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STRUCTURE OF SMALL CUMULUS CLOUDS

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1. INTRODUCTION

The Small Cumulus Microphysics Study (SCMS) held in Florida in 1995 provided an opportunity to deploy in a new way a Particulate Volume Monitor (PVM; Gerber et al. 1994) on the NCAR C-130 aircraft. Measurements of liquid water content (LWC) were made at 1000 Hz, and of effective radius (r_e) were made at 250 Hz. This gave a horizontal resolution of 10 cm for LWC for an aircraft speed of 100 m/s. This resolution is several orders of magnitude greater than usually used, thus providing a look of unprecedented clarity at the structure of the small cumulus clouds (Cu) found during SCMS.

The following outlines the results of studies that take advantage of this new look at Cu. The quantitative variability of LWC is determined as a function of the data sampling rate. The vertical dependence of LWC is found. The presence of adiabatic liquid water content (LWCa) is quantified in terms of parcel width and the probability as a function of height above Cu base. These findings are compared to the popular notion of "adiabatic cores", which are thought to exist in some Cu at heights up to 1 km or 2 km above cloud base, and with widths of hundreds of m. Spectral analysis is done on the high-frequency LWC measurements, and is compared to thoughts on droplet inhomogeneities caused by gradients at mixing interfaces and by inertial effects. The dominant type of mixing following entrainment is described.

2. DATA CHARACTERISTICS

The output of the PVM on the C-130 was recorded by the aircraft's data system. The scaling constants for LWC and r_e channels, and the droplet size response of the PVM are given in (Gerber, et al 1994). High-frequency PVM data were made available by NCAR for 11 of the SCMS flights listed in Table 1, which includes estimates of the height, pressure, and temperature of the lifting condensation level (LCL). The LCL was established with an uncertainty of about +/- 50 m by combining forward-looking video views of the Cu from the aircraft with downward calculations of LWC profiles from LWC measurements made about 100 m above cloud base and in updrafts. The mean cloud-base temperature for each flight varies over a small range for the 11 flights making it possible to reference all flights to the same cloud base, which is given by the parameters for flight 12 in Table 1. The resulting data base consists of 602 Cu traversed at various levels by the C-130, a total incloud distance of about 350 km, and 3.5 x 10^6 individual LWC measurements.

Table 1 *- Mean cloud-base conditions for flights of the NCAR C-130 during SCMS.*

Flt.	Date	Pressure (mb)	Temp. (C)	Ht.above surface (m)
4	7/22/95	955	23.8	490
5	7/24/95	924	23.0	747
6	7/26/95	958	23.0	465
8	7/28/95	953	23.4	580
11	8/4/95	957	23.0	474
12	8/5/95	960	23.2	450
13	8/6/95	958	22.9	457
14	8/7/95	948	22.3	411
16	8/10/95	959	23.0	458
17	8/11/95	960	23.2	444
19	8/13/95	966	23.5	399

3. SPATIAL VARIABILITY OF LWC

The variability of LWC in SCMS Cu depends on the rate at which LWC is measured. Figure 1 shows 1000-Hz and 1-Hz mean LWC data for a pass through a small Cu 885 m above cloud base. The high-resolution data show the typical complexity found in the Cu, while the 1-Hz data lose much of the detail. The 1000-Hz data show small portions of the Cu near time = 2.5 s where LWC approaches within 5% of the predicted LWCa. The low rate LWC data do not see this peak. This illustrates that 1-Hz LWC data is unreliable for identifying cloud parcels with LWCa. The average ratio for all Cu of the maximum LWC 1000-Hz data to the maximum LWC 1-Hz data found in each cloud is 1.41.

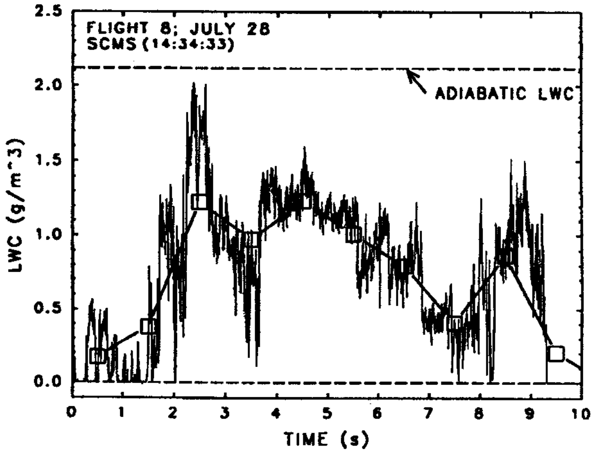

Fig. 1 *- Comparison of 1000-Hz and 1-Hz LWC data (squares) measured by the PVM in a SCMS cumulus cloud.*

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Figure 2 shows the vertical variability of the average LWC measured in each of the 602 Cu. The data follow the trend of the average LWC measured for Cu by Warner (1955). Also shown are LWC measurements at 1000 Hz in 10% of the Cu with largest values of LWC at given height intervals above cloud base. The good agreement of the largest values of LWC with the calculated adiabatic profle, at least up to a height of about 1000 m, suggests that the PVM measurements are physically meaningful, because measured LWC should not exceed the adiabatic value, yet should be equivalent to LWCa in portions of the Cu, especially near cloud base.

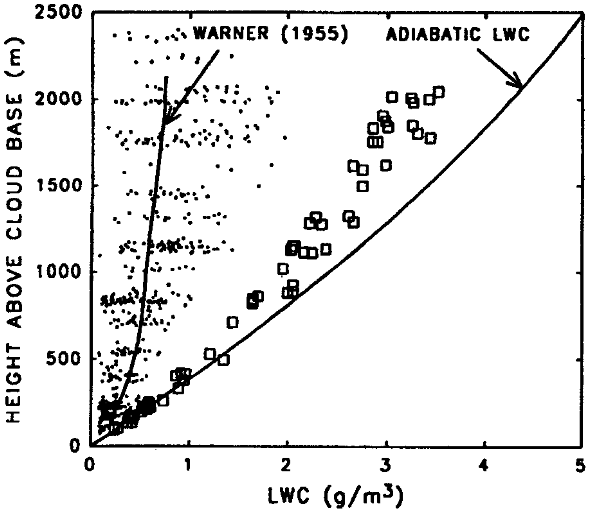

Fig. 2 - LWC in 10% of the Cu with the largest values of 1-kHz LWC (squares), and mean LWC (dots) in all Cu as a function of height above cloud base.

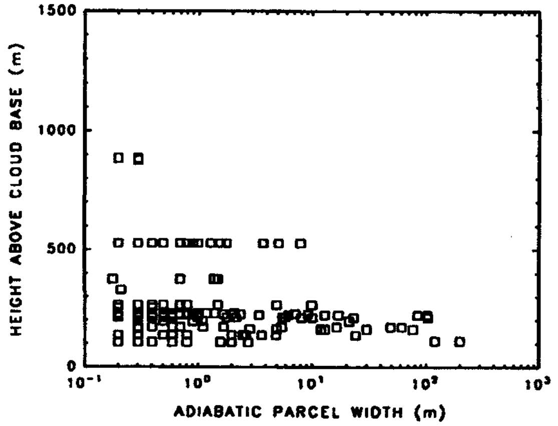

Fig. 3 - Adiabatic LWC parcels found in all Cu as a function of parcel width and height above cloud base.

The good agreement in Fig. 2 permits us to search the data base for the presence of cloud parcels with LWCa. Figure 3 shows the width of all the adiabatic parcels that were found as a function of height above cloud base; the criterion used for the presence of adiabatic water was that measured LWC was within +/-10% of predicted LWCa. The maximum width of the adiabatic parcels near cloud base is on the order of 100 m, smaller than 8 m at 500 m, and no more than 30-cm wide at 900 m. All Cu data and the data in Fig. 3 are used to calculate the probability of finding LWCa as a function of height. The results, given in Fig. 4, show a rapid decrease in the probability as height increases, with none above a limit of 900 m. This limit shows good agreement with the laboratory work of Johari (1992), where a bubble of buoyant fluid rises in a tank to a level above which all of the fluid is mixed with at least some ambient fluid in the tank.

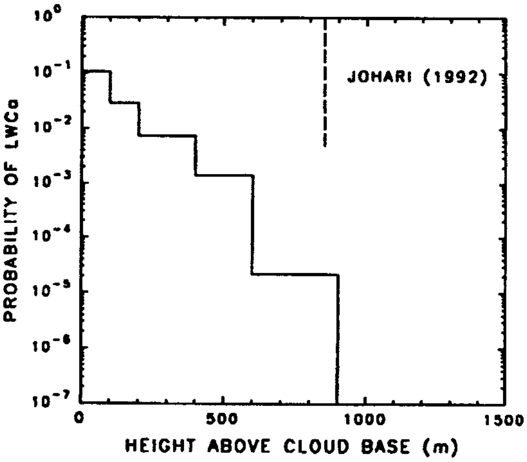

Fig. 4 - Probability of finding adiabatic LWC as a function of height above cloud base.

The results shown in Figs. 2 - 4 are inconsistent with the concept of "adiabatic cores", where some much wider and higher cloud parcels are thought to contain LWCa. The SCMS Cu entrain ambient air more effectively than expected, resulting in low probabilities and small parcels of LWCa except near cloud base. We conclude that the present concept of "adiabatic cores" is questionable, and does not apply to small Cu.

This conclusion carries the burden of showing that the previous publications that have claimed the presence of "adiabatic cores" are in error. A review of pertinent publications (Cooper 1978; Heymsfield et al. 1978; Paluch 1979; Boatman and Auer 1983; Jensen 1985; Jensen et al 1985; Raga et al. 1990; Cooper et al. 1996; Knight and Miller 1998; Lawson and Blyth 1998; Brenguier 1998; Brenguier and Chaumat 1999) finds potential problems with their claims of having observed "adiabatic cores". These problems include one or more of the following: use of 1-Hz or other low-rate LWC data, use of indirect methods to infer LWC, use of overestimates in cloud-base height, and the inability to measure accurately LWC or incloud temperature.

These results suggest that the Cu are less buoyant than expected, and raise the possibility that the unexplained residual droplet spectral broadening (e.g.,see Chaumat and Brenguier 1999; Vaillancourt and Yau 2000) is a result of the interaction between LWC gradients in the cloud caused by entrainment and vertical mixing as described by Cooper (1989).

4. SMALL-SCALE VARIABILITY

The 10-cm and larger resolution of the PVM LWC measurements during SCMS show that droplet-free voids in Cu are rare except near cloud boundaries. The data do show, however, that the variability of LWC at scales smaller than several meters is often larger than expected for clouds with fully developed turbulence (Davis et al. 1999; Gerber et al. 2000). This is evident from the spectral analysis of the LWC data, where the spectral density (or variance) of the data is determined as a function of frequency (or scale of the cloud parcels). Figure 5 shows examples of such analyses for three Cu. At scales smaller than about 2 m - 5 m, the LWC variance starts to exceed that predicted by the -5/3 scaling law. Similar results were seen earlier by Rodi et al. (1992) using droplet-concentration measurements. The explanation of the enhanced variability at small scales in some Cu is likely tied to the entrainment and mixing processes, which others (Baker 1992; Brenguier 1993) have suggested cause sharp droplet gradients at scales smaller than several cm. Droplet inertial effects (Pinsky and Khain 1997; Shaw et al. 1998) might be another reason for such small gradients. The time evolution of turbulence in the Cu may broaden sharp droplet gradients and result in the effects shown in Fig. 5.

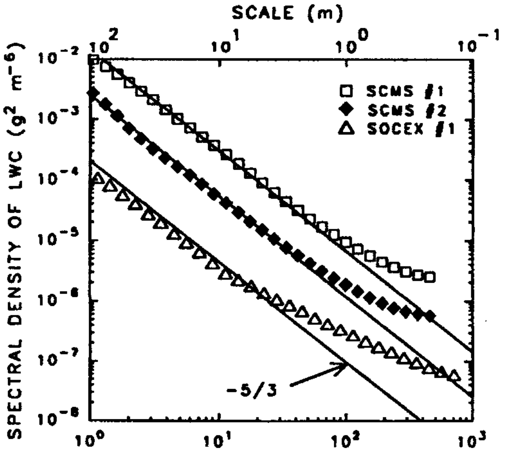

Fig. 5 - Power spectra of LWC in three cumulus clouds as a function of scale and frequency.

5. ENTRAINMENT AND MIXING

The value of LWC depends on droplet size and concentration. By looking at the two dependencies separately it is possible to infer the prevalent mixing process in warm Cu with insignificant coalescence and precipitation. Austin et al. (1985) showed that the large droplet concentration was closely related to LWC. Paluch (1986) found that at a given level the droplet size at the peak of the size spectrum for such Cu remained nearly constant, while droplet concentration changed over a large range. A similar result (Blyth and Latham 1991) in Cu showed nearly constant r_e values and large changes in LWC at a resolution of 10 m. These findings suggest that mixing following entrainment is of the inhomogeneous type. We repeated the analysis of Blyth and Latham (1991) of r_e vs LWC using the PVM data at a resolution of 40 cm. Figure 6 gives results for one pass through a SCMS Cu, which shows again the near independence of r_e on LWC.

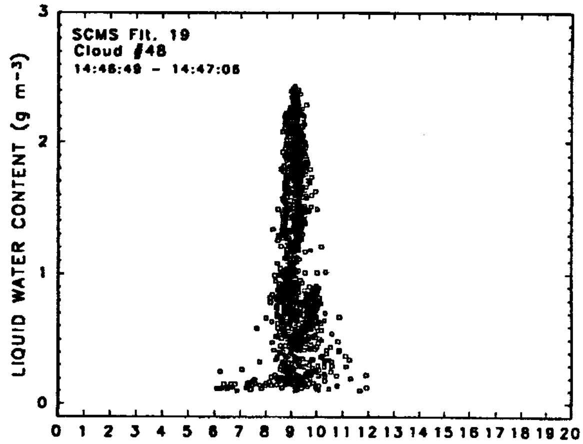

Fig. 6 - Liquid water content as a function of the effective radius of cloud droplets in one Cu pass.

We can estimate the quantitative dependence of LWC on droplet size and concentration (N) in the following manner (Gerber et al. 2000). If we assume that LWC $\propto$ N r_e^3, the PVM measurements can be used to estimate this dependence for each factor that makes up the expression for LWC; N is given by the PVM measurement consisting of LWC r_e^{-3}. Figure 7 compares r_e^3 and N calculated in this manner for one Cu, and shows again that changes in LWC are dominated by changes in the droplet concentration rather than changes in size of the droplets that contribute most to LWC and r_e. We conclude that the mixing at 40-cm resolution in the cloud is also primarily inhomogeneous, where the Cu are diluted by total evaporation of cloud parcels following entrainment. The droplets activated near cloud base and grown to the largest sizes by condensation appear to dominate LWC as well as the value of r_e at any given level of the Cu.

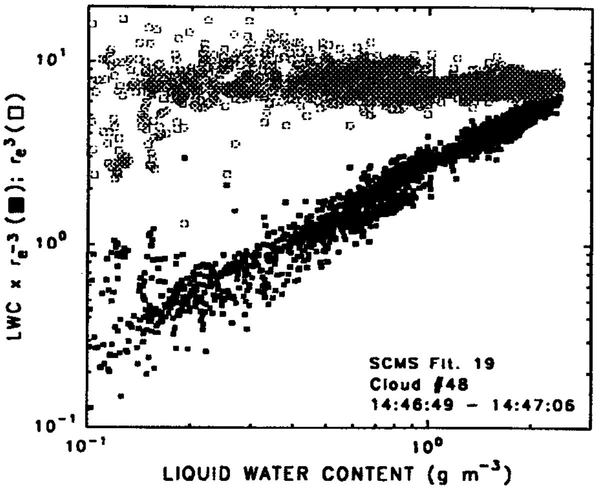

Fig. 7 - Relative change in the droplet concentration given by LWC/ r_e^3, and r_e^3 as a function of LWC in one Cu pass.

6. ACKNOWLEDGMENT

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