The Retrieval of Stratocumulus Cloud Properties by Ground-Based Cloud Radar

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ABSTRACT

The radiative characteristics of stratocumulus clouds are dependent upon their microphysical properties, primarily the liquid water content and effective radius of the drop population. Aircraft observations of droplet spectra in warm stratocumulus over the North Atlantic and around the British Isles by the Hercules C-130 aircraft of the U.K. Meteorological Office Meteorological Research Flight have been used to calculate the radar reflectivity, liquid water content, and effective radius. Empirically derived relationships, found from more than 4000 km of flight data on 11 separate days, that link reflectivity with either liquid water content or effective radius have been derived. These empirical relationships are significantly different from those predicted if the cloud droplet spectrum is modeled as a gamma function. Occasional drizzle-sized drops are frequently present within the cloud, and even though their concentration is very low, they dominate the reflectivity and these empirical relationships fail. However, although the drizzle drops increase the reflectivity, they have a negligible effect on the liquid water content and effective radius of the cloud. As these drops have a significant fall velocity in comparison to the cloud droplets, it is suggested that a ground-based Doppler radar could separate the components of the reflectivity due to bimodal drop spectra and the vertical structure of the cloud properties that determine radiative transfer could be retrieved.

1. Introduction

The microphysical characteristics of warm stratocumulus clouds are critical in determining their radiative properties. These clouds occur in large sheets in a number of areas, most notably off western continental coasts, and their presence plays an important role in the earth's radiation budget (Nicholls 1984). Slight changes in the effective radius (r_e) of the cloud droplets and the cloud depth can make a large difference to the albedo; for example, Slingo (1990) showed how a 2-μm change in stratocumulus r_e can cause an effect on the radiation budget on the same order as a doubling of atmospheric CO_2.

Combinations of spaceborne instruments are routinely used to determine cloud-top properties. Greenwald et al. (1993) showed how using Special Sensor Microwave/Imager data can retrieve cloud liquid water path. Nakajima and King (1990) provided the theoretical basis for retrieving cloud properties from reflected solar radiation. Han et al. (1994) have deduced effective particle radii for a near-global set of water clouds. Taylor and English (1995) have derived optical depth and effective radii from infrared and microwave radiometry and validated the technique with in situ aircraft measurements. These investigations, while being of great importance, will fail when multilayer clouds are present and are of a low resolution when compared to ground-based measurements. For example, Jonas (1994) models a cellular cloud structure of stratocumulus of a horizontal dimension on the order of 600 m. He shows how such a structure influences the radiative nature of the cloud. It therefore appears necessary to consider ground-based instruments for more detailed observations.

In this paper we present results suggesting that ground-based cloud radar could be used to find the profile of microphysical characteristics of stratocumulus. The technique involves deriving either liquid water content (LWC) or r_e (the two properties that determine radiative cloud character) from a single measurement of radar reflectivity. This is possible as all three variables are functions of the cloud droplet spectrum. This spectrum is not easy to accurately establish and is not consistent, but one can find empirical relationships between the reflectivity and the microphysical cloud properties.

Brown et al. (1995) discuss how a similar approach could be used for cirrus clouds, which also have a major influence on the earth radiation budget. Clothiaux et al. (1995) have demonstrated that a ground-based 94-GHz radar can be used to investigate parameters such as cloud layering, depth, and boundaries. Kropfli et al. (1990) describe a 35-GHz cloud radar with similar capabilities.

Early studies deduced theoretical relationships between radar reflectivity and LWC derived from the cloud

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particle size distributions. Atlas (1954) proposed a relationship of the form

$$Z\ (\mathrm{mm^6\ m^{-3}}) = 0.048\ \mathrm{LWC}^2, \qquad (1)$$

where Z is the radar reflectivity and the LWC is in grams per cubic meter. Later, Sauvageot and Omar (1987) used aircraft carrying particle probes to measure drop size spectra of cumulus and stratocumulus over the Pyrenees and found

$$Z\ (\mathrm{mm^6\ m^{-3}}) = 0.03\ \mathrm{LWC}^{1.31}, \qquad (2)$$

which they claim is valid up to a reflectivity of -15 dBZ. Above this level they found that drizzle-sized particles were present, which dominated the radar reflectivity (proportional to the sixth power of the drop diameter), making determination of microphysical properties from radar measurements difficult.

The presence of drizzle-sized drops in warm stratocumulus has been noted many times (Nicholls and Leighton 1986; Albrecht 1989), and the effect of these drops on radar reflectivity is discussed in Fox and Illingworth (1997). The effect that these particles have on attempts to measure microphysical properties of stratocumulus using ground-based radar is addressed in this paper.

2. Instrumentation and data

The instruments used in this study were the forward-scattering spectrometer probe (FSSP) and the 2D-C imaging probe carried aboard the Hercules C-130 of the U.K. Meteorological Research Flight (MRF). Details of the probes' operation can be found in Knollenberg (1976). The FSSP measures the intensity of the laser illumination, which is scattered in the forward direction, and uses Mie theory to separate the droplets into 15 different size categories. For the probe used these channels are 3 μm in width, corresponding to particle diameters of between 2 and 47 μm.

The C-130 has a true airspeed of about 100 m s^{-1}, and the sample volume for each particle is dependent upon the particle size. The microphysical parameters calculated herein were from 10-s samples of data corresponding to sample volumes on the order of 2×10^{-4} m^3. Brenguier et al. (1994) have analyzed possible errors in the FSSP, which are estimated to be about 20% in concentration and 18% in sizing the particles; because radar reflectivity is proportional to the sixth power of the diameter, this translates to an error of a factor of 2 for calculated absolute values of reflectivity and 50% for liquid water content, although relative values will be more accurate (see Fox and Illingworth 1997 for further details). Particles larger than 50 μm were detected with the 2DC imaging probe (Knollenberg 1970), which had a sample volume of about 0.05 m^3 for 10 s of data. Clouds were considered to contain drizzle if the reflectivity due to drops measured by the cloud probe exceeded that due to droplets detected by the FSSP. The data used were collected during the Atlantic Stratocumulus Transition Experiment (ASTEX; Albrecht et al. 1995) near the Azores and a series of flights around the British Isles. The flights covered 11 separate days and over 4000 km of cloud penetrations.

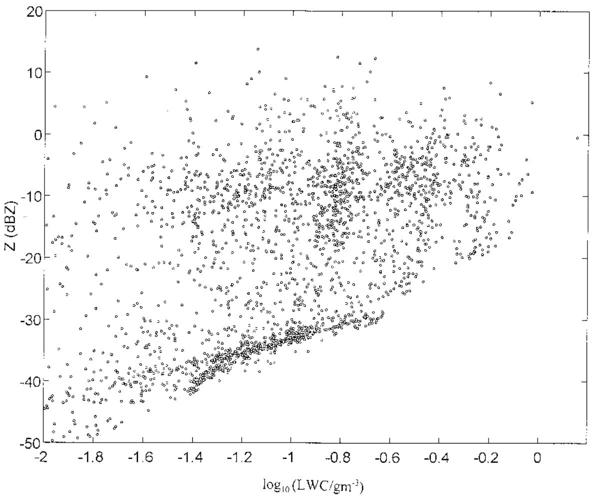

FIG. 1. Scattergram of Z against LWC calculated from FSSP and 2DC 10-s spectra made during 4000 km of cloud penetrations.

3. Drop size distributions and microphysical parameters

A plot of calculated radar reflectivity and liquid water content from all the 10-s size spectra in the dataset is presented in Fig. 1 and reveals little correlation between the two parameters. This is because clouds in maritime air masses invariably contain occasional drizzle droplets that dominate the reflectivity—a conclusion that was also reached by Sauvageot and Omar (1987). The cluster of points in Fig. 1 at the minimum value of Z for a given LWC is predominantly from continental airmass clouds that had no population of drizzle droplets. Frisch et al. (1995b) made direct radar measurements of reflectivity in ASTEX clouds and found a similar spread of Z values to that in Fig. 1.

Babb and Albrecht (1995) have used a vertically pointing radar to show that drizzle produces a bimodal Doppler spectrum, with the drizzle component having a velocity about 1 m s^{-1} greater than that of the cloud component; the reflectivities of the two components were similar. Frisch et al. (1995a) simulate a Doppler spectrum for cloud and drizzle that has two peaks separated by about 0.7 m s^{-1}. A typical Doppler spectrum computed from the size spectra of clouds containing occasional drizzle droplets measured by the C-130 is displayed in Fig. 2, which also shows a bimodal spectrum—this is the same spectrum as discussed in Fig. 2 of Fox and Illingworth (1997). These small droplets evaporated rapidly below cloud base, but in some cases

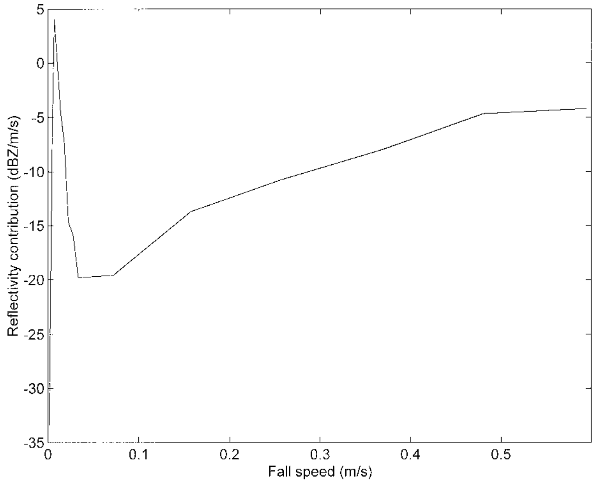

FIG. 2. A typical Doppler power spectrum calculated from FSSP and 2DC data, showing the bimodal contribution of cloud and drizzle drops.

larger drops (up to 400-μm diameter) were found, which fell a significant distance below cloud base. These drops would produce a separation in the two peaks of the Doppler spectrum of more than 1 m s^{-1}, which is comparable to the results of Babb and Albrecht (1995). This demonstrates that the component of Z due to the population of cloud droplets can be extracted using a vertically pointing Doppler radar, provided that the Doppler width, due to turbulence, is less than about 0.2 m s^{-1}.

If Doppler capability is unavailable it is possible to use a second method for identifying clouds that contain drizzle. Figure 3 shows the profiles of two clouds, calculated from aircraft data, one containing and one free of drizzle-sized drops. In both cases it can be seen that the LWC follows the classic profile in that it increases almost adiabatically from the base to the top of the cloud. Figure 3a demonstrates that the occasional drizzle-sized drops dominate the reflectivity but have a negligible contribution to the liquid water spectra. The vertical profile in Fig. 4 is for the same cloud as in Fig. 3a and shows that the drizzle makes a negligible contribution to the effective radius. In the case of the drizzle-free cloud the reflectivity follows a similar pattern, rising from a minimum at cloud base to a maximum at cloud top. The cloud containing drizzle-sized drops, on the other hand, had a maximum reflectivity toward cloud base. A simple discriminator is thus suggested to determine whether a cloud has a drizzle content and, therefore, is or is not a suitable candidate for retrieval of radiative properties by radar alone. The discriminator involves identifying the peak value of the cloud reflectivity and comparing this to the cloud-top value. This was done in Fig. 5 for the whole set of aircraft runs, which provided clear profiles of entire cloud depth. The circles represent those clouds in which no particles were registered by the 2DC probe. It appears that this simple

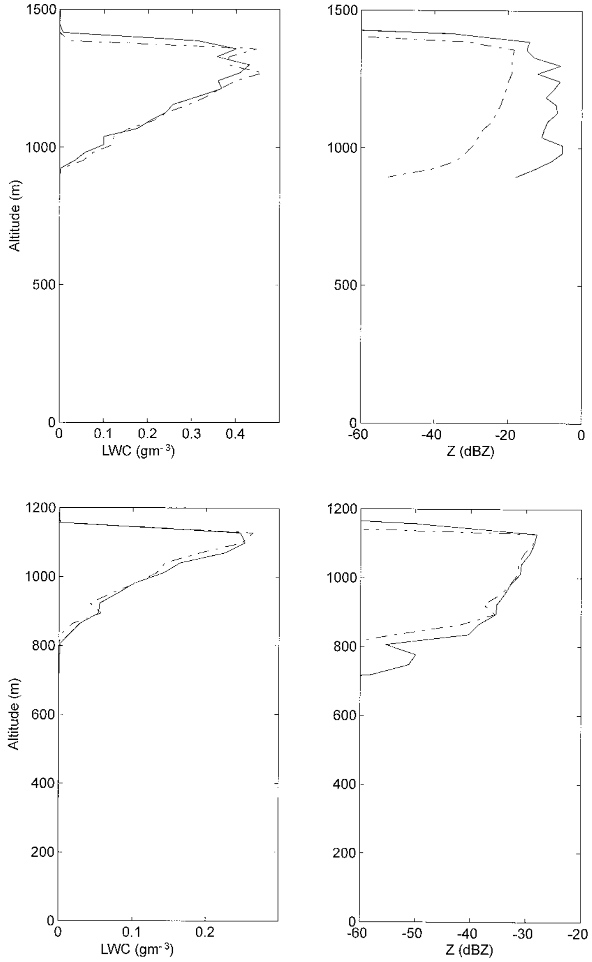

FIG. 3. (a) Vertical profile in Z and LWC of a cloud containing occasional drizzle drops. Solid line is for the FSSP and 2D-C probe, and broken line is for FSSP only. (b) As in (a) but for a cloud without drizzle drops.

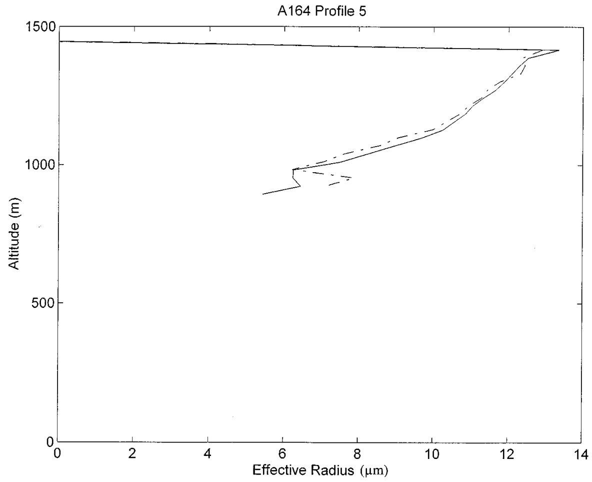

FIG. 4. As Fig. 3a but a vertical profile of r_e, showing that the drizzle drops do not affect r_e.

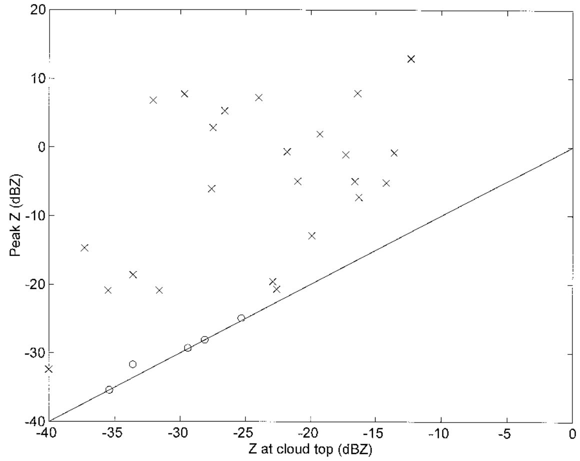

FIG. 5. Simple discrimination of clouds containing drizzle (×) from those without drizzle (○) by examination of the vertical profile of reflectivity.

discriminator is effective, but is unable to isolate the reflectivity contribution of the cloud droplets and is, therefore, inferior to the Doppler technique.

4. Model distributions of cloud droplets

Equations (1) and (2) give previously found Z–LWC relationships. No relationships have been proposed directly for Z and r_e, despite their importance in the modeling of cloud radiative properties. Atlas and Bartnoff (1953) worked before the importance of this parameter was understood and produced both theoretical and crude empirical relationships between Z and "visibility" (the extinction coefficient). Theoretical relationships can be derived by assuming a distribution of cloud droplet diameters. Gamma distributions are almost invariably employed of the form (Khrgian and Mazin 1963)

$$N(D) = AD^{\beta}\exp(-bD), \tag{3}$$

and it is possible to derive theoretical relationships between Z, r_e, and LWC, where β is the index of the gamma function. Integrating gives the following relationships:

$$Z = A\frac{(\beta + 6)!}{b^{(\beta+7)}} \tag{4}$$

and

$$\mathrm{LWC} = \frac{\pi\rho A}{6}\frac{(\beta + 3)!}{b^{(\beta+4)}}, \tag{5}$$

where ρ is the density of water and

$$r_e = \frac{\beta + 3}{b}. \tag{6}$$

Using $r_v^3 = kr_e^3$, where r_v is the mean volume radius (Martin et al. 1994) and N is the total drop concentration, gives

$$r_e^3 = \frac{3\ \mathrm{LWC}}{4\pi kN}, \tag{7}$$

and eliminating A and b we have

$$Z = \frac{6}{\pi}\frac{(\beta + 6)!}{(\beta + 3)!(\beta + 3)^3}\frac{4\pi kN}{3}r_e^6 \tag{8}$$

and

$$Z = \frac{9}{2\pi^2 kN}\frac{(\beta + 6)!}{(\beta + 3)!(\beta + 3)^3}\frac{\mathrm{LWC}^2}{\rho^2}. \tag{9}$$

As can be seen, these produce formulas of the form $Z \propto \mathrm{LWC}^2$ and $Z \propto r_e^6$, which would be anticipated from consideration of the relevant moments of the drop size distribution concerned, provided that β and the total concentration N are constant for all spectra.

The spectra of cloud and drizzle particles are bimodal, and therefore the distribution of cloud droplets can be separated from the drizzle population. As has been demonstrated earlier, a ground-based radar with Doppler capability would be able to separate the two reflectivity components, and in the next section we consider how the microphysical cloud properties may be derived from the component due to the cloud droplets. Gosset and Sauvageot (1992) have suggested that for a mixed phase cloud the LWC can be deduced from the difference in attenuation at two frequencies and then the ice water content derived from Z using an empirical relationship. The implicit assumption made is that the liquid water has negligible reflectivity when compared to the ice; this may not be true if there are drizzle drops present.

5. The Z–LWC relationship

The relationship between Z and LWC, as calculated from FSSP data alone, is shown by the scattergram in Fig. 6. This comprises all the sample points taken from straight level aircraft runs at different heights in clouds with reflectivity above −50 dBZ. As can be seen, the maximum LWC is just under 1 g m^{-3} and the value of the radar reflectivity rises, with the LWC reaching a maximum value of −17.8 dBZ. There is wide scatter among the points, representing samples with very low LWC, and this is due to the sampling errors involved when the probes encounter very small numbers of small particles, probably near cloud base. In such cases it is impossible to gain a representative sample of the cloud. For $Z > -40$ dBZ the correlation between the two variables is 0.82, and a line of regression fitted to the data gives a relationship of

$$Z\ (\mathrm{mm^6\ m^{-3}}) = 0.012\ \mathrm{LWC}^{1.16}, \tag{10}$$

which is comparable with the formulation given by Sauvageot and Omar in Eq. (2).

To find the expected error in a single value of LWC determined from Z, the data have been split into bins 2.5 dBZ wide and the mean value, standard deviation, and standard error of the LWC found. These values are

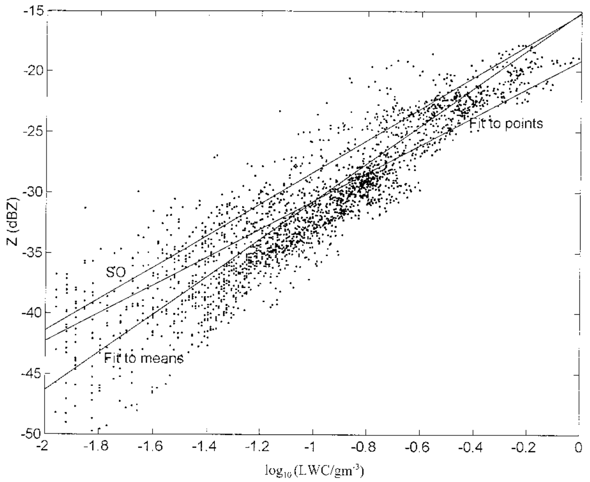

FIG. 6. Scattergram of Z against LWC, from FSSP data alone, for all cloud samples with $Z > -50$ dBZ. Lines representing the two relationships suggested here and that of Sauvageot and Omar (1987) are shown.

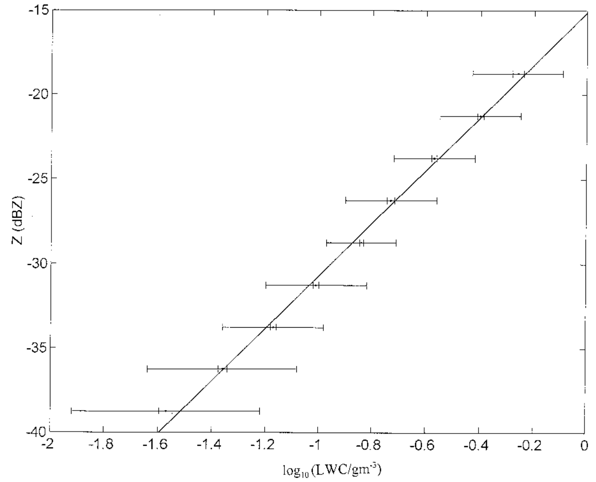

FIG. 7. Mean, standard deviation, and standard error of the mean of an estimate of LWC from a measurement of Z with a 2.5-dBZ resolution.

shown in Table 1 and plotted in Fig. 7. It can be seen that although the confidence we can give to a single LWC estimate from one radar reflectivity measurement is about 50%, the relative accuracy of the averaged properties of a large number of samples is on the order of 5%; this tenfold improvement in accuracy would require 100 samples.

The correlation between the central bin Z value and the mean LWC is greater than 0.99, and one can fit a regression line to the Z–$\log_{10}$(LWC) scatterplot to find a relationship of the form

$$Z\ (\mathrm{mm}^6\ \mathrm{m}^{-3}) = 0.031\ \mathrm{LWC}^{1.56}. \tag{11}$$

Lines representing the two relationships, Eqs. (10) and (11), are superimposed on the scatterplot in Fig. 6.

In Fig. 8 the new relationship [Eq. (11)] is superimposed on the theoretical relationships in Eq. (9), which predicts that Z is proportional to LWC^2 and $1/N$. The curve is for values of β from 1 to 5, for an N (total droplet concentration) of 50 cm^{-3} and $k = 0.7$. The empirical curve cuts across the theoretical lines, suggesting that as LWC increases either β increases or N rises.

Table 1. Results of binning the 10-s LWC data on 2.5-dBZ divisions.

Central bin Z (dBZ)	Mean $\log_{10}$LWC [log(g m^{-3}) : g m^{-3}]	Standard deviation	Standard error on the mean	Number of samples
−38.75	−1.57 : 0.026	0.35	0.025	199
−36.25	−1.36 : 0.043	0.28	0.017	259
−33.75	−1.17 : 0.067	0.19	0.010	352
−31.25	−1.01 : 0.097	0.19	0.010	379
−28.75	−0.84 : 0.145	0.13	0.007	333
−26.25	−0.73 : 0.186	0.17	0.014	143
−23.75	−0.57 : 0.269	0.15	0.010	248
−21.25	−0.40 : 0.398	0.15	0.012	168
−18.75	−0.26 : 0.549	0.17	0.021	65

6. The Z–r_e relationship

In this section the relationship of r_e and Z is investigated as an alternative to deriving LWC from Z. Because r_e is an intensive variable and Z an extensive variable, this is equivalent to assuming that N is constant in Eq. (4). Bower and Choularton (1992) used Eq. (4) to derive r_e, with fixed values of N of 150 cm^{-3} over the oceans and 600 cm^{-3} over the continents. Figure 9 shows the scattergram of Z versus $\log_{10}(r_e)$ for all the 10-s spectra in the dataset. As can be seen, above a

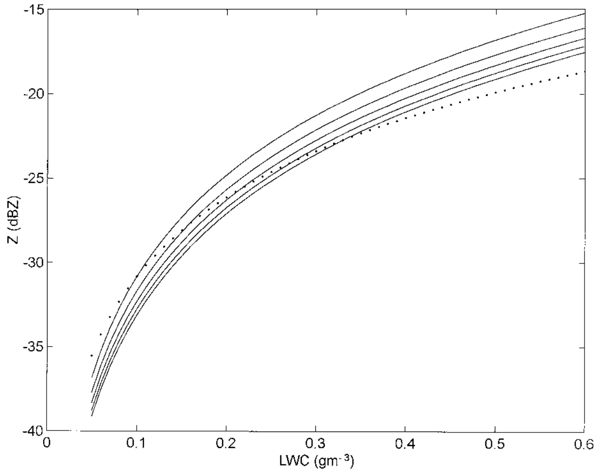

FIG. 8. Comparison of the empirical Z–LWC relationship (dotted line) to a series of theoretical gamma distributions of order 1 (upper line) to 5 (lower line) for $N = 50$ cm^{-3}.

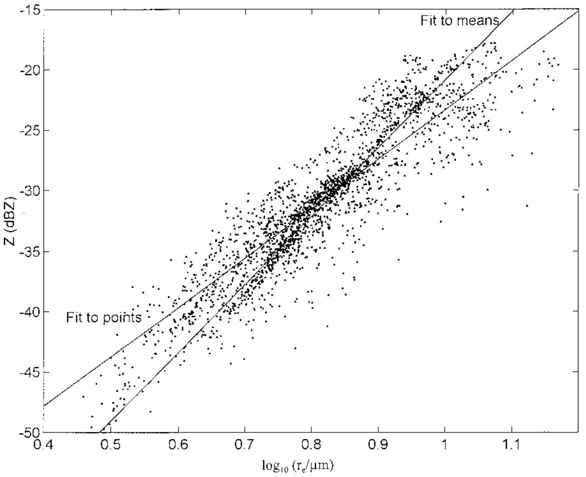

FIG. 9. Scattergram of Z against r_e, from FSSP data alone, for all cloud samples with $Z > -50$ dBZ. Lines representing the two relationships suggested here are shown.

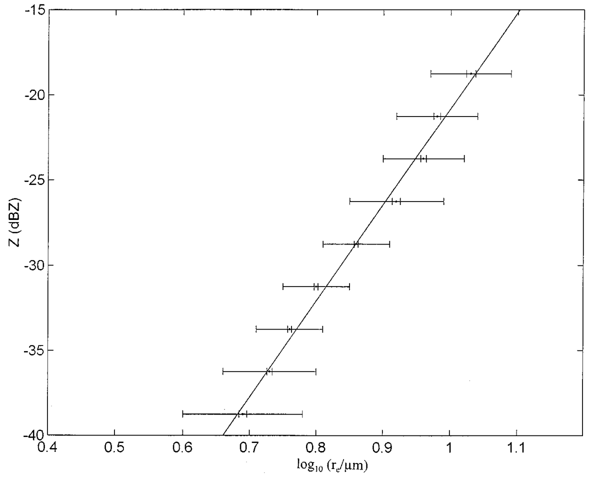

FIG. 10. Mean, standard deviation, and standard error of the mean of an estimate of r_e from a measurement of Z with a 2.5-dBZ resolution.

cloud reflectivity of −40 dBZ and corresponding to an r_e of about 4 μm, there is a strong correlation between the two parameters. The 2147 points found in this range give a correlation for Z(dBZ) and a $\log_{10}(r_e)$ of 0.83. The least squares best fit line computed for these data gives a relationship of the form

$$Z\ (\mathrm{dBZ}) = 40.9 \log_{10}(r_e) - 64.2. \tag{12}$$

We can now carry out an appraisal of the Z–r_e relationship similar to the one conducted for the Z–LWC relationship. If we bin the values of r_e in the same 2.5-dBZ divisions as before, then we obtain the means, standard deviations, and standard errors of the mean shown in Table 2 and plotted in Fig. 10. The standard deviation indicates that the absolute error of a single measurement is just over 1 μm, but the smaller standard errors of the means for each bin, suggesting that for a large number of radar measurements of cloud reflectivity the relative error of the average r_e is less than this. The correlation between the mean r_e and the central Z value of the bin is again over 0.99, and a least squares fit line yields the relationship

$$Z\ (\mathrm{dBZ}) = 56.5 \log_{10}(r_e) - 77.3. \tag{13}$$

This line is plotted with the original data points (Fig. 9), and, as in the case of Z–LWC, we believe it to be a more reliable version of the Z–r_e relationship than the line obtained by a best fit to the points themselves. It is suggested again that this relationship, rather than the one given in Eq. (12), be used for estimations of cloud effective radius from measurements of radar reflectivity.

We can now compare the experimental data and theoretical relationships between Z and r_e given by Eq. (8), which predicted Z proportional to r_e^6 and N if β is constant. The empirical curve, proportional to r_e^6, is similar to theory if $N = 300$ cm^{-3}. However, to get agreement with theoretical predictions of LWC we had to use N

Table 2. Results of binning the 10-s r_e data into 2.5-dBZ divisions.

Central bin Z (dBZ)	Mean ($\log_{10} r_e$) [log(μm) : μm]	Standard deviation	Standard error on the mean	Number of samples
−38.75	0.69 : 4.89	0.09	0.006	199
−36.25	0.73 : 5.37	0.07	0.004	259
−33.75	0.76 : 5.75	0.05	0.003	352
−31.25	0.80 : 6.31	0.05	0.003	379
−28.75	0.86 : 7.24	0.05	0.003	333
−26.25	0.92 : 8.31	0.07	0.006	143
−23.75	0.96 : 9.12	0.06	0.004	248
−21.25	0.98 : 9.54	0.06	0.005	168
−18.75	1.03 : 10.7	0.06	0.007	65

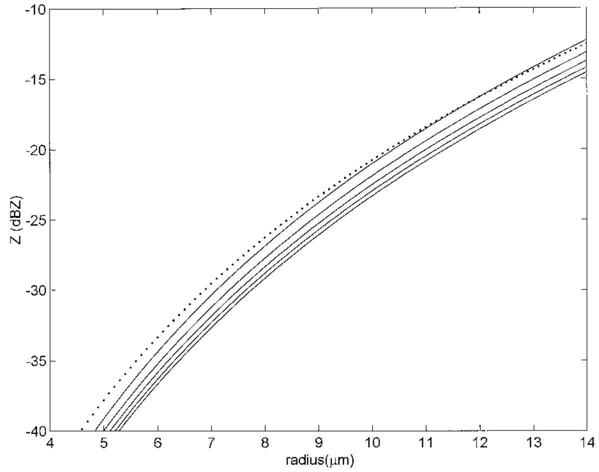

FIG. 11. Comparison of the empirical Z–r_e relationship (dotted line) to theoretical gamma distributions of order 1 (upper line) to 5 (lower line) for $N = 300$ cm^{-3}.

$= 50\ \text{cm}^{-3}$, which again implies that the gamma function representation of droplet spectra is not adequate and that the empirical relationships are more reliable.

7. Summary

Almost all maritime and some continental stratocumulus contain bimodal populations of drops—one of cloud droplets, the other of drizzle-sized drops. The former determines the radiative character of the cloud, and it is possible to separate the two components of the radar reflectivity by analysis of the Doppler spectrum at vertical incidence. If the radar used does not have Doppler capability it is simple to observe the vertical profile of reflectivity; if this shows a steady increase with altitude, then the cloud can be considered drizzle-free. If the drizzle component of the cloud reflectivity is absent or can be removed using the Doppler return, then the relationships linking Z to either LWC or r_e in Eqs. (11) and (13) can be employed.

The initial impetus for this line of research came from the work of Slingo (1990), who showed that a change in r_e of 2 μm would offset the global warming caused by a doubling of CO_2. Table 2 shows that the standard deviation in r_e for a single Z measurement is less than 2 μm. Similarly, Table 1 shows that the absolute error in LWC derived from a single measurement is on the order of 50%, but that for a series of measurements relative changes of less than this can be detected. Although a single radar measurement may not yield a reliable estimate of the cloud properties, a prolonged series of observations should provide information on the regional variation in the nature of warm clouds. The empirical fits derived from measured cloud spectra are significantly different from those predicted using an idealized gamma distribution to model the cloud properties.

A ground-based radar system would be able to monitor clouds over a single point, and this would be of great interest in determining the natural variability of cloud vertical structure. A further advantage of such a radar would be the possibility of the collocation of other instruments. If radar measurements are combined with others, such as lidar or radiometer measurements, an even more powerful method for investigating the vertical structure of clouds and their relation to radiative effects could be developed. Such measurements are not suggested as being practical for a spaceborne system (IGPO 1994), which would have an inadequate vertical resolution (500 m) and detection threshold (-30 dBZ), as well as a large Doppler broadening due to satellite motion, but it is noted that there are already ground-based 35- or 94-GHz radars in existence that could be used for such work.

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