Consideration of Dynamical Effects on Parameterization of Cloud Radiative Properties

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Introduction

Effective radius (r_e) (defined as the ratio of the third to the second moment of a droplet size distribution) is one of the key variables that are used for calculation of the radiative properties of liquid water clouds (Hansen and Travis 1974). The inclusion and parameterization of r_e in climate models has proven to be critical for assessing global climate change (Slingo 1990, Dandin et al. 1997). It has been demonstrated empirically (Pontikis and Hicks 1992, Bower and Choularton 1992, Bower et al. 1994, Martin et al. 1994, Liu and Hallett 1997, Reid et al. 1998, Liu and Daum 2000a), as well theoretically (Liu and Hallett 1997, Liu and Daum 2000b), that the r_e can be expressed as a "1/3" power law of the ratio of the cloud liquid water content to the droplet concentration,

$$r_e = \left(\frac{3}{4\pi\rho_w}\right)\beta\left(\frac{L^{1/3}}{N}\right) = \beta r_v, \quad (1)$$

where r_e is the effective radius, L is the liquid water content, N is the droplet concentration, ρ_w is the water density, r_v is the volume-mean radius, and the r_e ratio β is a dimensionless parameter that depends on the spectral shape of the cloud droplet size distribution. The only difference among different parameterizations lies in the specification of the r_e ratio β as a function of the relative dispersion (defined as the ratio of the standard deviation to the mean radius of the droplet size distribution).

Expressions for Effective Radius Ratio

For clouds with a monodisperse droplet size distribution as described by a delta function $n(r) = N\delta(r-r_e)$, $\beta = 1$. This value of the r_e ratio β was used by Bower and Choularton (1992), and Bower et al. (1994) to estimate the r_e of layer clouds and small cumuli. Martin et al. (1994) derived estimates of the r_e ratio β of 1.08 for maritime, and 1.14 for continental stratocumulus clouds based upon analysis of in situ microphysical data. These expressions with fixed values of the r_e ratio β totally ignore the dependence of β on the spectral shape. Pontikis and Hicks (1992) analytically derived an expression that relates the r_e ratio β to the relative dispersion. Liu and Hallett (1997) derived another expression for the r_e ratio β from the Weibull droplet size distribution which was itself obtained from the recently developed systems theory (e.g., Liu et al. 1995, Liu and Hallett 1998, Liu et al. 2002). Expressions can also be derived from the gamma and lognormal distributions that have been widely used to describe droplet size distributions. Liu and Daum (2000a,b) compared all the existing expressions to observations, and found that the expression corresponding to the Weibull or gamma distributions best describes the dependence of the r_e ratio β on the relative dispersion, and the two expressions perform almost equally well. The expression corresponding to the gamma droplet size distribution is

$$\beta = \frac{\left(1 + 2\varepsilon^2\right)^{2/3}}{\left(1 + \varepsilon^2\right)^{1/3}}, \tag{2}$$

where ε is the relative dispersion. Thus, the key to further improving the parameterization of r_e is to specify the relative dispersion. It would also be desirable to formulate the parameterization of the relative dispersion in terms of the liquid water content and/or the droplet concentration because these two variables are often predicted/diagnosed in state-of-the art climate models (Ghan et al. 1997a,b; Rotstayn 1997).

Effects of Pre-Cloud Aerosols

Recently, we (Liu and Daum 2002) have shown that the addition of anthropogenic aerosols to a marine air mass enhances not only the droplet concentration, but also the relative dispersion. This phenomenon is illustrated in Figure 1, which shows the dependence of the relative dispersion on the droplet concentration under the influence of anthropogenic aerosols. The points connected by lines represent cases identified by different investigators (see Liu and Daum 2002 for details) as evidence for the indirect aerosol effect. In each case, the points with lower droplet concentration were characterized as clean clouds and the higher points were characterized as similar clouds that were polluted by anthropogenic aerosols. The increased relative dispersion acts to offset the cooling of the first indirect

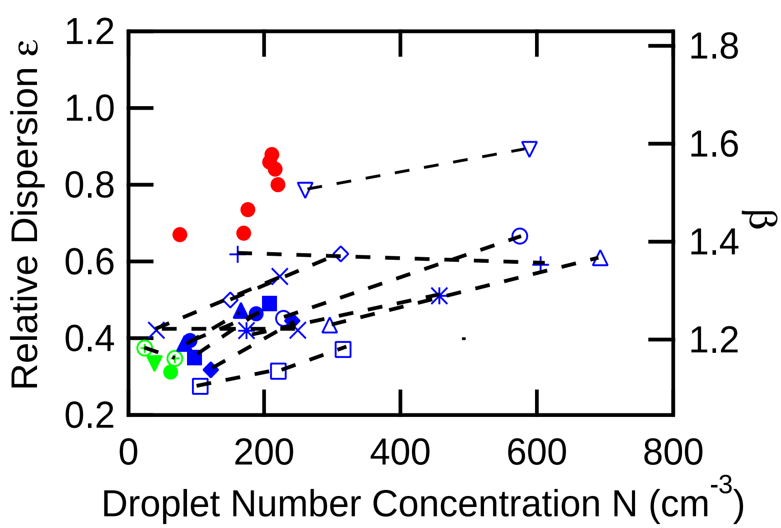

Figure 1. Relationship between the relative dispersion and the droplet concentration. See Liu and Daum (2002) for details about the data.

aerosol effect by as much as 10% to 80 % (Liu and Daum 2002), depending on the relationship between the relative dispersion and the droplet concentration. More evidence for the effect of the enhanced dispersion on indirect aerosol forcing has been later reported (Peng and Lohmann 2003, Rotstayn and Liu 2003).

Although Figure 1 clearly exhibits a substantial increase in the relative dispersion as the droplet concentration increases, the relationship is noisy. The “noise” likely arises from differences in cloud dynamics such as updraft velocity and turbulence.

Effect of Cloud Updraft

It is desirable from Eq. (1) to parameterize the relative dispersion (or the r_e ratio β) in terms of the ratio of the liquid water content to the droplet concentration (or the volume–mean radius). Physically, uniform/regular adiabatic growth tends to cause narrowing of the droplet size distribution as droplet grow, producing a decrease of the relative dispersion with increasing volume-mean radius (i.e., narrowing toward larger sizes). Furthermore, presenting data this way also relaxes the assumption of a constant liquid water content (updraft velocity) used in previous studies of the dispersion effect. In fact, Wood (2000) found that there is a negative correlation between the r_e ratio β and the volume-mean radius, and that this correlation is better than that between the r_e ratio β and the droplet concentration alone, suggesting that specifying the relative dispersion as a function of the ratio of the liquid water content and the droplet concentration will improve the parameterization of the relative dispersion.

Figure 2 shows the relative dispersion as a function of the volume-mean radius calculated cloud droplet size distributions measured with a FSSP probe. The data come from several projects (North Atlantic Regional Experiment [NARE], ARM 1997 Spring IOP, ARM 1997 Fall IOP, ARM 1998 Spring IOP, ARM 2000 IOP, and The First International Satellite Cloud Climatology Project [ISCCP] Regional Experiment [FIRE] - Arctic Cloud Experiment [ACE]). Each point in this figure represents a flight average. The result from Wood (2000) (tilted dash) is also shown as a comparison. It is evident from this figure that the relative dispersion generally decreases when the volume-mean radius increases as expected from the uniform adiabatic growth theory. The scatter is likely caused by differences in turbulent entrainment and mixing processes. It is interesting to note that data from Wood (2000) lie near the lower boundary, suggesting that the data were probably taken from clouds with minimal entrainment and mixing.

Effect of Entrainment and Mixing

It has been observed that updraft cores of clouds tend to exhibit a smaller spectral dispersion but a larger droplet concentration compared to cloud edges and cloud tops as a result of turbulent entrainment and mixing processes (Telford 1996). These studies seem to suggest the notion that a stronger turbulence causes a larger relative dispersion and a larger volume-mean radius (broadening toward larger sizes) contrary to that of adiabatic growth. The examples (solid curve) shown in Figure 2, provide additional evidence for this argument. Each curve represents a single flight sorted according to the relative dispersion. It is noteworthy that although the effects of updraft and pre-cloud aerosols are expected to be minimized for a given cloud by grouping the data according to the relative dispersion, some of the effects still remain elusive.

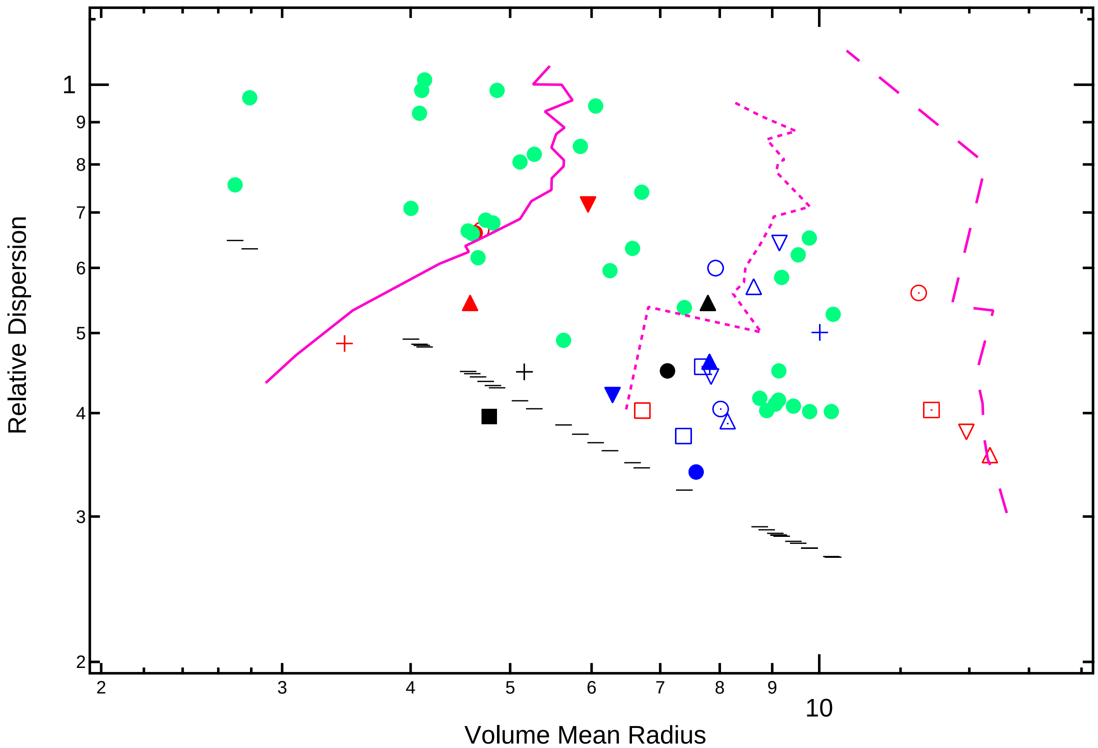

Figure 2. Relationship between the relative dispersion and the volume-mean radius. The data come from several projects (NARE, ARM 1997 Spring IOP, ARM 1997 Fall IOP, ARM 1998 Spring IOP, ARM 2000 IOP, and FIRE-ACE). Each point in this figure represents a flight average used to reflect adiabatic growth (aerosol effect and updraft effect). Each curve represents data from a flight sorted according to the relative dispersion, being used to reflect the effect of turbulent entrainment and mixing.

New Expression for Effective Radius

For the purpose of the parameterization of the r_e, it is desirable to perform similar analysis for the relationship between the r_e ratio β and the mean-volume radius. Figure 3 shows the results for the same dataset as in Figure 2.

Two points can be inferred from this figure. First, similar to the relative dispersion, the r_e ratio generally decreases when the volume mean radius increases. Second, as a first order approximation, the dependence of the radius ratio on the volume-mean radius can be approximated by a power-law

$$\beta = a r_v^{-b}, \quad (3)$$

where the exponent b (slope) is a constant; but, the coefficient a (intercept) seems different and is likely determined by the process of turbulent entrainment and mixing. We have b = 0.20 and a = 1.9 on average.

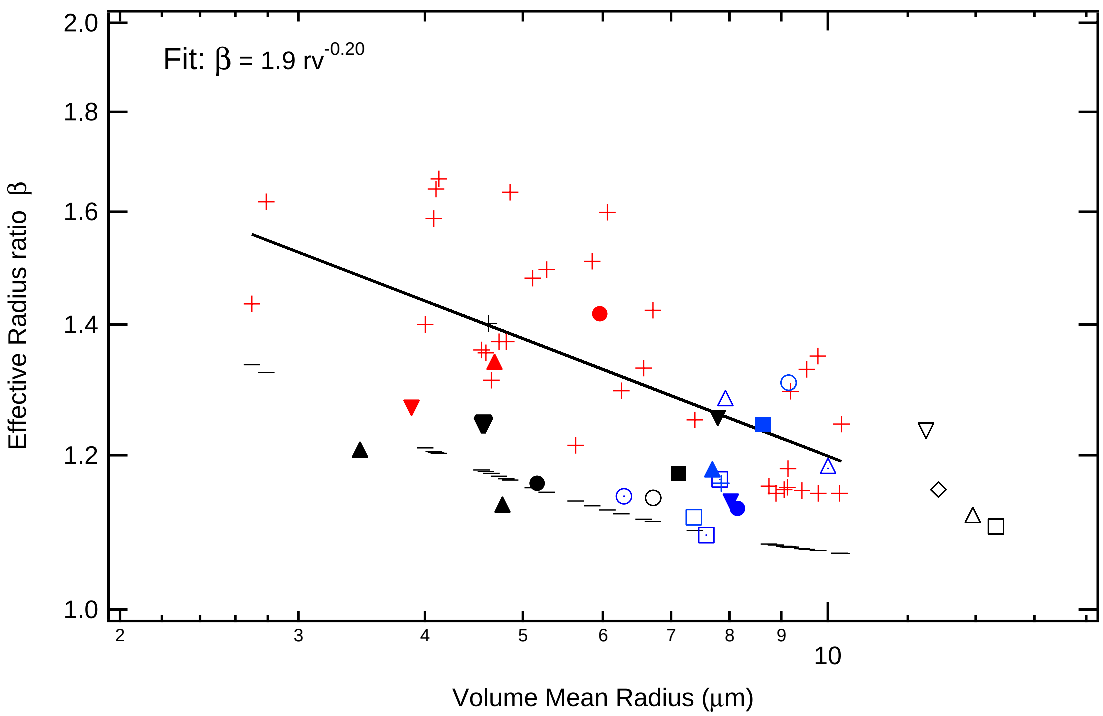

Figure 3. Relationship between the radius ratio and the volume-mean radius.

Substitution of Eq. (3) into Eq. (1) yields the improved expression for the r_e

$$r_e = a r_v^{1-b} = \left(\frac{3}{4\pi\rho_w}\right) a \left(\frac{L}{N}\right)^{(1-b)/3} \tag{4}$$

Because b is positive, the exponent of the power-law is less than 1/3 as assumed by most studies so far. Furthermore, it has been long argued that the relative dispersion is a function of the turbulence intensity. For example, Cooper (1989) suggested that a simple mixing would lead to a linear relation between the relative dispersion and the relative dispersion of the vertical velocity fluctuation. Consequently, we speculate that the r_e is described by

$$r_e = a r_v^{1-b} = a_w \varepsilon_w^{b_w} \left(\frac{L}{N}\right)^{(1-b)/3}, \tag{5}$$

where ε_w represents the relative dispersion of the vertical velocity fluctuation or its equivalent such as turbulent dissipation rate. Obviously, more work is needed to confirm Eq. (5) and to determine the coefficient a_w and exponent b_w.

Conclusions

The "1/3" power-law expression that has been widely used in the parameterization of the r_e is investigated. It is demonstrated that specification of the relative dispersion is the key to further improving the parameterization of the r_e. It is argued from uniform adiabatic growth theory that the relative dispersion should be represented in terms of the ratio of the liquid water content to the droplet concentration instead of the droplet concentration alone. Microphysical measurements from several projects conducted over continental and maritime air masses are analyzed. The results show that not only the relative dispersion decreases when the volume-mean radius increases as expected from the uniform adiabatic theory, but also turbulent entrainment and mixing processes play an important role in the relationship of the relative dispersion to the volume-mean radius. Furthermore, it is empirically demonstrated that the dependence of the radius radio β on the volume-mean radius can be approximately described by a power law. The exponent b in the power-law remains roughly unchanged under different conditions of entrainment and mixing whereas the coefficient a depends strongly on turbulent entrainment and mixing processes. The overall result indicates that consideration of the effect of the relative dispersion leads to a power-law expression for the r_e with an exponent other than the "1/3" as commonly used. It is also suggested that a simple power-law describe the effect of turbulent entrainment and mixing processes based on the results obtained in this study.

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