Spectral Density of Cloud Liquid Water Content at High Frequencies

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ABSTRACT

Aircraft measurements of liquid water content (LWC) made at sampling frequencies of 1 and 2 kHz with a particle volume monitor (PVM) probe from horizontal traverses in stratocumulus clouds during the Southern Ocean Cloud Experiment and cumulus clouds during the Small Cumulus Microphysics Study are described. The spectral density of the LWC measurements is calculated and compared to the −5/3 scaling law. The effect of PVM sampling noise is found to be small in most cases. Most measurements follow approximately the −5/3 law until cloud scales decrease below about 5 m in length. Below this length LWC variance can exceed that predicted by the −5/3 law. It is suggested that the enhanced LWC variance at small scales is related to entrainment of environmental air into the clouds, which changes primarily the droplet concentration.

1. Introduction

A recent paper by Davis et al. (1999) describes the behavior of the power spectrum (or spectral density) of liquid water content, LWC, as a function of the horizontal scale (or frequency) in stratocumulus-type clouds (Sc). These measurements, made with a particle volume monitor (PVM-100A; Gerber et al. 1994) on the CSIRO Fokker F27 aircraft during the phase 1 Southern Ocean Cloud Experiment (SOCEX) experiment off the western coast of Tasmania (Boers et al. 1996) were unique in that the PVM produced 2-kHz LWC data corresponding to a minimum spatial resolution of 4 cm for an aircraft speed of 80 m s^{-1}. This rate is about two orders of magnitude faster than LWC data usually collected with other typical LWC probes such as the King hot-wire probe (King et al. 1978). The PVM measures LWC for droplets found in the size range from about 3- to 50-μm diameter.

Davis et al. (1999) found that the LWC spectral density of these high-frequency data scales approximately according to the −5/3 law over a scaling range from about about 10 m to 10 km, in basic agreement with earlier spectral analyses of LWC measurements made with a hot-wire probe (King et al. 1981). However, at scales of about 2–5 m, Davis et al. (1999) found a ‘‘scale break’’ where the spectral density of the LWC data transitioned from the −5/3 scaling regime to one with larger than expected LWC variance. The simulation by Davis et al. (1999) of the performance of the PVM resulted in the conclusion that the scale break was indeed a physical effect, and larger than the expected sampling noise. This simulation was done for a typical Sc droplet spectrum, and it included the geometry and response characteristics of the PVM. Davis et al. (1999) focus primarily on the statistical similarities and differences they

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uncover when comparing the large-scale behavior with its counterparts from the Atlantic Stratocumulus Transition Experiment (Davis et al. 1994) and the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (Marshak et al. 1997, 1998). They do not attempt to explain the excess LWC variance at small scales in terms of cloud microphysics, as we do here.

This paper has several purposes: 1) We discuss further the PVM statistical sampling noise, which has the potential of causing a similar ''scale-break'' effect; 2) we extend the spectral analysis of LWC to examples of 1-kHz LWC measurements made in cumulus clouds (Cu) during the Small Cumulus Microphysics Study (SCMS) in Florida in 1995 (e.g., see Knight and Miller 1998; Gerber 1999); and 3) we speculate on the physical nature and implications of the scale break, taking into account primarily work done with the Particle Spacing Monitor (PSM; Baumgardner 1986; Baker 1992) and the fast Forward Scattering Spectrometer Probe (FSSP) (Rodi et al. 1992; Brenguier 1993; Brenguier et al. 1998), as well as the theoretical work of Mazin (1999).

2. PVM sampling noise

The PVM sums up optically the contribution of light scattered by droplets passing through its active volume. The summation is proportional to LWC, because the instrument weights the scattered light from each droplet by the droplet's radius (r) cubed. The variation in the measured values of LWC has two sources other than instrumentation error. The first is the natural variability of LWC in clouds, and the second is the variability due to the sampling error that results from measuring droplets randomly distributed in space with the PVM that has a finite sampling volume. The proper measurement of the natural variability requires that the sampling noise is taken into account.

The sampling noise depends on the geometry of the sampling volume and on the electronics of the PVM, both of which are known. A laser beam 11.4-cm long and 0.37-cm wide oriented perpendicular to the flight direction gives a projected area of about 4.2 cm^2 that sweeps out a slablike volume. The length of the slab depends on aircraft speed and on the characteristics of a low-pass electronic filter located at the analog output of the instrument. A filter cutoff frequency (50% response) of 2 kHz and an aircraft speed of 80 m s^{-1} used in the SOCEX experiment give a slab length of about 4.0 cm and sampling volume of 16.8 cm^3; and a cutoff frequency of 4 kHz and an aircraft speed of 100 m s^{-1} used in the SCMS experiment give a slab length of about 2.5 cm and a sampling volume of 10.6 cm^3.

The sampling noise also depends on the concentration, size distribution, and spatial distribution of the droplets. The effect of this noise on the $-5/3$ scaling law for LWC can be readily calculated for the simplest scenario, which assumes that the droplets are all of the

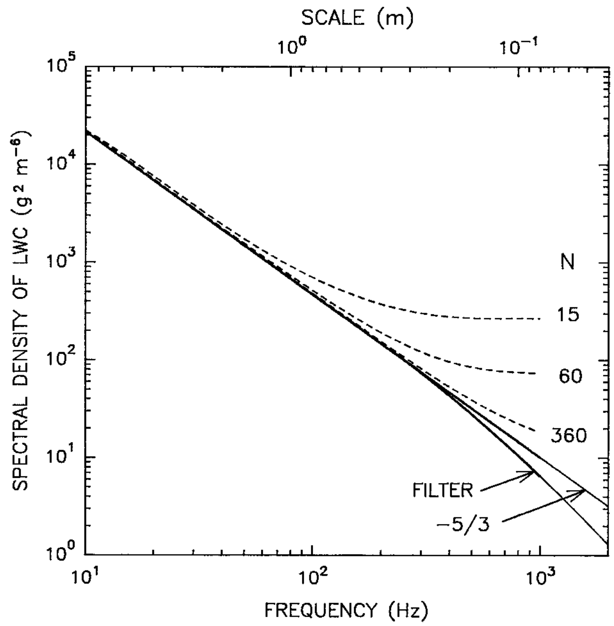

FIG. 1. Predicted statistical sampling noise (dashed curves) in the spectral density of LWC for N number of monodisperse droplets in the sampling volume of the PVM. The variability of LWC follows the $-5/3$ scaling law (straight solid line), and the droplets are spatially distributed according to the Poisson law. The effect of the low-pass filter in the PVM is also shown (see text).

same size, their concentration is known, and their spatial distribution is governed by the Poisson law. Figure 1 shows this effect as a function of the droplet number N found in the sampling volume of the PVM, where N is given by the ambient droplet concentration (cm^{-3}) times the PVM sample volume (cm^3) (here the sample volume corresponds to the SOCEX measurements). The curves in Fig. 1 were generated by using MATHCAD 6 software to perform an inverse Fourier transform of the $-5/3$ relationship into the time domain, where noise generated by a Gaussian random number generator for the given values of N was added. For N greater than 10, Gaussian and Poisson random number generators produce nearly equal results. The time domain data were then transformed back to the frequency domain to produce the curves in Fig. 1, with each curve showing the average trend of 10 000 data points. The curves show increasingly larger deviations from the $-5/3$ scaling as N decreases and they tend toward horizontal at small scales, which is the expected behavior of ''white noise'' caused by the sampling error governed by Poisson statistics. The low-pass filter has an additional effect on the $-5/3$ relationship as Fig. 1 shows for the 2-kHz filter.

The predictions of the sampling noise shown in Fig. 1 may be applicable only for the parts of clouds that have not mixed with any environmental air, resulting in an adiabatic LWC and a narrow droplet size spectrum with small size variability. The PVM sampling error for this type of cloud should obey the simple scenario described above, an example of which is shown in Fig. 1 of Gerber (1999). The remainder of the clouds have entrained and mixed with cloud-free air causing fine-scale microphysical gradients at mixing interfaces, larger-scale microphysical variations, and broadened droplet spectra. These effects need to be considered at scales similar to the dimensions of the PVM, because they have the potential of increasing the PVM sampling error from values shown in Fig. 1.

The effect of the width of the droplet spectrum on the sampling noise can be estimated as in Davis et al. (1999) where the number concentration in each size bin of the spectrum is effectively treated as a random variable with its own Poisson variability and where the sampling noise of the measured LWC is found by combining the variabilities in all bins. Davis et al. (1999) use in their simulation one value of the standard deviation and mean droplet size of a droplet spectrum thought to be typical for Sc, and they state that their results remain unchanged within the observed range of Sc spectra. Here, we follow a similar approach for estimating numerical values of the sampling noise as a function of the droplet spectral dispersion $\alpha = \sigma(r)/\overline{r}$, where $\sigma(r)$ is the standard deviation of the normally distributed droplet size distribution and $\overline{r}$ is the mean droplet radius. The same procedure used in Fig. 1 for deriving the sampling noise is applied to a wide range of different normal distributions with size bins that have Poisson variability in droplet concentration. As expected, at a given value of N and $\overline{r}$, the LWC sampling noise for the normal distribution is larger than for the monodisperse distribution. To judge the difference between the results shown in Fig. 1 and the calculations with the normal size distributions, we define N_e as the hypothetical number of droplets in a normal distribution with the same Poisson sampling error as in a monodisperse distribution with N in the sampling volume of the PVM. We find to a good approximation that $N_e/N \approx \exp(0.150 - 2.06\alpha)$. This equation means that the sampling noise for normal distributions must be calculated using N_e given values of N and α. A typical value of α for Sc is 0.13 (Gerber 1996) giving $N_e/N = 0.89$; and a typical value of α in nonadiabatic SCMS Cu about 1 km above cloud base is 0.20 giving $N_e/N = 0.77$. These values of N_e/N suggest that the assumption of using a monodisperse distribution to calculate the PVM sampling noise requires only a second-order correction for LWC measurements. The correction only becomes large when N is very small or when very large droplets are found in the size distribution. The latter is unlikely given the upper-size cutoff in the response of the PVM.

The preceding assumes that the statistical variability of the measured LWC is found only in the number concentration of the droplets. Another possibility is that the statistical variability is also significant for the size of the droplets. Measurements in clouds made at relatively large scales show this to be possible, but it appears to be a second-order effect compared with variability in

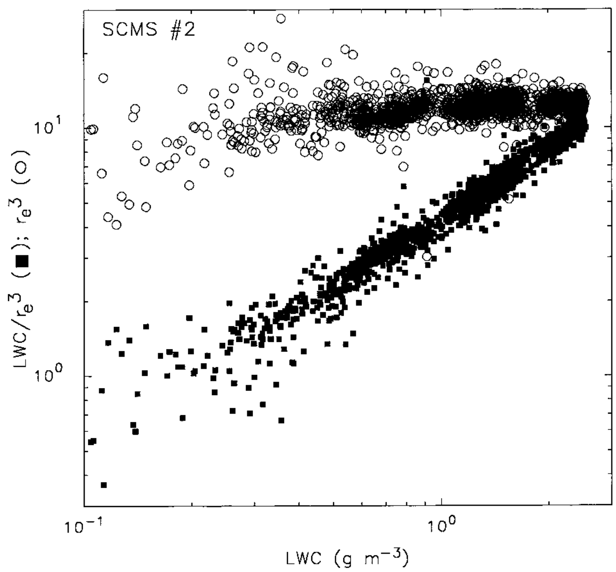

FIG. 2. The relative concentrations of cloud droplets estimated by LWC/r_e^3, and relative values of r_e^3 as a function of LWC measured simultaneously at 250 Hz (40-cm resolution) by the PVM in Cu cloud-pass SCMS #2 on 22 Jul 1995. No attempt has been made to identify and exclude 250-Hz samples that are part cloudy, part clear air.

the droplet concentration. For example, Nicholls and Leighton (1986) show entrainment in Sc causes only a dilution while essentially preserving the relative shape of the spectrum; and Blyth and Latham (1991), Bower et el. (1992), and Gerber (1996) find strong variability in LWC while the droplets' effective radius (r_e) remains nearly constant. We used the PVM data from SCMS to look at the relationship between LWC and r_e at 40-cm resolution (250 Hz) at constant flight levels; and we also find nearly unchanging values of r_e for widely ranging values of LWC. If we assume that LWC $\propto Nr_e^3$ [r_e and the mean volume radius r_v are related as shown by Martin et al. (1994) and Gerber (1996)], it is possible to estimate which of the two factors that make up this expression for LWC has the larger effect on its variability. The measurements in SCMS Cu of the relative changes in r_e^3 and $N \propto \mathrm{LWC}r_e^{-3}$ show that the variability of LWC depends primarily on changes in N, which varies more than r_e^3 by as much as a factor estimated at 15. Figure 2 shows an example of this behavior; the data are from cloud-pass SCMS #2 described in the next section. It is not known whether this behavior holds for the smallest scales depicted in Fig. 1; however, the 40-cm resolution falls within the 2- to 5-m scale size of the scale break suggesting that the variation in droplet number affects the LWC variation much more than the variation in droplet size for scales at least 40 cm in length.

These arguments also assume that the spatial distribution of the cloud droplets is governed by the Poisson law. This may not be the case, which leads to additional uncertainty in the calculation of the sampling noise at

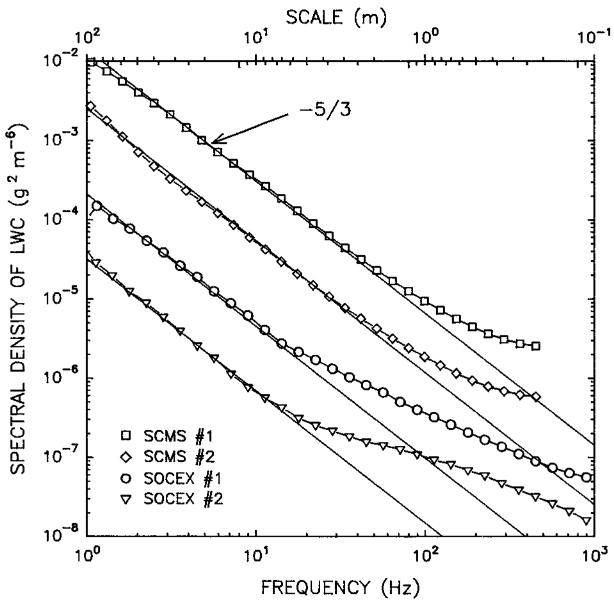

FIG. 3. Relative values of the spectral density of LWC measured during horizontal passes through two clouds in the SOCEX and in the SCMS experiments are compared to the $-5/3$ scaling law. Shifted scales shown on the SCALE axis apply to the SCMS aircraft speed of 100 m s^{-1} (upper scale) and to the SOCEX aircraft speed of 80 m s^{-1} (lower scale).

the smallest scales measured by the PVM. Sharp droplet-concentration gradients attributed to the entrainment and mixing process have been found in Cu (Baker 1992; Brenguier 1993), and similar gradients as well as droplet voids have been theorized (Pinsky and Khain 1997; Shaw et al. 1998) to result from droplet inertial effects. These processes would tend to enhance the sampling error, because the spatial variability of the droplets would exceed that predicted by the Poisson law. Not enough is known about the spatial frequency of these processes to be able to include their effect in calculating the sampling error. We suggest, however, that their effect is small, because the dimensions of the PVM sampling volume are large enough to average out the variability from these processes for which scales on the order of 1 cm and smaller predominate.

In summary, the calculation of the statistical sampling noise for PVM measurements of LWC is not entirely straightforward, because the details of droplet spectra and spatial distribution at scales similar to the dimensions of the PVM sampling volume are not fully known. In the following application of the sampling noise calculations, we assume that the Poisson distribution of the ambient droplet concentration and the width of the size spectrum affect the noise the most, and that the other potential contributions mentioned in the preceding are of secondary importance.

3. Measurements

Figure 3 shows four examples of LWC spectral density versus frequency and scale from the SOCEX and SCMS experiments. All are compared to the $-5/3$ scaling law. The largest frequency shown is equivalent to the Nyquist frequency of 1 kHz for the former and 0.5 kHz for the latter. The two SOCEX cases are from the flight on 26 July 1993 when the cloud field contained microcells (Kropfli and Orr 1993), where isolated cumulus clouds in a decoupled boundary layer were feeding moisture to a broken Sc layer formed by outflow from the Cu near the boundary-layer inversion. In a cloud labeled SOCEX #1 [11:51:34–11:51:54 (hr:min:s) local time] the aircraft flew horizontally through the top of an embedded Cu that was protruding above the associated Sc layer. Figure 4 shows the 2-kHz record of LWC for this cloud pass, which produced 19 300 values of LWC that were averaged over equal geometric

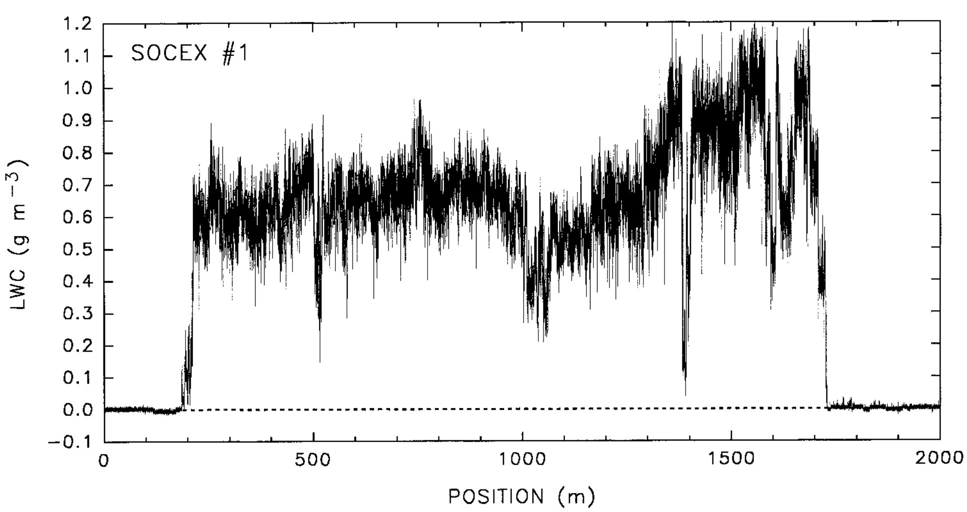

FIG. 4. LWC measured with the PVM at a data rate of 2 kHz for the cloud pass identified as SOCEX #1 in Fig. 3.

intervals of frequency. The mean ambient droplet concentration in this Cu was 91 cm^{-3}, which is equivalent to about $N = 1500$ in the sampling volume of the PVM. Figure 1 suggests that the sampling error for this value of N should be small enough that no correction is needed.

In a cloud labeled SOCEX #2 (11:15:13–11:15:38) the aircraft flew through Sc associated with the microcells, and 25 000 LWC data points were collected. The ambient mean droplet concentration was about 10 cm^{-3}, leading to $N \approx 170$. Figure 1 suggests that this value of N results in some Poissonian sampling error as the frequency approaches 1 kHz. This error was calculated as a function of frequency for $N_e = 150$ and was subtracted from the measured LWC power spectrum to result in the spectrum shown in Fig. 3. A small adjustment was made to both SOCEX #1 and #2 spectra to compensate for the loss of spectral density at high frequencies due to the action of the low-pass filter.

The two SCMS cases were taken from the NCAR C-130 flight number four on 22 July 1995. Both were horizontal passes about 1.3 km above cloud base through relatively small, isolated, and nonprecipitating Cu, where LWC approached the adiabatic value in portions of each cloud, and where the mean droplet concentration was about 400 cm^{-3}. The cloud labeled as SCMS #1 (15:11:14–15:11:19) had 4000 LWC data points, and the cloud labeled as SCMS #2 (15:19:59–15:20:08) had 9000 LWC data points. This droplet concentration leads to large values of N so that no corrections to the measured power spectra are necessary for the sampling error. Also, no adjustments were made for the low-pass filter, given the smaller effect of the 4-kHz 50% attenuation frequency. The out-of-cloud variance of the noise in the output signal from the LWC channel of the PVM was much smaller than the LWC variance measured in all of the clouds.

4. Discussion

The shape of the spectrum in Fig. 3 for the Sc is the same as described by Davis et al. (1999) where the LWC variance exceeds that predicted by the $-5/3$ law at scales smaller than about 5 m. One of the Cu in Fig. 3 shows a similar trend, while for the other two the excess variance begins at about 2 m. We also found that some passes through Cu showed little enhancement of LWC variance at small scales so that the $-5/3$ law is obeyed reasonably well over the entire range of scales shown in Fig. 3. This is a significant finding that differs from the results in Sc (Davis et al. 1999). The obvious question exists: what is the physical reason for the two LWC scaling regimes observed in the Sc and Cu?

A potential reason might be related to the formation of small-scale microphysical gradients in the clouds due to entrainment and mixing of the clouds with environmental air. Experimental studies of these gradients at small scales include that of Baker (1992), who used the PSM (Baumgardner 1986) and a statistical ''fishing test'' of droplet arrival times at the probe to deduce that, at scales on the order of a cm, the droplet spatial distribution was not always governed by the Poisson law, but was consistent with the existence of sharp droplet-concentration interfaces associated with the entrainment and mixing processes. Similar conclusions were reached by Brenguier (1993) who used the fast FSSP (Brenguier et al. 1998) at 1 kHz to show that sharp sub-cm gradients existed in the droplet concentration near cloud edge. Other reasons for the presence of microphysical gradients in clouds have also been described in the literature. These include nonuniform activation of droplets near cloud base (Nicholls and Leighton 1986; Cooper 1989; Srivastava 1989), mixing between parcels in cloud updrafts with vertical velocity variance (Cooper 1989), droplet inertial effects in turbulence fields (Pinsky and Khain 1997; Shaw et al. 1998), and effects due to larger drops (Kostinski and Jameson 1997; Jameson et al. 1998).

Most of these processes cannot be used to explain the present LWC scaling results. Processes that contribute to the LWC variance at cm and smaller scales do not apply; because, as mentioned, the dimensions of the PVM sampling volume are significantly greater than those scales, so that the PVM averages out such finescale fluctuations. Thus, the sharpest microphysical gradients found by Baker (1992) and Brenguier (1993) at sub-cm scales would not appear in PVM data. However, both authors found in addition microphysical fluctuations in mixing regions with scales on the order of meters, which are consistent with the PVM measurements. The theoretical work of Pinsky and Khain (1997) and Shaw et al. (1998), where cloud inhomogeneities are predicted to exist at cm and mm scales, would not apply to the PVM scaling results. Measurements of 1-kHz LWC PVM data in the SCMS Cu (Gerber 1999) suggest that LWC variability due to cloud-base droplet activation (Nicholls and Leighton 1986; Cooper 1989; Srivastava 1989) and the in-cloud mixing in updrafts with velocity variance (Cooper 1989) are also unlikely to apply to the above question. This is because LWC variability found in adiabatic cloud parcels is close to the expected amount for droplets varying spatially according to the Poisson law, and thus does not include an excess variability that could be assigned to those two processes. The application of the studies by Kostinski and Jameson (1997) and Jameson et al. (1998) to our results is also doubtful, because they deal primarily with the raindrop spatial distribution in the former and the distribution of 50-μm diameter droplets in the latter. The 50-μm drops contribute a minimal amount to LWC measured by the PVM, and the raindrops are beyond the measurement range of the PVM. Both sizes are large enough so that their spatial variability may be influenced more by other physical in-cloud processes (e.g., coalescence and droplet breakup) than those affecting the small-droplet mode measured by the PVM.

The present scaling results for LWC can be best compared with the experimental work of Rodi et al. (1992). They used the fast FSSP to make 1-kHz droplet concentration measurements in a Cu, and they showed (in their Fig. 5) a power spectrum of droplet concentration that bears a remarkable resemblance to the trends of the LWC spectra shown in Fig. 3. They concluded that concentration changes at small scales due to entrainment and mixing caused the enhanced variance that could not be explained by ''white noise.''

We agree with the conclusion reached by Rodi et al. (1992). However, this conclusion does not completely answer the question posed above. The following hypothesis may possibly explain the observations. The LWC spectra for some SCMS cloud passes containing subadiabatic LWC follow quite closely the $-5/3$ law, and this suggests that the turbulence is fully developed in those clouds over the scales observed. On the other hand, in cloud passes with LWC variance at small scales enhanced above the expected $-5/3$ behavior, the assumption of a global turbulence system, usually applied for spectral scaling, is not met. That is, we observe in the spectra from these cloud passes the effects of mixing of more than one turbulence system. One system might be an older ascending cloud mixing with a fresh injection of entrained air. If the largest scales in the entrained air are limited in size, and if their LWC variance is greater than the LWC variance in the ascending air, the shape of a LWC spectra of the mixture should be similar to the ones we show in Fig. 3.

This hypothesis is related to some other concepts of cloud structure. Entrainment events are thought by some to occur sporadically and initially on fairly large scales (Broadwell and Breidenthal 1982; Baker et al. 1984), which subsequently break down to smaller eddies by the dissipation of turbulence. If this mechanism operates in Cu, then the $-5/3$ scaling behavior of LWC found for some SCMS Cu might be possible, given the evolution of turbulence between entrainment events. Another means may exist to introduce enhanced finescale LWC variability into Cu. Radar measurements (Knight and Miller 1998) of SCMS Cu show finescale variability in a shallow layer near cloud top of some growing Cu, and Brenguier (1993) finds small-scale variability near the cloud edge. Given the conceptual models of Cu growth described by Blyth et al. (1988) and Siebesma (1998), it may be possible for some of this finescale variability to advect into the cores of Cu. We know that scales associated with entrainment events for Sc are limited in size as shown by Nicholls (1989) and Gerber (1996); however, the form of the spectral density distribution of LWC associated with those events is unknown.

It is worthwhile mentioning that deviations in the spectral density of LWC from the $-5/3$ scaling law were predicted theoretically much earlier by Kabanov and Mazin (1970) and reiterated by Mazin (1999). They showed that the condensation and evaporation processes in a turbulent cloud would cause power spectra to deviate from the $-5/3$ law at scales smaller than a ''phase scale'' that depended on the turbulence dissipation rate in the cloud and on the phase relaxation time (time for saturation in a mixed parcel to relax to its steady state). Mazin (1999) shows that such a scale-break in LWC would occur for length scales of the order of 10 cm–5 m. Mazin's arguments thus predict the scale where excess variance may be found, but not the magnitude of this excess.

5. Conclusions

We conclude, as in Davis et al. (1999), that the enhanced LWC variance observed in the spectral density of LWC in Sc at high frequencies, corresponding to scales smaller than several meters, is a physical phenomenon rather than the result of the statistical sampling error associated with PVM measurements. We find a similar phenomenon in Cu, although in some Cu the $-5/3$ law approximates the LWC spectra over the entire measured range. The sampling error of the PVM, associated with the spatial distribution of the droplets, is of secondary importance except for unusually small ambient concentrations of droplets.

We cannot explain with certainty our observations of the ''scale break'' and of the two scaling ranges in the spectral density of LWC. Instead we hypothesize that the enhanced LWC variance at small scales, which exceeds the extrapolation of the $-5/3$ scaling behavior found at larger scales, is a result of the mixing of existing cloud air with entrained air that is younger, more energetic, and with scales limited in size to a fraction of the existing cloud.

A suggested test for this hypothesis would consist of conditionally sampling entrainment zones in Sc that can be readily identified (Nicholls 1989; Gerber 1996; Vali et al. 1998), and by comparing LWC spectra in those zones to spectra measured in the rest of the cloud.

This work applied the high-speed capabilities of the PVM to a study of cloud microphysics associated with the entrainment process. The full potential of such measurements is far from being fully realized, so that further analysis of the SCMS PVM database and additional such measurements could well improve our marginal understanding of this process.

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