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16B.1 COHERENT PARTICLE SCATTER IN DEVELOPING CUMULUS CLOUDS

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1. INTRODUCTION

Two mechanisms important for the interpretation of radar observations of the atmosphere, are: coherent scattering from refractive index fluctuations of the clear-air and incoherent scattering from particles. These scattering mechanisms have very different wavelength dependencies and their contributions to the radar return can be separated by using two radars with different wavelengths. A difference of 0 dB or 19 dB in the radar reflectivities is expected when both returns are dominated by incoherent scattering or coherent scattering, respectively. Recent observations of small developing cumulus clouds (Knight and Miller 1998) show a puzzling correlation: the S-band and X-band reflectivities cluster around a line, but with a difference of about 10 dB. In this paper, an explanation will be proposed in terms of coherent scattering from the droplets. The spatial fluctuations in liquid water content that cause the coherent scattering could be due to mixing with environmental air. It will be argued that fluctuations of water vapor content inside clouds can be much smaller than those in liquid water content, contrary to common belief.

The paper is organized as follows. Firstly, some theory on coherent and incoherent scattering is reviewed. The measurements will be discussed next and a new explanation is presented. A discussion follows in section 5.

2. INCOHERENT AND COHERENT SCATTERING

The radar reflectivity for incoherent scattering from independently moving particles that are much smaller than the radar wavelength, is given by:

$$\eta = \pi^5 |K|^2 N D^6 \lambda^{-4} \qquad (1)$$

where $|K|^2$ is about 0.93 for water, for the wavelengths of interest here. N is the particle concentration, D is the diameter and λ is the radar wavelength. For ease of notation it is assumed that all particles have the same diameter. The radar reflectivity due to coherent (Bragg) scattering from spatial fluctuations in refractive index, is given by (Ottersten 1969):

$$\eta = 0.38 C_n^2 \lambda^{-1/3} \qquad (2)$$

where it has been assumed that the "-5/3 law" for the one-dimensional spectrum of spatial fluctuations of a conservative passive additive (CPA) is valid, for the inertial subrange of homogeneous, isotropic turbulence (Tatarski 1961). The radar reflectivity factor is obtained by multiplying the radar reflectivity by $\lambda^4/\pi^5 |K|^2$.

3. MEASUREMENTS

Measurements of small, developing cumulus clouds show many interesting features (Knight and Miller 1998). The most important features will be discussed with help of Fig. 1. This figure shows measurements of a small, developing cumulus cloud. The top frame shows the radar reflectivity factor at S-band (10 cm wavelength) expressed in dB, denoted by DZS. The middle frame contains the radar reflectivity factor at X-band (3 cm, DZX) and the bottom frame their difference (DZS–X).

3.1 Mixing with environmental air; mantle echoes.

The DZS–X pattern shows the largest values near the sides and the top of the cloud. These large values show the importance of mixing between cloudy air and

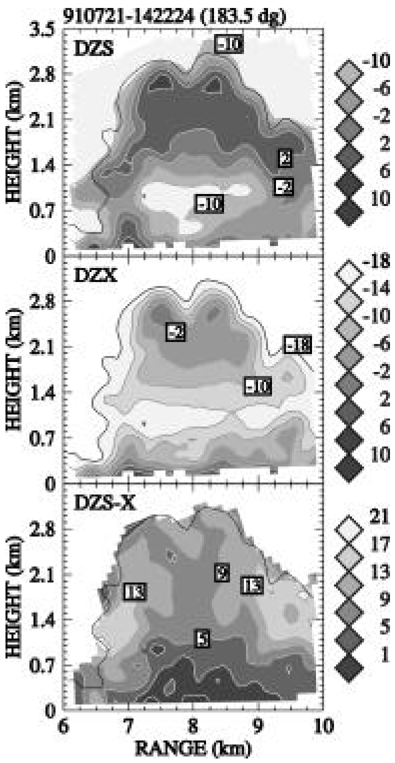

Fig. 1. An example of a developing cumulus cloud, showing a weak mantle echo, flat echo bases at X-band and a weak-echo region near cloud base. (Fig. 12 from (Knight and Miller 1998)).

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environmental air at the sides and the top of the cloud. The coherent scattering from water vapor fluctuations dominates DZS there. When the environmental air is dry, the contrast in water vapor concentration is large and a distinct mantle echo is visible at S-band. The intensity of this mantle echo is stronger when the environmental air is dryer. The mantle echo can sometimes be as thick as 1 km and fill the entire cloud top. In the early stages of development the droplets are still small and in that case the X-band return may also show a mantle echo. When both DZS and DZX are dominated by coherent scatter, the difference in reflectivity factors is close to 19 dBZ, the value predicted by theory. A peculiar thing is that it was quite common that DZS–X exceeded 19 dBZ in the mantle echo by several dB. One reason could be that the variations in humidity on the scale of half the wavelength at X-band, fall no longer in the inertial subrange and are reduced by dissipation. In this paper, an alternative explanation is proposed: the spatial spectrum of water vapor fluctuations may become steeper by the effects of condensation and evaporation, as will be explained in section 4.

3.2 weak-echo regions

The base of the cloud in Fig. 1 is probably somewhere between 400 m and 700 m. Near the cloud base, DZS shows a region with lower reflectivities. This region is called weak-echo region and is seen in nearly all the actively growing clouds. The bottom frame shows that this weak-echo region is a minimum in the coherent return at S-band. It is also sometimes present in the DZX pattern, but is then much less pronounced. The weak-echo region in DZS extends almost to the ground here.

3.3 Flat echo bases

The DZX pattern occasionally shows flat and horizontal echo patterns. Figure 1 shows a clear example of this. Here the DZS pattern also shows flat echo bases, but this is often not the case because of the mantle echoes. Knight and Miller interpret the flat echo bases as unmixed adiabatic ascent. If this interpretation is valid, an estimate of droplet concentration can be made.

3.4 Correlated radar returns

When both DZS and DZX are dominated by incoherent scattering from the droplets, the difference in radar reflectivity factor is close to 0 dBZ. When coherent scattering is strong enough to dominate also the X-band return, DZS–X reaches values close to 19 dBZ. In both cases one would expect similar patterns of reflectivity (i.e., a correlation in the reflectivities), because both returns are dominated by the same scattering mechanism. However, in many case there was a correlation between DZS and DZX, while the difference was somewhere in between 0 dBZ and 19 dBZ, a typical value was 10 dBZ. A strong example of this phenomenon is shown in Fig. 2. Figure 2(a) shows DZS, DZX and DZS–X, respectively, of another small cumulus cloud in development. Figure 2(b) shows a scatterplot of DZS versus DZX. For values of DZS greater than about 5 dBZ, the reflectivities correlate. For lower values of the reflectivities, the correlation may also be present, but could be hidden by the mantle echo.

We think that the phenomenon is due to coherent scatter from spatial variations in liquid water content. We suspect that the variations are caused by mixing with air from outside the cloud. The next section will explain this idea and a discussion will follow it.

4. COHERENT PARTICLE SCATTERING

The radar return from a volume with particles may have both an incoherent and a coherent component from the particles. Suppose there is mixing of air containing particles with particle-free air. Both the mean concentration and the amplitude of fluctuations in the mixing region will depend linearly on the initial concentration. Therefore, one can assume that the standard deviation of the mass concentration of particles is proportional to the mean mass concentration (the constant of proportionality will be denoted by β). The incoherent radar return will depend linearly on the initial concentration. The coherent return depends on the *variance* of the fluctuations and will therefore depend on the *square* of the initial concentration. Both the incoherent and coherent returns will depend on the diameter to the power of six. If it is assumed that the "-5/3 law" is valid and that there are no fluctuations on scales larger than the outer scale L_0 of the inertial subrange, then the total reflectivity factor can be written as (Erkelens *et al.* 1999)*:

$$Z(\lambda) = ND^6 + 2.44\times10^{-2} L_0^{-2/3} \beta^2 N^2 D^6 \lambda^{11/3} \qquad (3)$$

In addition to the coherent scattering from the particles, there can also be a coherent component from the fluctuations in clear-air refractive index.

The correlation visible in Fig. 2(b) could be caused by variations in droplet diameter, due to the growth of droplets in the ascent. The variations in the other parameters must be small. The scatter in Fig. 2(b) means that these variations are not allowed to vary more than about a factor 3. Rogers and Brown (1997) report a correlation between UHF and X-band radar measurements of the smoke of a large industrial fire. This correlation could be caused by variations in particle concentration (Erkelens *et al.* 1999).

There is large uncertainty in the values of β and L_0 and they may be related. VanZandt *et al.* (1978) used 10 m for L_0. Davis *et al.* (1996) found a value of 0.18 for the relative standard deviation of liquid water

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* This is the formula used here and in the IGARSS'99 paper. However, the numerical factor 2.44×10^{-2} is incorrect, it should be 4.2×10^{-3}. (correction: 20 July 1999)

content in marine stratocumulus clouds from FSSP measurements. These values may not apply to developing cumulus clouds, but they can give an indication of the droplet concentration needed to give DZS–X=10 dBZ. If DZS is dominated by the second

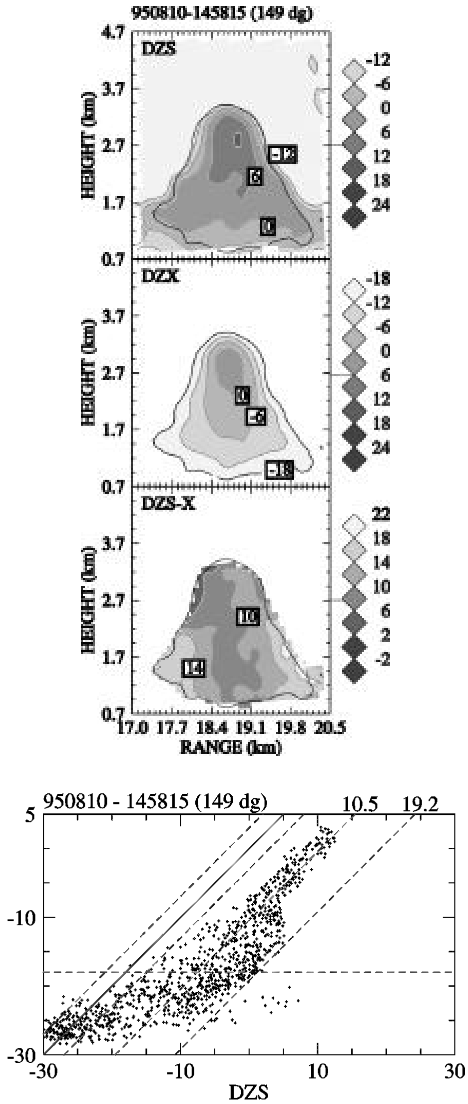

Fig. 2 (a). A developing cumulus cloud, showing a strong correlation between DZS and DZX, and a difference DZS–X of about 10 dBZ. (b) Scatterplot of DZS versus DZX. (Figs. 10 (c) and 11 (c) from (Knight and Miller 1998)).

term of (3) and DZX by the incoherent term, then a 10 dB difference is obtained when the droplet concentration is about 300 cm^{-3}. This value is lower than the value of 800-900 cm^{-3} as observed by Paluch *et al.* (1996) in similar clouds with an FSSP, but the order of magnitude is correct.

If the observed correlation is due to coherent scattering from fluctuations in liquid water content on centimeter-scales, then these fluctuations must be much larger than those in water vapor content in the core of the clouds. For, coherent scattering from fluctuations in water vapor content is about 30 times stronger as coherent scattering from equal fluctuations in liquid water content (Gossard and Strauch 1983).

Air outside the cloud does not contain droplets. If that air is very humid, then the fluctuations in water vapor caused by mixing with cloudy air may be smaller than those in liquid water content.

Fluctuations in water vapor content are removed by molecular diffusion. Molecular diffusion is more effective on smaller scales.

Diffusion of water droplets is absent. However, fluctuations in liquid water content may be removed by droplet sedimentation. The broader the droplet size distribution is, the larger are the differences between the fall velocities of the droplets and the more effective is sedimentation in removing variations in liquid water content.

Condensation and evaporation also influence fluctuations in water vapor content and liquid water content. Condensation and evaporation will always tend to bring the relative humidity toward 100% and is increasingly effective for increasing deviation from saturation. So, condensation and evaporation will *always* reduce fluctuations in water vapor content. The fluctuations in liquid water content are not necessarily reduced. If the spatial fluctuations in water vapor content are positively correlated with the fluctuations in liquid water content, then condensation and evaporation may even tend to increase the fluctuations in liquid water content.

All these processes can influence the strength of the fluctuations in water vapor content and liquid water content. Grabowski (1993) discusses several processes and gives estimates for their time-scales.

Due to the effects discussed above, fluctuations in liquid water content can exist for longer times than those in water vapor content and may be much stronger. They can therefore penetrate the cloud more deeply. Mixing could be effective over larger parts of the clouds than might be concluded on the basis of the thickness of the mantle echo. For, the mantle echo mainly represents the area where fluctuations in water vapor content contribute strongly to the S-band reflectivity. Its apparent thickness, however, depends on the contrast in humidity between the saturated cloudy air and the subsaturated environmental air and on the strength of the incoherent contribution.

An interesting effect of condensation and evaporation is that it may affect the slope of the spatial spectrum of water vapor and liquid water fluctuations. Water vapor content and liquid water content are not conservative passive additives (CPAs) and the "-5/3 law" may not be valid. For a CPA, the theory says that the fluctuations are passed on from larger scales to smaller scales and are removed by molecular diffusion. Condensation and evaporation tend to remove fluctuations in water vapor content. This will happen at all scales, but more strongly at larger scales, because the largest deviations from saturation appear at the largest scales. There will be an extra sink at all scales, so not all of the fluctuations will be passed on to smaller scales. This means that the water vapor spatial spectrum could show a steeper slope than that of a CPA. This is an alternative explanation to the occurrence of DZS-X values larger than 22 dBZ that were often observed in the mantle echoes.

5. DISCUSSION

An argument against mixing being the cause of the correlation between DZS and DZX, is the occurrence of flat echo bases at X-band. These are interpreted as unmixed adiabatic ascent. The weak-echo regions could also be an indication of that.

An argument in favor of mixing is that the correlation in Fig. 2 is strongest near the top of the cloud, where the scattering from droplets is largest. This is exactly the place where strong mixing is taking place.

An other argument against mixing is that any fluctuations in the parameters β and L_0 would decrease the correlation between DZS and DZX, if DZS is dominated by the second term of (3) and DZX by the first term. Also, variations in concentration would not lead to a slope of 1, but to a slope of 1/2 in scatterplots of DZS versus DZX. All the variations in β, L_0 and concentration should not be to larger than about a factor of 3, to explain the high correlation shown in Fig. 2(b). However, these variations would *all* lead to a slope of 1, if *both* DZS and DZX were dominated by coherent scattering. As pointed out by Knight and Miller, the 10 dBZ difference between DZS and DZX would mean then a significantly smaller difference in the fluctuation strengths at scales of half the radar wavelengths, than predicted by the "-5/3 law". If DZX would also be dominated by coherent scatter, the droplet concentration estimated from a scatterplot of DZX versus height, assuming an adiabatic liquid water profile, would be underestimated, because DZX is too large. In fact, the measurements suggest this. A concentration of about 100 cm^{-3} was found in one example.

Baker (1992) found indications in FSSP data of centimeter-scale fluctuations in droplet concentration, and homogeneity at larger scales. It could be that fluctuations in liquid water content are not caused by mixing but by some other mechanism. One such mechanism could be the one proposed by Pinsky *et al.* (1999). They present a model that predicts fluctuations in droplet concentration on centimeter scales, due to the inertia of the droplets. It is not known at present whether or not their model can explain the observations.

6. CONCLUDING REMARKS

An explanation is proposed for a puzzling correlation in dual-wavelength radar measurements of developing cumulus clouds: coherent scatter from fluctuations in liquid water content. It has been argued that the fluctuations could be caused by mixing with environmental air, but other explanations are also possible. It has also been argued that spatial fluctuations in water vapor content are damped in clouds due to condensation and evaporation and this may lead to a spectrum which is steeper than –5/3. There are indications that both S-band and X-band reflectivities are dominated by coherent scattering. Most of the phenomena that are discussed can be explained in more than one way. It is our belief that progress in the understanding of what happens in clouds can only be made when some of the possibilities are disproved, and this may be done by looking at measurements from other instruments. For example, millimeter-wavelength radar and in-situ airplane measurements may either show or rule out the possibility of significant coherent droplet scattering at X- and S-band.

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