396	19	0.37	0.60	0.31
17 May	OK	27	4.7	−8.9	3296	26	0.27	1.09	0.99
		32	5.0	−8.1	10 080	28	0.16	0.76	0.81
		89	3.9	−9.8	16 866	26	0.22	0.87	0.87
		75	3.0	−8.1	3402	26	0.26	0.68	0.72
17 Jun	CO	11	1.6	1.9	0	12	0.14	0.23	0.36
		31	2.0	2.0	0	13	0.14	0.28	0.39
		259	2.2	1.8	403	18	0.26	0.57	0.51
		47	2.4	−2.1	165	17	0.14	0.36	0.32
		166	3.4	−2.1	389	20	0.34	1.06	0.70
		115	4.3	−2.0	309	21	0.18	0.74	0.50
		30	4.1	−5.7	459	23	0.15	0.58	0.37
		38	2.8	−5.6	0	21	0.29	0.77	0.45
		31	2.8	−5.7	0	22	0.15	0.40	0.37
22 Jun	CO	56	2.1	0.7	233	19	0.83	1.74	1.01
		77	2.5	0.7	180	20	0.58	1.35	0.95
		29	3.6	0.1	275	18	0.20	0.65	0.54
27 Jun	CO	69	1.5	−2.2	0	14	0.35	0.55	0.64
		40	1.9	−1.3	472	12	0.13	0.24	0.60
		47	2.2	−3.2	426	16	0.33	0.65	0.85
		35	1.5	−3.9	346	14	0.36	0.54	0.62
		30	3.9	−4.5	249	17	0.13	0.56	0.81
		131	3.8	−5.5	428	17	0.25	0.87	1.13
		81	2.4	−7.6	194	16	0.29	0.68	1.07
		84	2.9	−7.5	335	15	0.16	0.45	0.93
		122	3.8	−6.4	327	17	0.30	1.09	1.40
		59	1.7	−4.7	191	14	0.37	0.55	1.05
28 Jun	CO	15	4.5	0.80	335	27	0.11	0.49	0.40

* Flights on 4, 5, 17 May—PMS 2D-P shadow OR counts; flights on 17, 22, 27, 28 Jun—HVPS particle image counts.

ference in results between our work, Strapp and Schemenauer (1982), and Personne et al. (1982), compared to Spyers-Duran (1968), to the different character of the droplet size distributions encountered in the Spyers-Duran work compared to those encountered in the other studies, to the different techniques employed to measure droplet concentrations and sizes, and possibly to differences in maintenance and calibration of the J–W probes themselves (Strapp and Schemenauer 1982).

5. Reinterpretation of previously published T-28 cloud LWC measurements

The instrument comparisons described above provide a basis for reassessing T-28 J–W LWC measurements from earlier projects. These are summarized in Table 2. In any given project a range of conditions were encountered, and it is impossible to assign one multiplier for each project that will serve to optimally compensate for the tendency of the J–W probe to underestimate cloud LWC for all passes during the project. At a given distance above cloud base, more vigorous updrafts will have smaller droplet sizes, and the J–W indications should be more nearly correct. Cloud base at a single project site is lower and warmer on some days than others, leading to broader droplet spectra and greater underestimates at a given altitude on some days than others. Precipitation scavenging alters the droplet distribution, and the effects of scavenging vary from region to region in a given cloud even during one pass. Here we discuss a general range of corrections that are consistent with the data obtained during 1995. Consideration of the droplet size spectrum for any given situation will indicate a more specific correction factor. Implicit in this discussion is the hypothesis that the King probe, while suffering from some deficiencies (most importantly, partial response to drizzle, rain, and even ice particles), in general responds more accurately and completely to a broader range of cloud droplet sizes than does the J–W probe.

The first major field program in which the T-28 was involved was the National Hail Research Experiment (NHRE), conducted from 1972 to 1976. During NHRE, the aircraft performed numerous penetrations of convective storms in the same northeastern Colorado region as the June 1995 flights included in the analysis presented above. In a summary of the microphysical measurements obtained from the T-28 during NHRE, Knight et al. (1982) compare J–W LWC measurements to estimated adiabatic values. They conclude that the T-28 J–W measurements are at least 20% too low, on average. They also comment that the results of the wind tunnel

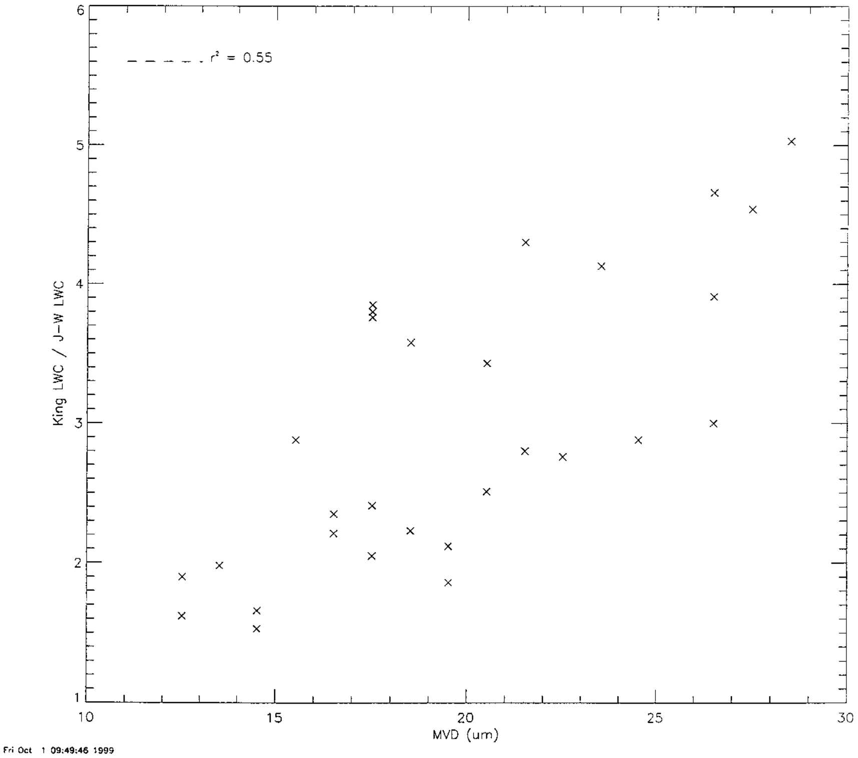

FIG. 3. Scatterplot of the mean ratio of King LWC to J–W LWC for periods identified in Table 1, as a function of median volume diameter. Two points are overplotted on top of each other for MVD = 14 μm and mean ratio = 1.5.

tests reported in Strapp and Schemenauer (1982) show that the T-28 J–W reads low by 50%. The wind tunnel data shown in Fig. 1 do not support this comment, at least for the droplet distribution produced in the tunnel. Presuming that the King probe responds nearly completely to all of the LWC in the Colorado clouds; that almost all of the liquid present is in the form of cloud droplets; and that the contribution of ice particles to the readings is negligible, the ratios of King to J–W probe readings for the relevant episodes in Table 1 range from somewhat higher to appreciably higher than the ratio that would be expected on the basis of the comparisons to adiabatic LWC of Knight et al. or on the basis of the wind tunnel tests of the J–W and King probes. While there are uncertainties, these past studies and the present data support the idea that some of the LWC values in the NHRE clouds were appreciably higher than was perceived in the earlier analyses.

Heymsfield and Hjelmfelt (1984a), in their analysis of T-28 microphysical observations in convective clouds in central Oklahoma during the Severe Environmental Storms and Mesoscale Experiment (SESAME), compared cloud LWC measurements from the J–W probe to those from the T-28 FSSP. The FSSP was carefully and frequently calibrated during SESAME and careful measurements were made of the beam diameter, depth-of-field, and velocity acceptance ratio. This allowed accurate estimates of droplet sizes and concentrations during the project, comparable to those obtained in the present study. They compared J–W and integrated

TABLE 2. Summary of J–W LWC multipliers for previous T-28 projects.

Project	Year	Typical range of J–W LWC multiplier	References
NHRE	1972–76	1–3	Knight et al. (1982)
SESAME	1979	1.6–4	Heymsfield and Hjelmfelt (1984a)
CCOPE	1981	1–3	Musil et al. (1986); Rasmussen and Heymsfield (1987); Kubesh et al. (1988)
Grossversuch IV	1982–83	1.6–3	Waldvogel et al. (1987); Blackmore et al. (1989)
COHMEX	1986	1.6–3	Musil and Smith (1989)
North Dakota 1987	1987	1.5	Stith et al. (1990)(one cloud)
CaPE	1991	1.5–4	Ramachandran et al. (1996); French et al. (1996); Bringi et al. (1997); Smith et al. (1999)

FSSP LWC and concluded that typically the FSSP LWC was ~3 times the J–W LWC. This is the median of the range of King to J–W ratios from Oklahoma presented in Table 1, though for the flight on 17 May 1995 (involving penetrations through updrafts in hailstorms roughly 4 km above cloud base), it is possible that the King probe was responding partially to precipitation-size particles. The large underestimate of LWC by the J–W probe in SESAME led Heymsfield and Hjelmfelt (1984b) to rely solely on FSSP LWC in their summary analysis of SESAME microphysics.

During the Cooperative Convective Precipitation Experiment (CCOPE) near Miles City, Montana, in 1981, the T-28 encountered some of the most vigorous updrafts it has ever penetrated, including a 35 m s^{-1} updraft in a storm on 1 August (Rasmussen and Heymsfield 1987; Kubesh et al. 1988), and a 50 m s^{-1} updraft in a supercell on 2 August (Musil et al. 1986). The J–W probe reported near-adiabatic readings in these two vigorous updrafts, at altitudes between 6 and 7 km MSL. The droplet median volume diameter was not presented in the published reports, but the reported number mean diameters are 10 μm or less, indicating narrow cloud droplet size distributions peaked at very small sizes. This indicates that in such an environment, the J–W probe can respond accurately to the cloud LWC. Underestimates similar to those in Colorado clouds presumably occurred in other situations.

Blackmore (1987), Waldvogel et al. (1987), and Blackmore et al. (1989) report microphysical characteristics of high-reflectivity zones in Swiss hailstorms penetrated at the −8°C level by the armored T-28 during the Grossversuch IV project in the summers of 1982 and 1983. Blackmore et al. report general agreement between FSSP and J–W LWC during this project, despite relatively broad droplet spectra. The processing of FSSP data from this project was done using default channel droplet size assignments from the manufacturer with a simplified estimate of the volume sampling rate. Based on later comparisons between this procedure and more exacting procedures for FSSP data processing (e.g., Heymsfield and Hjelmfelt 1984a; Baumgardner and Spowart 1990) we suspect that the Grossversuch IV FSSP LWC estimates were, on the average, low. Unfortunately, it is impossible to reprocess the Grossversuch IV FSSP data using more modern techniques because the necessary optical and electronic characteristics of the FSSP were not documented. As these characteristics change with time, to assume that more recent measurements of them might be representative of the FSSP during Grossversuch IV would be questionable. Consistent agreement between the T-28 J–W LWC and FSSP LWC estimated using the manufacturer's default channel size assignments and simplified estimate of volume sampling rate was observed between 1981 and 1991; this indicates stable performance of both probes over this time period. (The FSSP was overhauled after 1991.)

Droplet spectra presented in Blackmore (1987) suggest that typical Swiss spectra were broader, in terms of number of FSSP size channels with significant counts, than typical Colorado spectra, and generally closer in most characteristics to the Oklahoma spectra observed during SESAME in 1979 and VORTEX in 1995. This suggests that the Grossversuch IV J–W LWC measurements were also generally low, by factors similar to those in the Oklahoma observations. However, Waldvogel et al. (1987) show that some LWC peaks were encountered in stronger updrafts with narrower droplet spectra. In these areas with narrower spectra, the underreporting by the J–W probe should have been less severe. The cloud LWC data included in Blackmore (1987) and Blackmore et al. (1989) are mostly from the FSSP, while those in Waldvogel et al. (1987) are mostly from the J–W probe. As all report general agreement between the J–W and FSSP LWC, the characteristic peak LWC values reported in high-reflectivity zones in the Swiss storms are probably low by a factor of as much as 2 in some cases (e.g., young updrafts, and nearer cloud base), and perhaps more in others (e.g., more mature cloud regions, and farther above cloud base).

Musil and Smith (1989) present a microphysical summary of storms penetrated by the armored T-28 during the Cooperative Huntsville Meteorological Experiment (COHMEX), in northern Alabama, during the summer of 1986. About ⅓ of the penetrations were above the 0°C level. The highest penetration was at the −7.5°C level, while the lowest was at the +5.5°C level. During this project, FSSP data were processed using manufacturer's default channel size assignments and sample volume calculation, as was done with the Grossversuch IV data. Figure 6 of Musil and Smith (1989) shows that on the average J–W and FSSP LWCs agree reasonably well but that the scatter in their agreement increases as LWC increases above 1 g m^{-3}. Some tendency also appears for relative underreporting by the J–W probe compared to the FSSP at these higher LWCs. The FSSP cloud droplet spectra were noted to be quite similar to those observed during Grossversuch IV. The reported COHMEX LWC measurements were therefore probably low by similar factors. This suggests that LWC values higher than half of the adiabatic value were encountered, compared to the peak LWC values of ~¼ of adiabatic reported on the basis of the actual J–W and FSSP readings. Thus the updraft cores were less strongly diluted by mixing and precipitation scavenging than was originally inferred from the J–W and FSSP LWC measurements.

Stith et al. (1990) include microphysical characteristics in their analysis of transport and dispersion of tracer material in a growing cumulus congestus cloud that was observed in western North Dakota in the summer of 1987. The FSSP droplet spectra in this cloud (not included in the published report but available to the present authors) resemble closely the spectra of northeastern Colorado clouds in terms of number of size channels with significant counts. The T-28 J–W cloud LWC readings included in this North Dakota study are probably about ⅔ of the true cloud LWC values, based on our intercomparison between recent J–W and King probe readings. This suggests less dilution by entrainment of outside air into the updrafts than would be estimated based on the observed J–W readings. Less dilution is, in fact, more consistent with the observed slow dilution of plumes of tracer material released into the base of the updraft and carried upward to higher levels where the T-28 and another aircraft were sampling.

Ramachandran et al. (1996), French et al. (1996), Bringi et al. (1997), and Smith et al. (1999) all present studies involving armored T-28 observations of microphysical characteristics of Florida thunderstorms during the Convection and Precipitation/Electrification (CaPE) experiment of the summer of 1991. The cloud LWC observations included in all of these studies came from the J–W probe. The T-28 FSSP generally did not work well during CaPE. Based on one flight when it did work reasonably well, and on observations from two other FSSPs on other aircraft involved in CaPE, the droplet spectra in these clouds were similar to those of the Oklahoma, Swiss, and Alabama clouds. The analyses presented above indicate that the actual LWCs could have been two or more times the J–W LWCs. Readings in the young, nearly precipitation-free updraft penetrated on 29 July 1991 and described in the Ramachandran et al. (1996) study as Cell C should be least affected by this underreporting. The droplet spectral characteristics in this updraft are not known (the FSSP was not working properly on this flight), but the spectra were probably relatively narrower than in more mature updrafts. The peak reported LWC of 4 g m^{-3} was probably within a factor of 2 of the true value in this updraft. (If it were low by more than a factor of 2, then the true LWC would have exceeded the adiabatic LWC at this level in this cloud; this is physically unlikely in a precipitation-free updraft.)

6. Conclusions

Comparisons between J–W and King probe LWC readings from the armored T-28 in several representative microphysical environments show that the King probe LWC typically exceeds the J–W value, and at times is more than three times the J–W LWC. In some cloud regions containing relatively low cloud LWC but also containing significant precipitation, this ratio exceeded four. The cause of this difference is mostly incomplete response of the J–W probe to the large end of the cloud droplet spectrum, and, less significantly, partial response of the King probe to drizzle raindrops and ice particles. In regions with broader droplet spectra (typically, in clouds with warmer cloud bases, and also higher above cloud base), the King probe LWC can exceed the J–W LWC by a factor of 3 or greater. In young updrafts and nearer cloud base, where clouds are characterized by narrower droplet spectra, the King to J–W probe LWC ratio generally is less than two. These results are consistent with earlier comparisons reported by Heymsfield and Hjelmfelt (1984a) between J-W and carefully processed FSSP data from the T-28 system. The King probe should generally provide more accurate indications of cloud LWC, so we conclude that LWC values measured with the J–W probe used on the T-28 were too low in most situations. A review of published studies in which T-28 J–W measurements were used suggests that the magnitude of precipitation scavenging and of entrainment of environmental air into the updrafts sampled in these studies, deduced from the ratio of measured to adiabatic LWC, was overestimated. It is likely that some nearly-adiabatic updraft cores were encountered in continental clouds in most T-28 field projects in both mid-latitude and subtropical regions.

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