Particle Size Truncation Effect on the Inference of Effective Particle Diameter①

Liu Chunlei (刘春雷)② and *Yao Keya* (姚克亚)

Department of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026

Advanced Centre for Earth Sciences and Astronomy, University of Science and Technology of China, Third World Academy of Sciences, Hefei 230026

Received July 15, 1996; revised November 11, 1996

ABSTRACT

The effective ice crystal particle diameter (D_e) of cirrus clouds can be inferred by comparing the measured radar / lidar backscattering ratio with the theoretically calculated one. The calculated ratios are based upon assumptions of ice crystal particle density and size distribution, and it will be affected by the artificially assumed particle size ranges. This size truncation effect on the inference of effective particle diameter will be investigated theoretically by assuming the cirrus ice particle spherical and particle density of 0.9g / cm^3. Results show that the truncation at large particle end has very small effect on the inference of D_e, but the truncation at the small particle end will have some effect on the inference of D_e.

Key words: Size truncation, Effective particle diameter, Cirrus cloud

I. INTRODUCTION

The climatic variation forecasting needs accurate information of the cirrus cloud ice water content (IWC) and the effective particle diameter (or radius) in climate model parameterization procedures. Stephen et al. (1990) pointed out that the sign of cloud temperature feedback varied from positive to negative depends upon the specific choice of D_e. Based on their findings, they concluded that prediction of even the sign of any feedback that might exist between cirrus clouds and climate seems premature, and these predictions are limited by our lack of understanding of the relationship between size and shape of ice crystals and the gross radiative properties of cirrus and more researches should be directed to these issues. So the determination of the effective particle diameter is very important.

The radar / lidar backscattering ratio method has been developed by Intrieri et al. (1993) for the inference of the effective particle diameter. Their theoretical studies indicated that the small changes in the effective diameter D_e will result in the large changes of the ratios, suggesting that this method is very robust for the inaccurate measurement of either radar or lidar backscattering.

Intrieri et al. (1993) pointed out that: because of instrument limitations and their necessary dynamic ranges, there are unsampled regions in the size spectrum, there remain uncertainties in cloud particle sizes, which is a factor in properly assessing the sign of ice cloud feedback during a global temperature change (Stephens et al. 1990). There is substantial

①This work was supported by LAPC.

②Current affiliation: University of Reading, Reading RG6 2AU, U. K..

disagreement between observed cloud microphysical properties and those derived from radiative transfer models. One explanation for these discrepancies is the possibility of very small, undetected ice crystals. Particle measuring probes on aircraft have not been able to provide complete size distributions adequately, especially at diameters less than 30 μm, thus creating the uncertainty about the numbers of small particles (Heymsfield et al., 1990). Even if aircraft instruments could obtain the essential size distribution information, they are limited by their spatial coverage of highly variable cirrus clouds. In earlier studies, Heymsfield and Platt (1984) found that from 35% to 53% of the total visible extinction is due to the small ice crystals with the size ranging from 1 to 20 μm. Very recent study by Arnott et al. (1994) indicated that there can be significant number of small particles (diamter < 60 μm) and very few large particles in cirrus. So, accurate information of the particle spectrum (or effective particle diameter) will be very useful for the parameterization of the cirrus cloud optical property.

Intrieri et al. (1993) also pointed out that there is an upper and lower bound of D_e that can be determined by radar / lidar backscattering ratio method. The smallest effective particle size that can be determined is limited by the radar sensitivity and corresponds to approximately 60 μm. The largest particle diameter that can be determined is approximately 700 μm; this is due to the combination of effects resulting from lidar attenuation from very large particles and also because the ratio curves become almost flat when $D_e > 700$ μm. But the possible size truncation effect on the inference of D_e has not been investigated.

The measured radar / lidar ratio is the value from real particle spectra in cirrus clouds, which has wide ranges of size and different shapes of spectra distributions. For the theoretical calculations, the particle size has to be limited in certain ranges, and the measured radar / lidar ratios have to be compared with the theoretical values in order to infer the effective particle diameter.

In this paper, we are trying to investigate the smallest or largest perticle size truncation effect on the inference of the effective particle size, in order to give confidence to this radar / lidar backscattering ratio method. Because the large particles mainly affect the long wave backscattering coefficient, and small particles mainly affect the short wave backescalttering coefficient, the wavelength of 0.69 μm (wavelength of Ruby lidar) and 8.66 mm (wavelength of K_a band radar) will be used here to study the particle truncation effect on radar / lidar backscatter. Following Intrieri et al. (1993), the ice particles are assumed to be spherical here for quick and exact Mie calculations, and the ice particle density is assumed to be 0.9 g / cm^3.

II. SOME USEFUL EQUATIONS

The theoretical backscattering ratio of radar / lidar defined by Intrieri et al. is

$$r_t = \frac{\sigma_{\text{radar}}}{\sigma_{\text{lidar}}} , \tag{1}$$

where σ is the volumetric backscattering coefficient

$$\sigma_{(\text{radar, lidar})} = \sum_i Q_{\text{bscat},i}\, n(D_i) \pi \left(\frac{D_i}{2}\right)^2 , \tag{2}$$

where D_i is the particle diameter, $Q_{\text{bscat},i}$ is the particle backscattering efficiency, and $n(D_i)$ is the particle number density in ith particle counter channel.

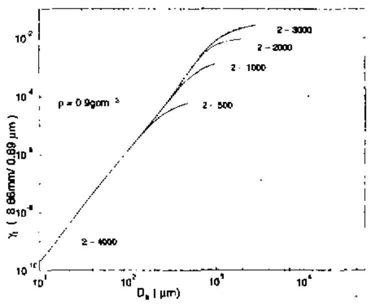

Fig. 1. Large particle cut-off effect on the backscattering ratio.

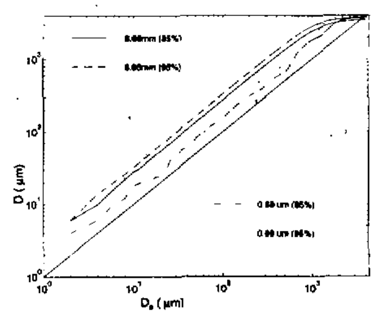

Fig. 2. The maximum D required to get 85% and 95% of the total backscattering for given D_e.

The cirrus ice particle spectrum can be expressed as an exponential one (Brown et al., 1995)

$$N(D) = N_o e^{-3.67\frac{D}{D_o}} , \tag{3}$$

where D_o is the median particle diameter, it is defined as that the diameter on both sides of which the total particle volume are equal. It is related to the effective particle diameter by

$$D_e = \frac{3D_o}{3.67} . \tag{4}$$

Ice particle refractive indices are $1.307-i2.62\times 10^{-8}$ for wavelength of 0.69 μm, and $1.784-i1.89\times 10^{-3}$ for wavelength of 8.66 mm (Warren, 1984).

III. PARTICLE SIZE TRUNCATION EFFECT

If the real particle size in clouds ranges from 2 to 4000 μm, and the ice particle density is assumed to be 0.9 gcm^{-3}, then the backscattering ratio for different particle diameter ranges (assumed) can be plotted in Figure 1. With the truncation of large particles, it can be seen that there are discrepancies at the large particle end due to large particle cut-off, but for most part of the size ranges, the truncation has little effect on D_e. This implies that the large particle cut-off has little effect on the inferrence of D_e.

For given D_e and minimum $D_{\min} = 2$ μm, we test what the required maximum particle size (for theoretical calculations) is for 85% of the total backscattering being accounted. The result is plotted in Figure 2. The straight line represents $D = D_e$. The nearer the curve to this line, the smaller the large particle's effect. It is indicated that for lidars, the large particles have small effect on the backscattering signal, and for radars, the large particle effect should be considered. There are similarities for 95% of the total backscattering. Both cases show that the truncation at the large particles has smaller effect on lidar backscattering than on radar backscattering. This is tested and plotted in Figure 3. The plot shows that only when D_e near two ends of the particle spectrum, the particle cut-off effect on the ratio will become obvious. The minimum particle size needed for the 85% and 95% of the total backscattering is calculated and plotted in Figure 4. The small particle cut-off has very small effect on radar

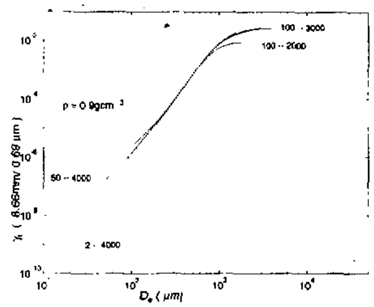

Fig. 3. Small particle cut–off effect on the backscattering ratio.

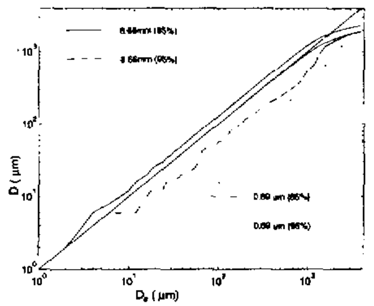

Fig. 4. The minimum D_i required to get 85% and 95% of the total backscattering for given D_e.

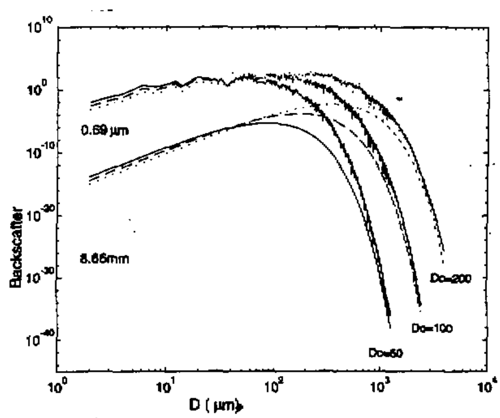

Fig. 5. The bulk particle backscattering variation with the particle diameter D.

backscattering, but is serious for the lidar backscattering depending on the particle spectrum. If D_e is very large, the small particle cut–off has effects on both radar and lidar backscattering.

Table 1. D_e *Values for Different Particle Size Ranges*

	2–4000 μm	50–4000 μm
D_e (μm)	80	75
	70	60

The study for the small particle end cut–off shows that for lidar backscattering, if the total ratio of 95% is used, for D_e = 200 μm, the minimum particle diameter needed is about 70 μm; for D_e = 100 μm, the minimum particle diameter needed is about 30 μm; and for D_e = 10 μm, the minimum particle diameter needed is about 6 μm. The particle counter can generally count particles with minmum diameter of 50 μm, so if $D_e > 200$ μm, the small particle truncation will have little effect on the determination of the effective particle size of cirrus cloud. But if $D_e < 200$ μm, the neglect of small particles will result in the underestimation of the particle backscattering signals significantly.

Based on Figure 3, if the particle counter has small particle size limitation of $D = 50$ μm, the theoretically derived D_e will be smaller than the real D_e for $D_e < 100$ μm. If we use size ranges of $D = 2 - 4000$ μm and $D = 50 - 400$ μm respectively to calculate D_e, the differences for some cases can be seen in the following table.

So, once the backscattering ratio is obtained, the accuracy of the effective particle diameter will depend on the assumed or measure particle spectra, and it is particularly sensitive to the small particle cut–off.

For the large particle truncation, the effect is small. This can be seen from the plot of total backscattering coefficient (considering radar and lidar wavelengths and the particle spectrum with $D_0 = 50$, 100 and 200 μm, respectively) variation with particle diameter as shown in Figure 5. At the larger particle end, the particle backscattering contribution to the total backscatter is very small and it dropps very quickly as the diameter increases.

IV. CONCLUSIONS

From our results, it can be seen that the small particle truncation of $D < 50$ μm, which is very difficult to measure using the currently employed particle counters (such as 2–D probes used in both laboratories and aircrafts), has some effects on the inference of D_e; large particle truncation seems to have less effect than that of small one, considering that D_e is generally less than 1000 μm in cirrus clouds. Figures 1 and 3 can be used as a tool to determine the particle size ranges based on the observed backscattering ratios, so that D_e is not near either end of the particle spectrum, and the effective particle diameter can be inferred by the method of the backscattering ratio of radar / lidar.

REFERENCES

Arnott, Q.P., Y. Dong, and J.Hallett (1994), Role of small ice crystals in radiative properties of cirrus: A case study, FIRE II, November 22, 1991. *J. Geophys. Res.*, **99**: D1, 1371–1381.

Brown, P.R.A, A.J.Illingworth, A.J.Heymsfield, G.M.McFarquhar, K.A.Browning and M. Gosset (1995), The role of spaceborn millimetre–wave radar in the global monitoring of ice cloud, *Appl. meteor.*, **34**: 2346–2366.

Heymsfield, A.J., and C.M.R.Platt (1984), A parameterization of the particle spectrum of ice clouds in terms of the ambient temperature and the ice water content, *J. Atmos. Sci.*, **41**: 846–855.

Heymsfield, A.J., K.M.Miller, and J.D.Spinhirne (1990), The 27–28 October 1986 FIRE cirrus case study: Cloud microstructure, *Mon. Wea. Rev.*, **118**: 2313–2328.

Intrieri, J. M., G. L. Stephens, W.L.Eberhard, and T.Uttal (1993), A method for determining cirrus cloud particle sizes using lidar and radar backscatter technique, *J. Appl. Meteor.*, **32**: 1074–1082.

Stephens, G.L., S.C.Tsay, P.W.Stackhouse, Jr., and P.J.Flatau (1990), The relevance of the microphysical and radiative properties of cirrus clouds to climate and climatic feedback, *J. Atmos. Sci.*, **47**: 1742–1753.

Warren, S. G. (1984), Optical constants of ice from the ultraviolet to the microwave, *Appl. Opt.*, **23**: 1206–1223.