Dispersion of Cloud Droplet Size Distributions, Cloud Parameterizations, and Indirect Aerosol Effects

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Introduction

Most studies of the effect of aerosols on cloud radiative properties have considered only changes in the cloud droplet concentration, neglecting changes in the spectral shape of the cloud droplet size distribution. However, it has been shown that that the spectral dispersion of the cloud droplet size distribution (defined as the ratio of the standard deviation to the mean radius of the droplet size distribution) has a significant role in determining cloud radiative properties (e.g., Liu and Daum 2000). It has also been shown that the addition of anthropogenic aerosols to a marine air mass enhances not only the droplet concentration, but also the spectral dispersion, and that the increased spectral dispersion acts to offset the cooling of the first indirect aerosol effect by as much as 10% to 80% (Liu and Daum 2002). As for the droplet concentration, the spectral dispersion is a function not only of pre-cloud aerosols, but is also affected by the dynamical properties of clouds such as updraft velocity and turbulence. These dynamical effects cause uncertainties in the relationship between the spectral dispersion and droplet concentration. Here we seek to differentiate between the effects of cloud dynamics and pre-cloud aerosols on the spectral dispersion. We also address the effect of the spectral dispersion on the parameterization of warm rain microphysics, and on the second indirect aerosol effect.

Effect of Pre-Cloud Aerosols and Cloud Dynamics on Spectral Dispersion

Figure 1 shows the dependence of the spectral 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.

As shown in Figure 1, although there is clearly a substantial increase in the spectral dispersion as the droplet concentration increases due to increases in aerosol loading, the relationship is noisy. The "noise" likely arises from different cloud dynamics such as updraft velocity and turbulence. It has been observed that updraft cores of clouds tend to feature a smaller spectral dispersion but a larger droplet concentration compared to cloud edges and cloud tops as a result of cloud dynamics such as turbulent entrainment and mixing (Politovich 1993; Telford 1996). These studies seem to suggest that a stronger updraft causes a smaller spectral dispersion but a larger droplet concentration. On the other hand, a stronger turbulence causes a larger spectral dispersion but a smaller droplet concentration due to

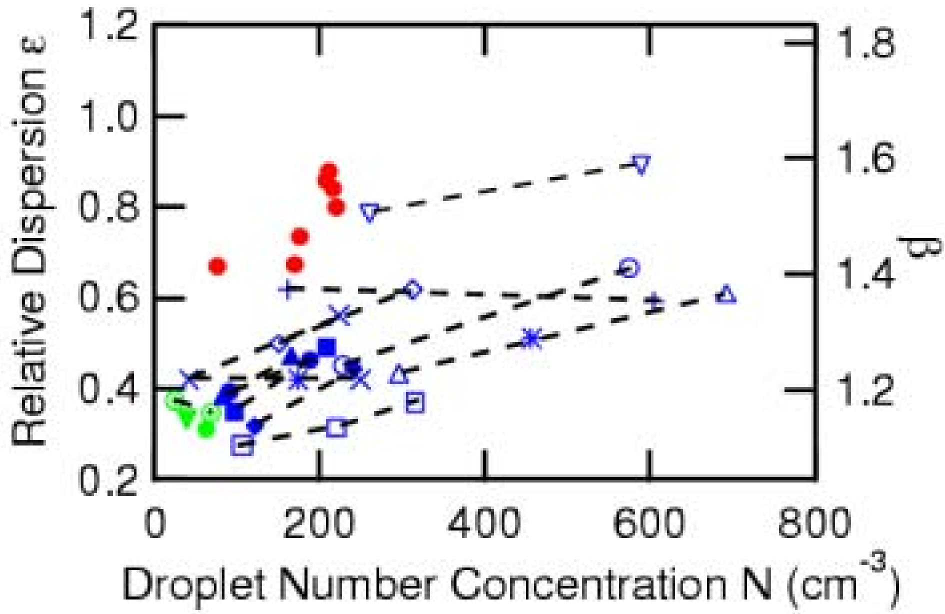

Figure 1. Relationship between the relative dispersion and β as a function of cloud droplet number concentration for marine clouds (clean and polluted) from published datasets (see Liu and Daum 2002 for the sources of the data).

evaporation and dilution. Therefore, contrary to the effect of pre-cloud aerosols, cloud dynamics as a whole will result in a negatively correlated relationship between the spectral dispersion and droplet concentration. This notion is supported by the data collected during the Atmospheric Radiation Measurement (ARM) 1997 intensive operational period; Figure 2 shows an example.

Results shown in Figures 1 and 2 suggest the following important message: Pre-cloud aerosols and cloud dynamics oppositely affect the relationship between the spectral dispersion and the droplet concentration; similar aerosols may be activated and grow very differently in clouds of different dynamics. It is very likely that the upper-bound and lower-bound fitting curves represent different dynamical effects. A recent general circulation model investigation demonstrates that the average of the two extreme cases gives the best general circulation model results (Rotstayn and Liu 2003).

Dispersion Effect on Autoconversion Rate and Second Indirect Aerosol Effect

Rain is initiated in liquid water clouds by collision and coalescence of cloud droplets wherein larger droplets with higher settling velocities collect smaller droplets and become embryonic raindrops. Accurate parameterization of this so-called autoconversion process is important for improving the treatment of cloud and precipitation in atmospheric models of various scales (from cloud-resolving models to global climate model, and for investigating aerosol-cloud-climate interactions, particularly the second indirect aerosol effect (Boucher et al. 1995; Lohmann and Fleichter 1997; Rotstayn 2000).

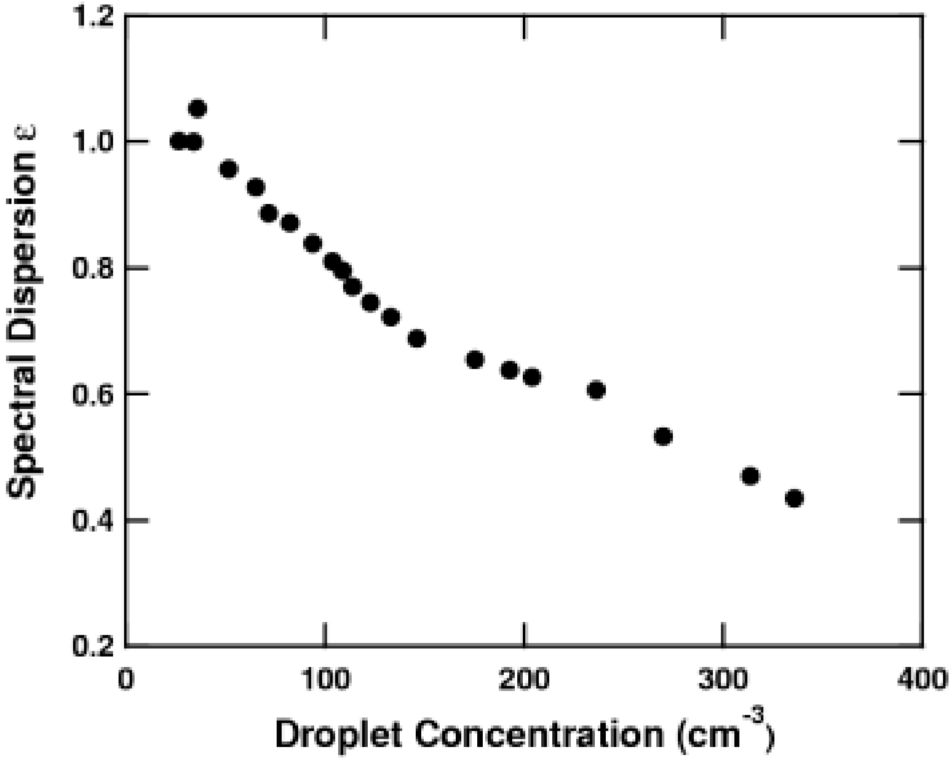

Figure 2. The relationship between the spectral dispersion and droplet concentration. Because the aerosol effect is minimal for an individual cloud, this relationship is largely caused by cloud dynamics in contrast with Figure 1 where the aerosol effect is dominant.

However, most existing parameterizations do not include the spectral dispersion as a dependent variable, and are therefore unable to address the effect of the spectral dispersion on the autoconversion rate and the second indirect aerosol effect. To fill this gap, we have developed a new parameterization for the autoconversion rate P_6 (see Liu and Daum 2003 for details on this scheme):

$$P_6 = \left(\frac{3}{4\pi\rho_w}\right)^2 \kappa_2 \beta_6^6 N^{-1} L^3 H\left(R_6 - R_{6c}\right) \tag{1a}$$

$$\beta_6 = \left[\frac{\left(1+3\varepsilon^2\right)\left(1+4\varepsilon^2\right)\left(1+5\varepsilon^2\right)}{\left(1+\varepsilon^2\right)\left(1+2\varepsilon^2\right)}\right]^{1/6} \tag{1b}$$

where κ_2 is an empirical coefficient and H is the Heaviside step function used to incorporate the threshold radius R_{6c}.

A unique feature of this new parameterization is its inclusion of the spectral dispersion as a dependent variable via. Eq. (1b), which can be used to quantity the effect of the spectral dispersion on the autoconversion rate. Figure 3 shows the increase of the $\beta_6^{\,6}$ with increasing spectral dispersion. It indicates that for a given liquid water content and droplet concentration, the effect of spectral dispersion alone can cause a difference in the autoconversion rate up to a factor of more than 10. In other words, the assumption of a monodisperse cloud droplet size distribution underestimates the autoconversion rate.

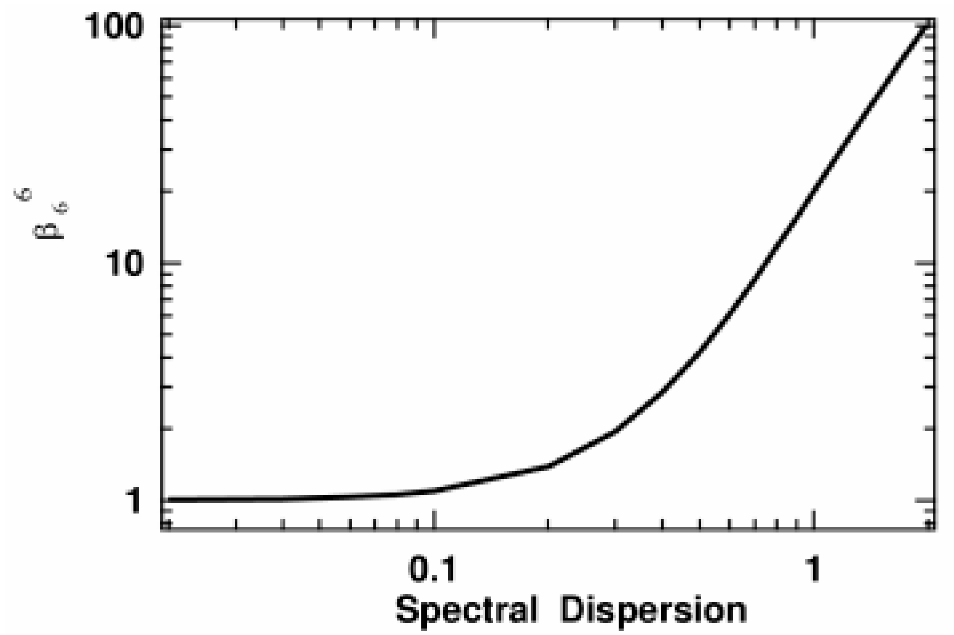

Figure 3. Dependence of the α_6^6 on the spectral dispersion as given by Eq. (1b).

A major assumption behind the second indirect aerosol effect is that an increase in anthropogenic aerosols reduces precipitation, increase the liquid water content, and cloud albedo, cooling the atmosphere. Therefore, any increase in parameterized precipitation will offset the traditional second indirect aerosol effect. Therefore, the enhanced spectral dispersion caused by anthropogenic aerosols will further offset the cooling by increasing the autoconversion rate.

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References

Boucher, O., H. L. Treut, and M. B. Baker, 1995: Precipitation and radiation modeling in a general circulation model: Introduction of cloud microphysical process. *J. Geophys. Res.*, **D100**, 16,395-16,414.

Liu, Y., and P. H. Daum, 2000: Spectral dispersion of cloud droplet size distributions and the parameterization of cloud droplet effective radius. *Geophys. Res. Lett*., **27**, 1903-1906.

Liu, Y., and P. H. Daum, 2002: Indirect warming effect from dispersion forcing. *Nature*, **419**, 580-581.

Liu, Y., and P. H. Daum, 2003: Toward a unified formulation of the Kessler-Type autoconversion parameterizations. This Proceeding.

Lohmann, U., and J. Fleichter, 1997: Impact of sulfate aerosols on albedo and lifetime of clouds: A sensitivity study with the ECHAM 4 GCM. *J. Geophys. Res*., **D102**, 13,685-13,700.

Rotstayn, L. D., 2000: On the "tuning" of the autoconversion parameterizations in climate models. J. *Geophys. Res*., **D105**, 15,495-15,507.

Rotstayn, L. D., and Y. Liu, 2003: Sensitivity of the indirect aerosol effect to the parameterization of cloud droplet spectral dispersion. *J. Climate*. (Revised)