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Abstract

Airborne measurements of liquid water content (LWC) and drop size distribution were made in adiabatic regions of small, growing cumulus clouds during the Small Cumulus Microphysics Study (SCMS). A new instrument, the cloud drop spectrometer (CDS), which measures LWC and also drop size from an ensemble of drops, was flown for the first time in the field. Measurements from other sensors, including a Particle Measuring Systems (PMS) forward scattering spectrometer probe (FSSP), the 'fast' FSSP (FFSSP) developed by the Centre National De Recherches Meteorologiques (CNRM), and a Gerber Scientific airborne particulate volume monitor (PVM-100A), are compared with the CDS data collected in adiabatic and other regions. The CDS appeared to reliably measure very close to the predicted value of LWC in regions identified as being adiabatic. In addition, the drop size distribution measured by the CDS compared very well with the FSSP and FFSSP measurements, except where the 3–200 μm range of the CDS allowed it to measure larger drops than the nominal 3–45 μm range of the FSSP, and the 2.7 to 38.4 μm range of the FFSSP. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Drop spectrometer; Liquid water content; Drop size distribution; Cumulus clouds; Adiabatic regions

1. Introduction

Aircraft measurements of liquid water content (LWC) and drop size distribution in growing cumulus clouds have been collected for five decades (e.g., Warner, 1955, 1969, 1973; Telford, 1975; Cooper and Lawson, 1984; Paluch, 1986, Blyth et al., 1988; Baker,

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1992; Gerber et al., 1994). Both of these parameters are fundamental to studies of entrainment and mixing, development of the drop size distribution and the eventual formation of precipitation. Yet, in reviews of entrainment and mixing (Blyth, 1993) and warm-rain initiation (Beard and Ochs, 1993), a lack of reliable measurements of LWC and drop size are mentioned as major obstacles that must be overcome. One objective of the Small Cumulus Microphysics Study (SCMS) field project was to implement new technology for making in situ measurements of LWC and drop size distributions in small, warm cumulus clouds.

The project took place near Cape Canaveral, FL from 17 July–13 August 1995. Small cumuli were observed with three instrumented aircraft and the NCAR CP-2 radar with a view toward investigating the onset of the coalescence process. In this paper, we discuss data collected with a new probe, the cloud drop spectrometer (CDS) made by SPEC. The instrument provides information on LWC and drop size distributions. We compare the LWC measurements to the theoretical values expected in adiabatic parcels, and also to measurements from other optical devices which were installed on the research aircraft. Measurements were made from about 500–2000 m above cloud base in both unmixed and mixed regions of growing cumulus clouds. The primary objective of this paper is to report on the measurements made by the new CDS.

2. Instrumentation

Three research aircraft were extensively instrumented for making microphysical measurements: A C-130 operated by the National Center for Atmospheric Research (NCAR), the University of Wyoming (UW) King Air and a Merlin operated by the Centre National De Recherches Meteorologiques (CNRM) of France. Measurements from five optical devices installed on the C-130 are discussed in this paper: (1) A Particle Measuring Systems (PMS) forward scattering spectrometer probe (FSSP-100) described by Knollenberg (1981), (2) a PMS 260X optical array probe (Knollenberg, 1981), (3) a Gerber Scientific particulate volume monitor (PVM-100A) described by Gerber et al. (1994), (4) a Fast FSSP (FFSSP) modified by the CNRM (Brenguier et al., 1993), which was usually flown on the Merlin, but was installed on the C-130 for flights on 22 July and 24 July, and (5) the cloud drop spectrometer (CDS) described by Lawson and Cormack (1995).

A King hot-wire LWC device (King et al., 1978) was also installed on the C-130. The King device is commonly used to measure LWC on research aircraft; however, during this project the King probe read systematically too low and often ceased to operate less than an hour into the flight. This response from the probe is unusual and the reasons for these problems are unknown.

The PVM-100A measures LWC, drop surface area and effective radius at a sample rate of 1 kHz. The measurements presented here were averaged to 1 Hz by the NCAR data processing routine. Gerber et al. (1994) calibrated the PVM-100 (the ground-based version of the PVM) in a low-speed wind tunnel and a cold room. They state that the accuracy of the LWC (filter) measurement system in the wind tunnel is 5%. However, there were no calibration runs made for LWC > 1 g m^{-3}.

The FSSP has been under considerable scrutiny since its introduction into the field. Processing of FSSP data by NCAR for this project included partial recovery of losses due to coincidences and probe dead time (Baumgardner et al., 1985), and adjustment of channel widths to account for airspeed corrections to the electronics (Cerni, 1983; Dye and Baumgardner, 1984; Baumgardner, 1987). Corrections have not been made for problems in the droplet spectrum due to coincidences, as discussed by Cooper (1988) and Brenguier (1989), or due to laser beam inhomogeneities (Baumgardner and Spowart, 1990; Wendisch et al., 1996). The principle measurement of the FSSP is drop size and signals were sorted into 15 equal drop size bins in the 3–45 μm range. The measurements were summed and recorded every 0.1 s. The dynamic accuracy of the FSSP in measuring LWC and drop size is difficult to quantify. Baumgardner (1983) suggests that FSSP measurements of drop size are accurate to 17% and LWC is accurate to within 34%. However, subsequent evaluations of the FSSP have shown additional potential error terms due to coincidences (e.g., Cooper, 1988), inhomogeneities in the laser beam and effects of airspeed (e.g., Wendisch et al., 1996). In addition, the accuracy of the FSSP appears to depend on factors which are not always quantifiable, such as field calibrations, optical contamination, airflow effects due to position on the aircraft, etc.

The FFSSP was developed to overcome some of the drop sizing limitations of the FSSP. The FFSSP eliminates electronic dead time and improves depth of field definition. The instrument sizes drops in 255 size bins and was set during SCMS to cover the range from 2.7 μm- $-$ 38.4 μm. The drop sizing measurements from the FFSSP in this study are thought to be reliable, except for cases with large (i.e., $> \sim 600$ cm^{-3}) drop concentrations. In such cases, coincidence of drops create broadening at the large end of the size distributions measured by both the FFSSP and the FSSP (Cooper, 1988).

The CDS was flown on the C-130 for the first time in a field project, so here we present an explanation of its principle of operation and calibration. The CDS is shown in Fig. 1 installed in a standard PMS canister next to the PVM-100A under the right-wing pod of the C-130. The technique of computing LWC by optically weighting and summing the light scattered in the forward direction from an ensemble of drops was pioneered by Chittenden (1976) and is reported by Blyth et al. (1984). The instrumentation developed by Blyth et al. (1984) was improved by Gerber et al. (1994), who used an annular filter and improved electro-optics to measure LWC in the PVM-100A. The CDS differs from these instruments in that it measures the raw forward-scattered light and applies a weighting function to the measurements in software. It measures the forward-scattered light from 0.15° to 9° using a CCD detector with 512 pixels, producing an angular measurement resolution of 0.017°. The computation of LWC does not require an inversion algorithm; however, the weighting function, which is a one-dimensional vector, is determined using a least-squares optimization. Lawson and Cormack (1995) discuss the methodology used to compute LWC and show some results from icing tunnel tests. An example of a comparison of LWC measured by the King device and a ground-based version of the CDS in the Ottawa icing tunnel (Strapp and Schemenauer, 1982) is shown in Fig. 2.

The CDS is the first airborne instrument to measure both cloud LWC and drop size distribution from an ensemble of drops. The mathematics of the drop sizing technique was originally developed by Chin et al. (1955) and is similar to the drop sizing method

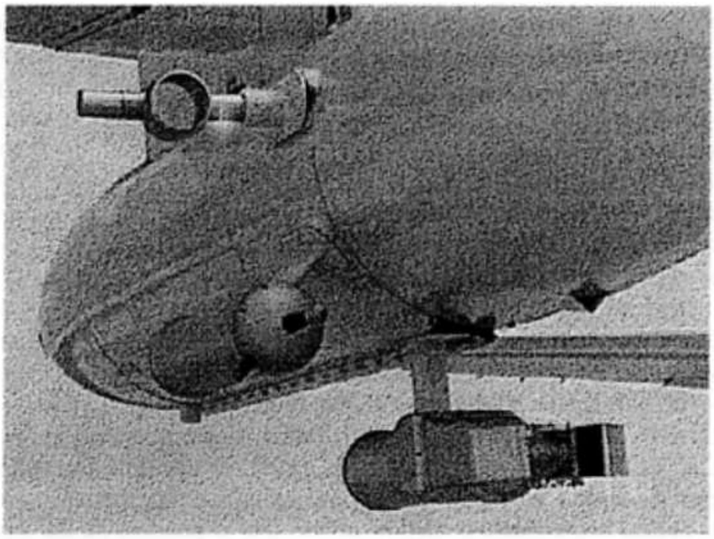

Fig. 1. Photograph of the instrumentation pod under the right wing of the NCAR C-130 showing the CDS mounted at the six o'clock position and the PVM-100A installed at the nine o'clock position.

used in the Malvern particle analyzer, which has been used to measure drop sizes from spray nozzles (see Riley and Agrawal, 1991 for a discussion of similar particle sizing techniques). The basic measurement technique has some inherent advantages over single-particle sizing and counting used in the FSSP, FFSSP and the phase Doppler particle analyzer (Bachalo and Houser, 1984). The sample volume of the CDS is 6 cm^3 and the measurement is independent of airspeed. Thus, coincidence and dead-time errors inherent in the FSSP (Cerni, 1983; Baumgardner et al., 1985; Cooper, 1988; Brenguier,

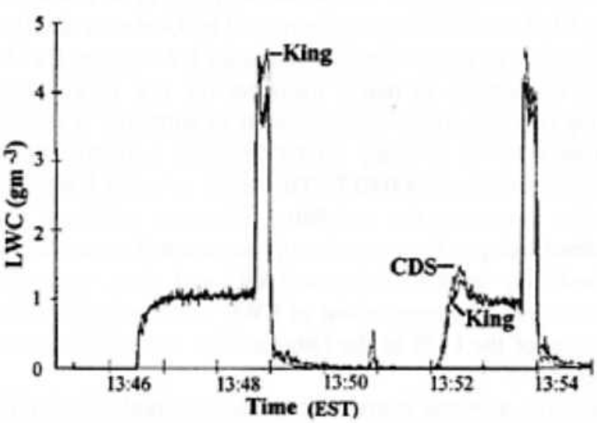

Fig. 2. Comparison of LWC measured by the King device and a ground-based version of the CDS in the Ottawa icing tunnel.

1989) are not a problem in the CDS. A disadvantage inherent to sampling an ensemble of drops (as is done in the CDS and PVM) is that some minimum population of drops must occupy the sample volume to provide a signal which is detectable above background noise. The minimum number of drops is a function of the drop size distribution and this dependency has not been quantified. Another disadvantage (also shared by the FSSP and PVM), is that the measurement technique assumes that the sample volume contains only (spherical) water drops; introduction of nonspherical particles, such as ice crystals in mixed-phase clouds, may produce significant errors. The sample rate of the CDS during the SCMS project was 5 Hz and the measurements were averaged in hardware and recorded at 1 Hz; however, faster sample rates are possible.

Since the CDS measurements were recorded at 1 Hz, higher rate LWC measurements from other instruments (such as the FSSP and PVM) were averaged to 1 Hz for purposes of comparison. It should be noted that the (hardware and software) averaging procedures used to process the CDS, FSSP and PVM measurements may reduce the magnitude of any narrow ($< \sim 100$ m) spikes in these LWC data.

The CDS was calibrated in the laboratory from first principles. An example of theoretical and measured scattering patterns for polystyrene spheres ranging from 5 to 200 μm that were suspended in an aqueous solution in the laboratory is shown in Fig. 3. The theoretical scattering patterns are exact Mie functions scaled only by the gain of the CDS. The overall agreement in Mie theory and the measured light scattered from the solutions of spheres with known diameters is excellent. The slight discrepancies are most likely due to uncertainties in the actual size distributions of the spheres and the gain function of the CDS. The measurements shown in Fig. 3 show that the CDS responds to drops with sizes of at least 200 μm. Using the inversion algorithm discussed later in this paper, the CDS sizes monodispersed solutions of polystyrene beads so that $> 95\%$ of the recovered size distribution falls within about 10% of the mean size of the beads.

The computation of LWC from CDS measurements is accomplished by applying the relative gain of the instrument, determined unambiguously from the optical geometry and electronics, and by multiplying each of the 512 angular outputs by a single scale factor. This is necessary to account for optical losses, which cannot be measured directly, but are linear and can be adjusted by the scale factor. The scale factor is determined by placing known concentrations and size distributions of polystyrene beads in the sample volume and measuring the signals. Several measurements with the beads are taken and the results are averaged. Based on a composite measurement uncertainty analysis of the type described by Abernethy and Benedict (1984), 95% of the CDS LWC measurements, excluding flow enhancement and environmental effects from installation on the C-130, are estimated to be accurate to within about 0.1 g m^{-3} $\pm$ 12% of the signal level.

The very strong correlation between theory and measurements in Fig. 3 provides a solid foundation for development of a drop sizing algorithm. The technique used here to recover drop size distribution from the patterns of scattered light is called the estimate maximize (EM) method (Latham and Anderssen, 1994). The EM and the EMS (smooth) methods are particularly suited to poorly posed systems of linear equations. In the CDS, the scattered light measurements are used to determine the shape of drop size spectra

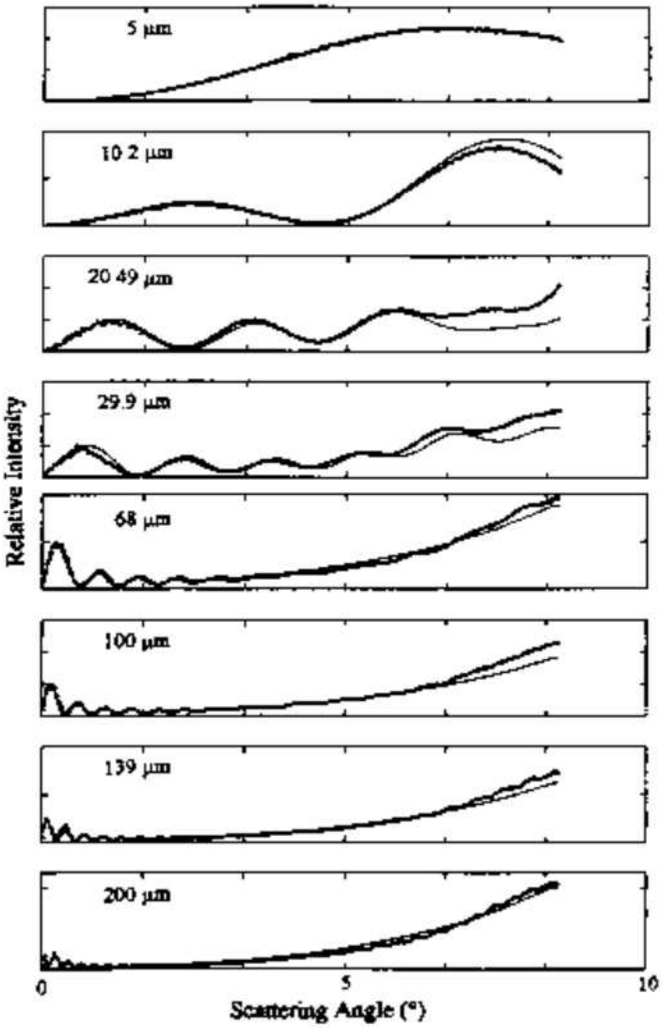

Fig. 3. Comparison of Mie theoretical (light line) and CDS measured (heavy line) distributions of light scattered from aqueous solutions of (from top) 5 ± 0.035 μm, 10.2 ± 0.061 μm, 20.49 ± 0.2 μm, 29.9 ± 0.2 μm, 68 ± 1.4 μm, 100 ± 2.0 μm, 139 ± 2.8, 200 ± 4 μm polystyrene spheres, where the listed standard deviations are defined by the manufacturer, Duke Scientific.

and LWC separately, then the LWC is used to compute a linear scale factor which gives absolute number concentrations for each drop size bin.

The EM method has been successfully used in a wide variety of physical solutions of poorly posed linear systems of equations where the solutions are known a priori to be nonnegative (Latham and Anderssen, 1994). A set of nonnegative linear equations which describes the scattered light signal from the CDS can be written as

$$I = Sf(r) \tag{1}$$

where I is a column vector with length $L_I = 512$, corresponding to the output of the 512 pixels of the CCD array, S is the scattering vector computed from Mie theory with a size $L_I \times B$ and $B = 33$ is the number of drop size bins, and $f(r)$ is a column vector with length B corresponding to the actual drop size distribution. The EM method computes $f(r)$ using the iterative procedure

$$F_b^{(n)} = \sum_{d=1}^{D} \frac{I_d S_{bd}}{\left[S f^{(n)}(r) \right]_d} \qquad b = 1,2,3,\ldots,B \tag{2}$$

$$f_b^{(n+1)}(r) = F_b^{(n)} f_b^{(n)}(r) \qquad n = 0,1,2,3\ldots \tag{3}$$

The final output is not highly sensitive to the initial guess for the drop size distribution and $f(r) = 1$ is used in all applications. Methods for terminating the EM iterative

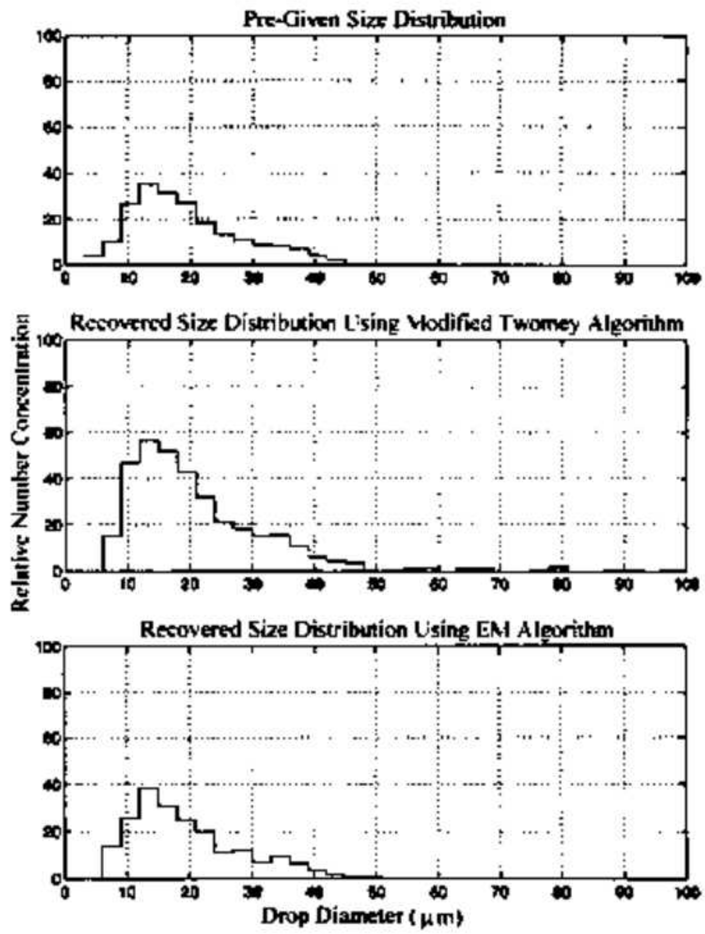

Fig. 4. Comparison of results from a modified Twomey algorithm and the EM method applied to a pre-given drop size distribution.

algorithm are not obvious and in processing the SCMS data we fixed the number of iterations at 200. Tests using substantially more iterations did not appear to produce better results; however, a method to terminate the algorithm after a specified level of precision is obtained would potentially decrease computation time.

The EM and EMS methods have been commonly used in emission tomography and stereology, (Latham and Anderssen, 1994); however, to our knowledge, this is the first published use of this technique in cloud drop sizing. While an extensive study of inversion algorithms has not been attempted, we have found the EM algorithm to produce more reliable results than some inversion techniques commonly used to compute drop size distribution in the atmospheric sciences. In particular, the EM algorithm has the attractive feature of minimizing or eliminating higher-order harmonics which often result in 'ringing', i.e., the introduction of artifacts at the larger sizes in the drop size distribution (for an example, see Kouzelis et al., 1988).

Fig. 4 shows a comparison of results from the EM method and a modified Twomey algorithm (Riley and Agrawal, 1991) applied to a pre-given drop size distribution. The modified Twomey algorithm used here is not a strict inverse of the scattering matrix, but instead, uses a row-by-row matrix multiplication. The iterative EM algorithm is appreciably slower than the matrix-multiply method, and unless it can be optimized, this precludes using it in real-time applications. The shape of the pre-given drop size distribution in Fig. 4 is typical of one which might be observed in a cumulus cloud with a tail extending out to about 45 μm. The modified Twomey algorithm reconstructs the shape of the original distribution fairly well, however, it introduces artifacts in the larger size bins, out to about 90 μm. The EM algorithm reproduces the original size

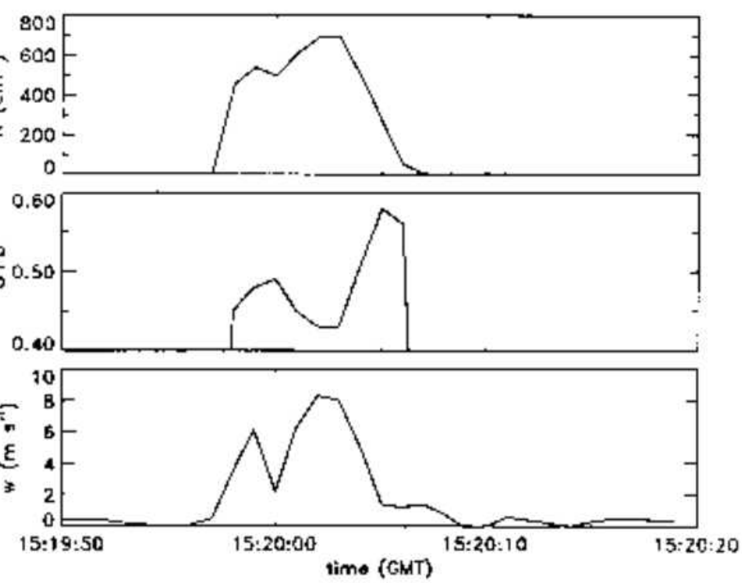

Fig. 5. Concentration, FSSP drop dispersion and updraft velocity measurements (from top to bottom) from the air motion system in adiabatic region of cloud on 22 July 1995.

Date, time, cloud base pressure (P), temperature (T), observation level (P_{OBS}), adiabatic value of LWC (LWC_{AD}), LWC from CDS, PVM and FSSP, FSSP . mean drop diameter ($\bar{D}$) and number concentration (N) for the 14 adiabatic regions plotted in Fig. 6

Date	Times (GMT)	Cloud base P (mbar)	Cloud base T (°C)	P_{OBS} (mbar)	LWC_{AD} ($g\ m^{-3}$)	FSSP LWC ($g\ m^{-3}$)	PVM LWC ($g\ m^{-3}$)	CDS LWC ($g\ m^{-3}$)	FSSP $\bar{D}$ (μm)	CDS $\bar{D}$ (μm)	FSSP N (cm^{-3})	CDS N (cn
Jul 20	170327	915	22	730	3.88	3.0	2.89	3.90	17	N/A	750	N/A
Jul 20	171952	915	22	880	0.82	0.95	0.66	0.80	10	N/A	1000	N/A
Jul 22	152002	950	23	820	2.87	2.12	2.18	2.86	16	15	700	1440
Jul 24*	152719	937	24	915	0.32	0.75	0.35	0.32	10	8	1120	1350
Jul 24	153940	937	24	915	0.32	0.5	0.24	0.28	8.5	8	1070	870
Jul 24*	154547	937	24	912	0.38	0.53	0.20	0.19	9	8	1200	640
Jul 24	155008	937	24	915	0.32	0.54	0.29	0.27	9	8	1100	920
Jul 24	163317	937	24	760	3.62	3.0	2.67	3.43	16	16	900	1460
Jul 24*	170852	937	24	730	4.17	3.2	2.66	3.72	17	17	870	1190
Jul 24	172233	937	24	730	4.17	3.1	2.59	3.3	16.5	16.5	890	1160
Aug 11*	141149	950	23	945	0.36	0.53	0.42	0.40	10.5	8	725	890
Aug 11	143650	950	23	910	1.18	1.1	0.86	0.94	14	12	620	970
Aug 11*	150106	950	23	755	4.32	4.0	2.42	3.93	23	19	450	670
Aug 13	145133	960	23	945	0.25	0.37	0.14	0.22	8	9	900	270

The * denotes penetrations where one of the adiabatic criteria was questionable (usually that the vertical velocity in the region was variable). Note th measurements from flights on 20, 22 and 24 July are activity corrected using only total strobes and are therefore approximate.

distribution without introducing appreciable ringing. This is an especially important feature relative to the determination of drop size distributions for analysis of the onset of coalescence.

3. Observations in adiabatic regions

There are usually large differences in the LWC measured by different devices (e.g., Baumgardner, 1983). Little insight has been gained over the years for the reasons for the discrepancies (see e.g., the discussion in Miller (1991) of LWC measurements in cumuli during the Hawaiian Rainband Project). One way of providing a good 'standard' is to compare measured and theoretical values in regions of cloud that have ascended adiabatically from cloud base to the observation level (e.g., Jensen et al., 1985). In these regions, the number concentration N and vertical wind velocity w are nearly constant and at a maximum, and the droplet spectrum is narrow (i.e., the dispersion, defined as the standard deviation of the droplet spectrum divided by the mean diameter $\sigma/\overline{D}$, is relatively small—the average dispersion for these regions is 0.43 as measured by the FSSP). These were the criteria used, determined from 10 Hz FSSP measurements of N and $\sigma/\overline{D}$ and 25 Hz measurements of w, to ascertain whether or not a region was adiabatic.

The liquid water content in a parcel that ascends adiabatically from cloud base can be calculated using a variety of methods. One method, employed in this paper, uses the fact that entropy (i.e., the wet equivalent potential temperature) is constant in adiabatic ascent (Iribarne and Godson, 1973). The entropy is calculated at cloud base. Successive approximations of the temperature are then found by inverting the equation for entropy. The liquid water content is calculated by subtracting the saturated water vapor mixing ratio at the level of interest from that at cloud base.

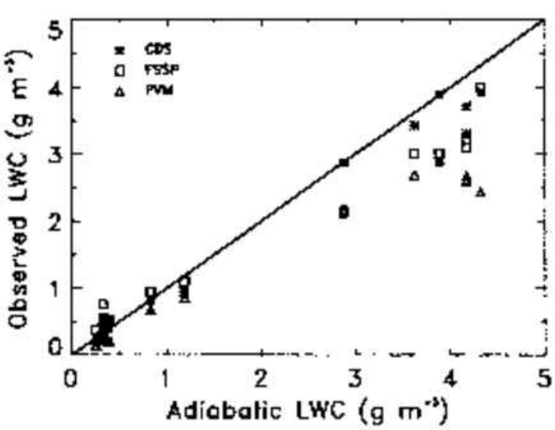

Fig. 6. Scatterplots of measurements from Table 1 showing CDS, FSSP and PVM LWC compared with LWC_{AD} for 14 penetrations of adiabatic regions.

The cloud base temperature and pressure were obtained using a combination of methods. Simultaneous measurements from the UW King Air at cloud base were used when available. The C-130 often flew in the vicinity of cloud base before or after penetrations were made higher in the cloud, thus giving a good estimate of the temperature and pressure of cloud base. CLASS soundings were also used to compute the lifting condensation level. In the Florida region where the SCMS was conducted, there was a consistent trend for cloud base altitude to start at about 960 mbar in the late morning and increase monotonically to about 930 mbar later in the afternoon. For a typical cloud base at 950 mbar and 23°C, measurement errors of 10 mbar and 1°C result in about 0.2 and 0.1 g m^{-3} errors in LWC_{AD}, respectively. Uncertainties in the determination of cloud base measurements can result in errors in LWC_{AD} of up to about 20–50% near cloud base. The error decreases to about 5–10% higher in clouds where $LWC_{AD} \approx 4$ g m^{-3}.

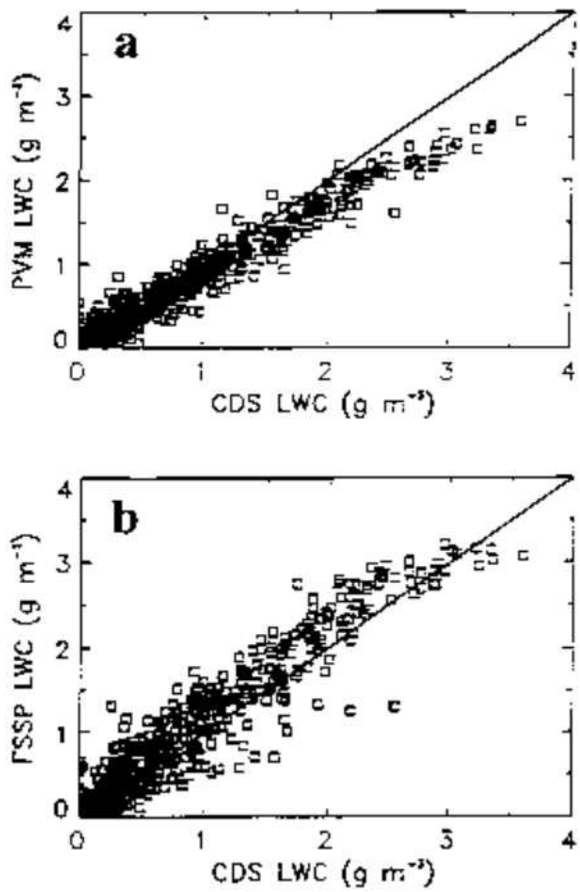

Fig. 7. Scatterplots of all 1-s values of LWC measured on 24 July and 13 August 1995 by the (a) CDS and PVM, and (b) CDS and FSSP, respectively.

The CDS was installed on the C-130 on 20, 22, 24 July, 11 and 13 August, so only data from penetrations of adiabatic regions on those days are discussed. Fig. 5 shows an example of these measurements for a pass 1150 m above cloud base on 22 July. Data points at 152 002 and 152 003 show a region where the (unsaturated) FSSP-100 drop concentration is a maximum value of 700 cm^{-3} and flat, the dispersion is a minimum value of 0.42 and flat, and there is a relatively flat 9.8 m s^{-1} peak in updraft velocity. Measurements with this combined pattern are very typical of those found in adiabatic regions in cumulus clouds (see, for example, measurements in Lawson and Cooper, 1990).

Nine adiabatic regions of at least 100 m in length that satisfied the above criteria were identified—see Table 1. As can be seen from the table, a further five regions satisfied the number concentration criterion, but the vertical winds were not smooth and/or the region was smaller than 100 m. We believe these regions to be very close to adiabatic mainly because of the large number concentration, but clearly mixing has begun to take place. In addition, there were some regions about 2 km above cloud base in which the LWC measured by the CDS was approximately equal to the adiabatic value, but the number concentration measured by the FSSP was too low. These regions were not included in the analysis. The regions may have actually been adiabatic and errors associated with FSSP dead-time and coincidence caused the number concentrations to be underestimated (Baumgardner et al., 1985; Cooper, 1988; Brenguier, 1989). One possibility in these regions as well as the others we have included is that the CDS measurements were an overestimate and the regions were not adiabatic. However, it is worth noting that the CDS LWC in regions 1–2 km above cloud base did not exceed the adiabatic value by more than 5%.

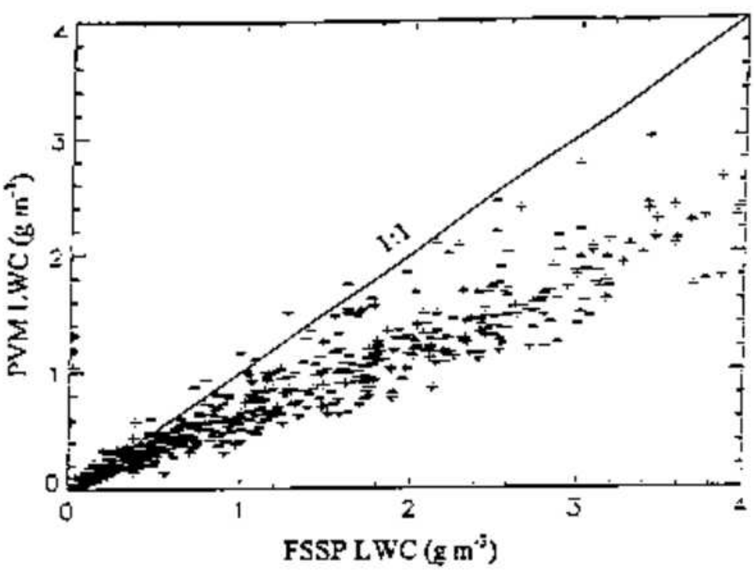

Fig. 8. Scatterplot of maximum 1-s LWC measurements from the PVM and FSSP devices for 568 SCMS cloud penetrations from 26 July–13 August 1995.

Fig. 6 shows scatterplots of FSSP, PVM and CDS measurements of LWC in all 14 regions. The scarcity of LWC measurements in adiabatic regions prohibits a rigorous statistical analysis; however, some trends are evident. The CDS measurements show the best overall agreement with LWC_{AD} and show no systematic trends. The FSSP measurements are also in fairly good agreement with LWC_{AD}, tending to overestimate LWC_{AD} at the low end and underestimate slightly at the higher end of the range. However, FSSP coincidence and dead-time errors are known to broaden the drop size distribution and underestimate the concentration (Cooper, 1988; Brenguier, 1989), so the relatively good agreement in adiabatic and FSSP LWC may be due to a cancellation of errors. The PVM measurements are in good agreement for LWC_{AD} of $< \sim 1$ g m^{-3}.

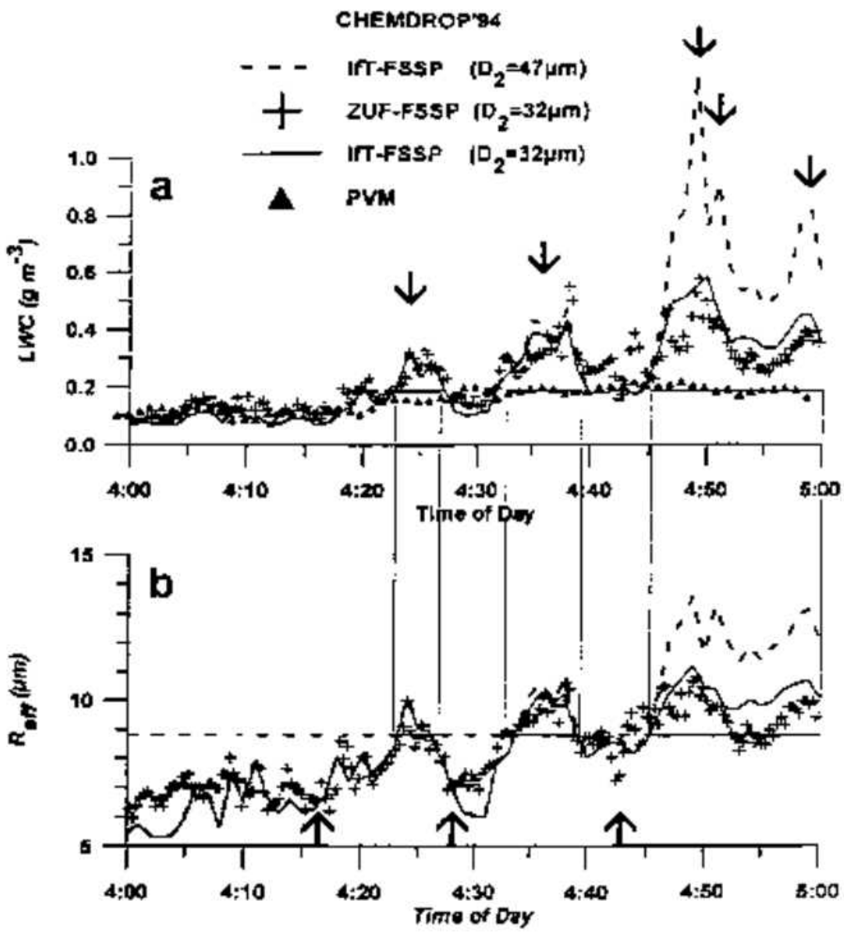

Fig. 9. (a) Liquid Water Content (LWC) and (b) Effective Drop Radius (R_{eff}) obtained by integration of the corrected drop size distribution of two different FSSPs from Center for Environmental Research, Frankfurt/M., Germany (ZUF-FSSP) and Institute for Tropospheric Research, Leipzig, Germany (IfT-FSSP). The critical Effective Drop Radius, above which differences between PVM and FSSP derived LWC becomes notable (= 8.8 µm), is included as a dashed, horizontal line (from Wendisch, 1997).

Fig. 7a and b shows scatter plots of all the 1-s values of LWC measured on 24 July and 13 August by the CDS and PVM, and CDS and FSSP, respectively. Figs. 6 and 7a display a common feature; the CDS measures a higher value of LWC than the PVM at higher liquid water content values. The CDS-determined LWC also appears to be closer to the adiabatic and the FSSP values. We compared LWC measured by the FSSP and PVM in 568 penetrations from 26 July–13 August. Fig. 8 shows the maximum LWC (measured in a penetration) by the PVM and FSSP for the 568 penetrations. The FSSP LWC is higher than the PVM LWC at higher values of LWC.

The CDS and FSSP values of LWC compare reasonably well with each other and with adiabatic values of LWC (Figs. 6 and 7b). The instruments both use scattering of light in the forward direction, but the method of obtaining the LWC is completely different (cf. Baumgardner, 1983; Lawson and Cormack, 1995), so the result showing that the LWC values agree to a reasonable approximation is encouraging. The result showing the apparent discrepancy between the PVM LWC and the other measurements of LWC requires further investigation.

Measurements from FSSP-100 and PVM-100 ground-based probes reported by Wendisch (1997) are reproduced in Fig. 9. The arrows in the time series measurements shown in Fig. 9 indicate regions where the effective radius R_{eff} exceeded 8.8 μm. The FSSP recorded increasingly higher LWC with increasing drop size while the PVM-100 remained essentially constant. It should be noted, however, that the PVM measurements in Fig. 9 are from a ground-based device, the PVM-100 (Gerber, 1984, 1991), which has the same principle of operation as the PVM-100A airborne device (Gerber et al., 1994), but is not identical. One explanation for the apparent decreased sensitivity of the PVM-100 to drops with $r_{eff} > 8.8$ μm has recently been put forth by Wendisch (1997) (personal communication), who suggests that the effect may be a problem of the PVM detecting low drop concentrations. Also, the measurements reported by Wendisch (1997) are in contrast to extensive wind tunnel and airborne measurements reported by Gerber et al. (1994) and Gerber (1996). They compared the PVM-100, FSSP-100 and several hot-wire instruments and found that LWC measured by the FSSP was systematically less than the PVM-100, when either drop diameter or LWC was large. Vong and Kowalski (1995) report good agreement between activity-corrected FSSP and PVM-100 measurements; however, their results were for 30 min averages when the drop diameters were well below 35 μm.

4. Drop spectra

Fig. 10a–e shows FFSSP, FSSP, and CDS measurements of drop spectra made while the FFSSP was on the C-130 on 22 and 24 July, 1995, and also includes the 260 ×

Fig. 10. FSSP, FFSSP and CDS measurements of drop size distribution in (a) an adiabatic region at 22°C about 50 m above cloud base on 24 July at 155008, (b) an adiabatic region at 13.1°C about 2 km above cloud base on 24 July at 155008, (c) at 10.3°C about 2 km above cloud base on 24 July at 155008, (d) at 10.5°C about 2 km above cloud base on 24 July at 155008 and (e) in a region where the CDS measured drops with diameters to 60 μm on 22 July at 152808 about 2 km above cloud base at 12.0°C. PMS 260X measurements starting with the fourth (50–60 μm) size bin are also shown in (e).

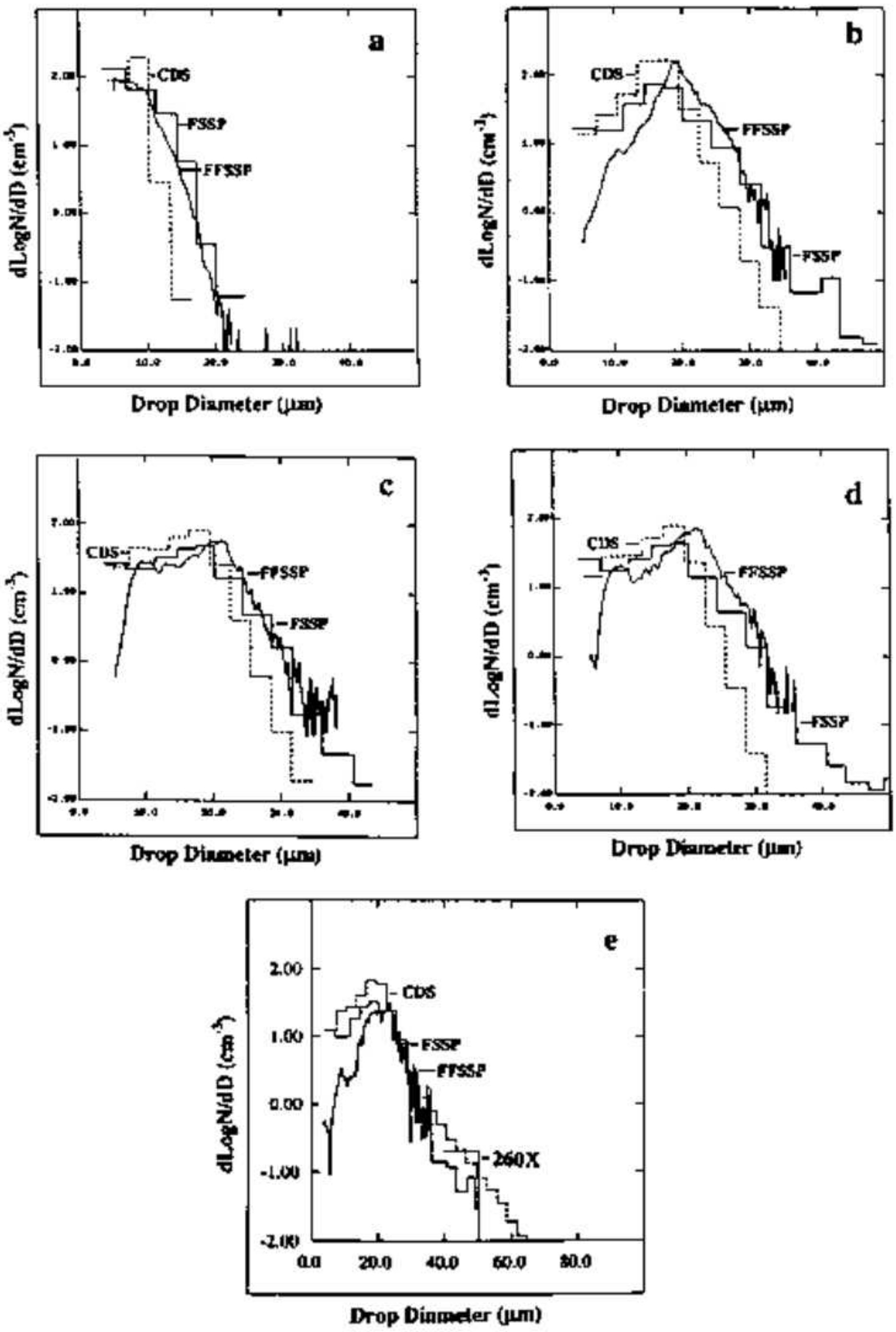
a
CDS
FSSP
FFSSP
dLogN/dD (cm⁻³)
Drop Diameter (μm)
b
CDS
FFSSP
FSSP
dLogN/dD (cm⁻³)
Drop Diameter (μm)
c
CDS
FFSSP
FSSP
dLogN/dD (cm⁻³)
Drop Diameter (μm)
d
CDS
FFSSP
FSSP
dLogN/dD (cm⁻³)
Drop Diameter (μm)
e
CDS
FSSP
FFSSP
260X
2.00
1.00
0.00
-1.00
-2.00
0.0
20.0
40.0
60.0
80.0
dLogN/dD (cm⁻³)
Drop Diameter (μm)

Table 2
Values of LWC, mean drop diameter ($\overline{D}$), total number concentration (N) and dispersion ($\sigma / \overline{D}$) measured by the CDS, FSSP and FFSSP for the five drop spectra shown in Fig. 10

Date	Time	CDS LWC ($g\ m^{-3}$)	FSSP LWC ($g\ m^{-3}$)	FFSSP LWC ($g\ m^{-3}$)	CDS $\overline{D}$ (μm)	FSSP $\overline{D}$ (μm)	FFSSP $\overline{D}$ (μm)	CDS N (cm^{-3})	FSSP N (cm^{-3})	FFSSP N (cm^{-3})	CDS $\sigma / \overline{D}$ (μm)	FSSP $\sigma / \overline{D}$ (μm)	FFSSP $\sigma / \overline{D}$ (μm)
22 Jul	152808	4.06	2.21	1.38	17.8	17.0	20.5	1019	519	263	0.37	0.46	0.62
24 Jul	155008	0.27	0.54	0.31	8.0	8.6	10.2	919	1053	503	0.42	0.44	0.42
24 Jul	163318	3.33	3.03	3.62	15.6	16.0	19.6	1463	914	830	0.29	0.43	0.49
24 Jul	173233	1.89	2.14	2.13	14.7	14.4	17.5	891	798	602	0.36	0.49	0.73
24 Jul	170014	1.15	1.66	2.52	15.0	14.7	18.8	524	600	602	0.35	0.48	0.65

measurements in Fig. 10e when the CDS measured drops with diameters up to ~60 μm. Table 2 shows LWC, N, $\overline{D}$, and $\sigma/\overline{D}$ for the five drop spectra shown in Fig. 10. For the data presented here, the CDS measurements of scattered light were solved using the EM algorithm for 33 equal size bins with the first bin centered at 3 μm. We have shown, in Fig. 10, a representative sample of spectra. The measurements are taken from an adiabatic region near cloud base and at a higher level in the cloud (Fig. 10a and b, respectively), and also from mixed regions where the spectra are bimodal (Fig. 10c and d), or very broad (Fig. 10e). We can see from the figure that generally, the agreement between the drop size spectra measured by the three probes is good. It is interesting to note that the FSSP and FFSSP spectra have comparable large droplet tails while the CDS spectra are about 3 μm narrower (Fig. 10a and b). Fitzgerald (1972) showed with theoretical calculations and measurements that the drop size spectra near cloud base are typically very narrow. As shown in Tables 1 and 2, the total drop concentrations measured by the FSSP on 22 and 24 July were 700 to 1200 cm^{-3}. Coincidences are known to be a problem for the FSSP with such large concentrations (Cooper, 1988; Brenguier, 1989) and the effect is to broaden the spectrum at the large end. The FFSSP suffers in a similar manner. The spectra can be corrected statistically, but the technique to do so is still under development.

The total concentration of drops calculated from the CDS signals were also in this range (Table 1), with concentrations occasionally as high as 1460 cm^{-3}. Such large concentrations are consistent with the values measured by the FSSP considering the problem the FSSP has with coincidences. Coincidences do not occur in the CDS. Certainly the CDS spectrum shown in Fig. 10b where the total concentration was over 1400 cm^{-3} is narrower than both the FSSP and FFSSP spectra. The CDS and FFSSP probes were not on board the same aircraft when the total drop concentration was low. Notice, however, that the FFSSP spectra fall off much more rapidly at the small size end than the FSSP spectra. The broadening at the small end is thought to be mainly due to laser beam inhomogeneity (Wendisch et al., 1996), but also signal attenuation as a function of signal duration (bandwidth of the amplifiers). It is likely that the broadening at the large end of the FSSP spectrum at the low levels in the cloud is the reason why the FSSP LWC is sometimes almost twice the adiabatic value.

5. Discussion

This was the first time the new cloud drop spectrometer (CDS) was flown in a field program. The results reported are very encouraging, albeit, preliminary. The CDS appeared to reliably measure the adiabatic values of LWC from about 0.5 to 2 km above cloud base in undiluted updraft regions in small, warm ($T > 0$°C) Florida cumuli. The FSSP-100 also agreed well with the adiabatic values, showing a trend to overestimate LWC at the lower (< 1 g m^{-3}) values and to slightly underestimate LWC at the higher (3–4 g m^{-3}) values. However, FSSP coincidence and dead-time errors are known to broaden the drop size distribution and underestimate the concentration (Cooper, 1988; Brenguier, 1989), so the relatively good agreement in adiabatic and FSSP LWC may be due to a fortuitous cancellation of errors. The PVM-100A was in good agreement with adiabatic LWC 0.5 km above cloud base (up to about 1 g m^{-3}), but generally underestimated (by about 20–40%) the predicted adiabatic LWC at 1 and 2 km above cloud base. We want to point out that the measurement trends seen here are based on limited data and are not statistically significant. The King hot-wire device, which is commonly used to measure LWC from research aircraft, did not function properly and was not used in this analysis. Clearly, more research supporting the evaluation of LWC measurements from the various instruments is needed.

The CDS drop size distribution in adiabatic regions at 0.5 km above cloud base was about 3 μm narrower than the FSSP. The validity of the CDS drop size measurements are strengthened by: (1) condensational drop growth theory predicts very narrow drop size spectra near cloud base (Fitzgerald, 1972) and (2) the FSSP is known to artificially broaden the drop size distribution (Cerni, 1983; Cooper, 1988; Brenguier, 1989). On the other hand, the drop size distribution in one of the high LWC regions on 22 July (Fig. 10e) had a 'tail' which was larger than seen by the FSSP. The concentration of 40 μm diameter drops was about twice as great as that measured by the FSSP during this penetration 2 km above cloud base. While no explanation is offered for the existence of the large tail, the combination of very high (up to 4 g m^{-3}) LWC in this region and the broadened drop size distribution provide a strong catalyst for the very early development of coalescence and the rapid development of warm rain. A future investigation is anticipated to compare CDS measurements and predictions of condensation-coalescence using numerical models (e.g., Cooper et al., 1996).

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