A GCM Parameterization of Bimodal Size Spectra for Mid-latitude Cirrus Clouds

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Introduction

The solar radiative properties of ice clouds are primarily a function of the ice water content (IWC) and the effective diameter (Mitchell et al. 1998; Wyser and Yang 1998), defined as

$$D_{eff} = IWC / (\rho_i P_t), \tag{1}$$

where ρ_i = bulk ice density corresponding to refractive index measurements (0.92 g/m^3) and P_t = projected area of size distribution (SD). However, D_{eff} cannot be determined from the SD alone, but also depends on ice crystal shape and associated mass and area properties (Mitchell et al. 1998).

To date, the representation of D_{eff} for the ice phase in general circulation models (GCMs) has been highly uncertain, and is sometimes treated as constant or nearly constant. The aim of this work is to provide a means for estimating SDs and D_{eff} for mid-latitude cirrus clouds, the latter estimated with some informed assumption about ice particle shape. We parameterize SDs as bimodal, with both the small and large particle modes expressed as a gamma distribution having the form

$$N(D) = N_o D^v \exp(-\lambda D), \tag{2}$$

where D is maximum dimension, while the SD parameters are estimated as a function of temperature and IWC.

Small Ice Crystals and the FSSP

The role of small ice crystals in cirrus continues to be uncertain, although new evidence shown here indicates the forward scattering spectrometer probe, or FSSP, may, given some criteria, at least approximately measure the small ice crystal mode for D < 50 μm. In a cloud chamber at Desert Research Institute (DRI), ice crystals were sampled by the DRI Cloudscope (CS), where ice crystals were aspirated and impacted onto a lens 1 mm wide, having a high collection efficiency for D > 10 μm (Schmitt and Arnott 1999). Simultaneously, the same ice cloud was sampled by the FSSP, where sizing is based on the forward scattering lobe, primarily due to diffraction, which is determined by a particle=s area cross section. The FSSP uses Mie theory for spheres to describe this forward lobe, and it is unclear to what degree it may be distorted by nonsphericity. The mean SD from 11 samples is shown in Figure 1 for each probe, where all crystals were hexagonal columns, and D = maximum dimension regarding the CS. The probe measured optical depth over a 2-m path was 0.04, corresponding to a number concentration of about 60 cm^{-3} (exceeding FSSP concentrations in natural cirrus). Errors due to distortion of the forward scattering lobe through nonspherical effects appear marginal, since FSSP and CS spectra are in relatively good agreement. Similar good agreement was found when hexagonal plates were sampled.

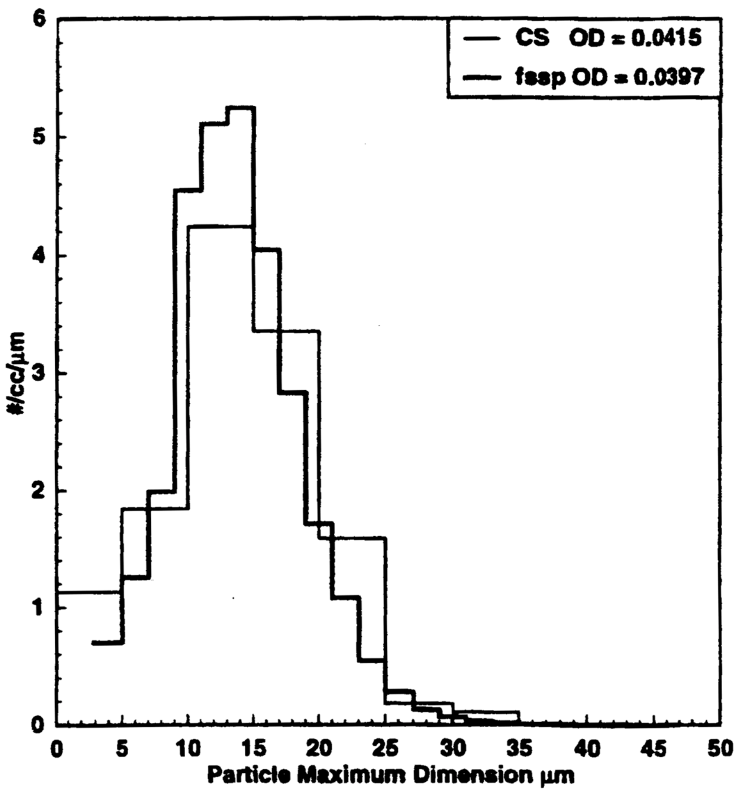

Figure 1. Comparison of size spectra measured by the Cloudscope and FSSP for hexagonal columns in a laboratory grown ice cloud.

The two probes were also compared when collocated on the Citation aircraft during an Atmospheric Radiation Measurement (ARM) Program intensive operational period (IOP), sampling cirrus blowoff from Hurricane Nora. Size spectra are shown in Figure 2, where the CS, FSSP, DRI replicator, and 2DC probes are intercompared. The CS and 2DC clearly indicate bimodal spectra, with the FSSP in fair agreement with the CS, especially at the peak concentration near 15 μm. The replicator collection efficiency apparently falls off rapidly for D < 50 μm. In Gardinar and Hallett (1985), the FSSP and replicator were intercompared, with concentration differences reported up to a factor of 300. Because the replicator collection efficiency appears to decay rapidly for D < 50 μm, about the largest size the FSSP measures, it is not surprising that concentration differences between these two instruments can be quite large.

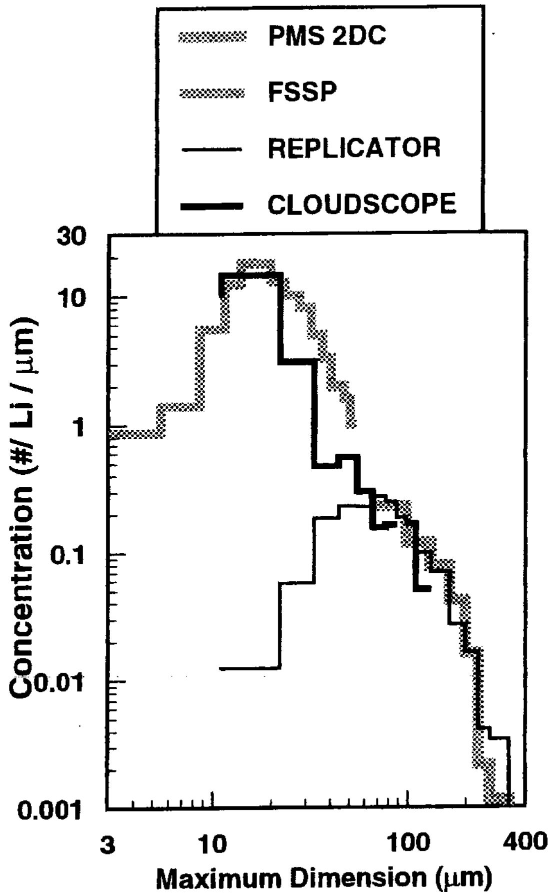

Figure 2. Size spectra from September 26, 1997, U.S. Department of Energy (DOE)-ARM IOP, Hurricane Nora outflow, 19:09:15 - 19:11:00 Universal Time Coordinates (UTC), -48.3 C to -50.3 C, 11.95 km to 12.18 km, true air speed (T.A.S.) = 118.5 m/s.

Twohy et al. (1997) found that IWCs measured by the CVI and FSSP in wave clouds were in good agreement. Also, the FSSP and 2DC were intercompared by Gayet et al. (1996), who found good agreement in the overlap region near 50 μm when SDs were narrow (i.e., contrail cirrus where D ≤ 100 μm). In natural cirrus with broader SDs, measured SDs from the two probes were discontinuous in their overlap region, and these authors recommended using overlap criteria as a means of accepting or rejecting SDs from the FSSP. This policy was adopted in this study to the extent possible. An exact overlap was not obtainable since the maximum size bin of the FSSP was 52.4 μm, while the smallest reliable 2DC bin was centered on 81.5 μm. To estimate concentrations between these two sizes, the FSSP SD was parameterized as described in Mitchell (1991), using Eq. (2).

$$\nu = \left[(\beta + 0.67)\overline{D} - D_m\right] / \left(D_m - \overline{D}\right), \quad (3)$$

$$\lambda = (\nu + 1) / \overline{D} \quad (4)$$

$$N_o = IWC\lambda^{\beta+\nu+1} / \alpha\Gamma(\beta + \nu + 1), \quad (5)$$

where β refers to the ice particle mass-dimension power law $m = \alpha D^{\beta}$, $\overline{D}$ is the SD mean D, and D_m is the SD median mass dimension. The choice of m-D relation does not matter so long as one is consistent, and IWC, $\overline{D}$, and D_m were determined from the measured SD. The criteria used for accepting FSSP data was that the parameterized FSSP SD had to intersect the measured 2DC SD in either the 1st or 2nd usable bin (centered at 81.5 μm or 114.5 μm). Examples are shown in Figures 3 and 4. Since this parameterization scheme conserves IWC, $\overline{D}$, and D_m, the extrapolation to D = 81.5 μm appears reasonable.

Parameterization for Mid-Latitude Cirrus

This parameterization is based on flights during IOPs over the Southern Great Plains ARM Cloud and Radiation Testbed (CART) site as well as some flights during FIRE II, totaling 17 flights between 1994 and 1998. SDs measured were based on a 10 s sampling interval where T.A.S. were about 120 m s^{-1}. After screening each SD using the above criteria, 996 SDs were used in this parameterization. However, since this is work in progress, the relationship between $\overline{D}$ and cloud temperature T, shown below, is based on only 357 SDs. The method for obtaining gamma distribution parameters for the small mode, measured by the FSSP, has already been described. The same method was used to obtain these

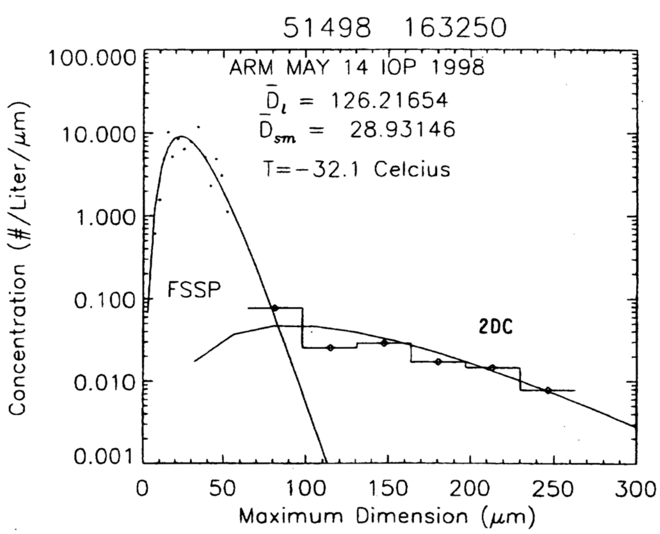

Figure 3. Example of FSSP and 2DC size spectra, their parameterized gamma fits, and how FSSP data was extrapolated to larger sizes via its gamma fit to test for continuity with 2DC spectra.

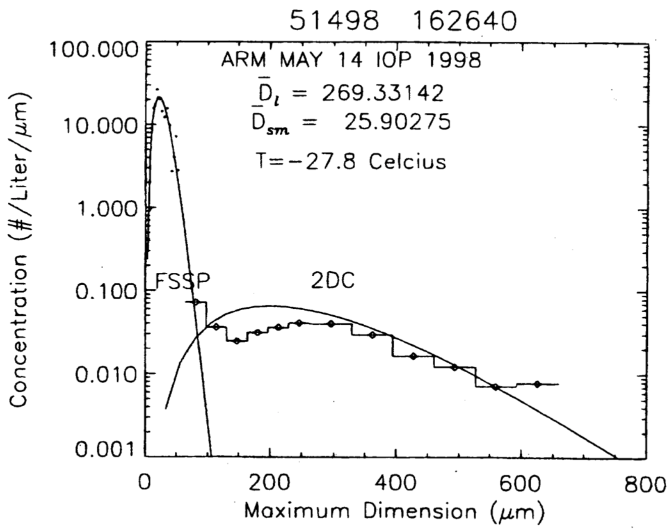

Figure 4. As in Figure 3, but for a different size distribution.

parameters from the large mode, measured by the 2DC probe. Since this approach conserves IWC, $\overline{D}$,and D_m, the SD area and mass, which radiative properties are based on, are accurately represented by the parameterized SD.

The parameterization was derived as follows. First, the measured $\overline{D}$ of the large mode, $\overline{D}_1$, was correlated with T as shown in Figure 5, resulting in the correlation

$$\overline{D}_1 = 440.2 \exp(0.02290\ T), \tag{6}$$

where T and $\overline{D}_1$ are in Celsius and µm. Over the range of T in this work, our data agree well with the $\overline{D}_1$-T relation described in Platt (1997) for mid-latitude cirrus, also shown. For comparison, the $\overline{D}_1$-T relation for the three Central Equatorial Pacific Experiment (CEPEX) tropical anvil cases described in McFarquhar and Heymsfield (1996) is also shown (D > 100 µm).

Next, the measured $\overline{D}_1$ was related to the IWC of the parameterized FSSP and 2DC SDs, assuming planar polycrystals. These IWCs for the small and large modes were normalized by their sum, the total IWC. These normalized IWCs are plotted against $\overline{D}_1$ in Figure 6, with "+" indicating the large mode and "◊" indicating the small mode. It is seen that the normalized small mode IWC, IWC_{sm}, is described fairly well by the expression:

$$IWC_{sm} = 0.11 + 0.89 \exp\left(-\left(\overline{D}_1 / 50\right)^2\right), \tag{7}$$

where $\overline{D}_1$ is in microns. The normalized large mode IWC, IWC_{lg}, is simply 1 - IWC_{sm}. Since these IWCs are normalized, they do not depend on initial assumptions of crystal shape used to derive them. The true IWC for each mode is given by multiplying each normalized IWC by the total IWC.

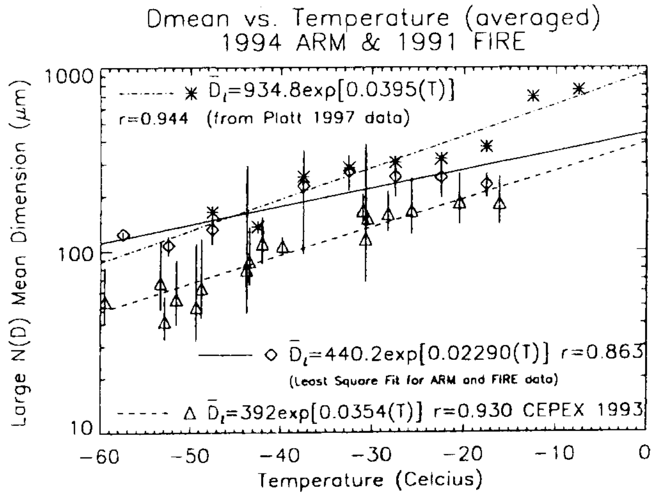

Figure 5. Mean dimension measured by the 2DC versus sampling temperature for this study (ARM and FIRE data), mid-latitude cirrus from Platt (1997), and tropical anvil cirrus (CEPEX). Vertical bars are standard deviations.

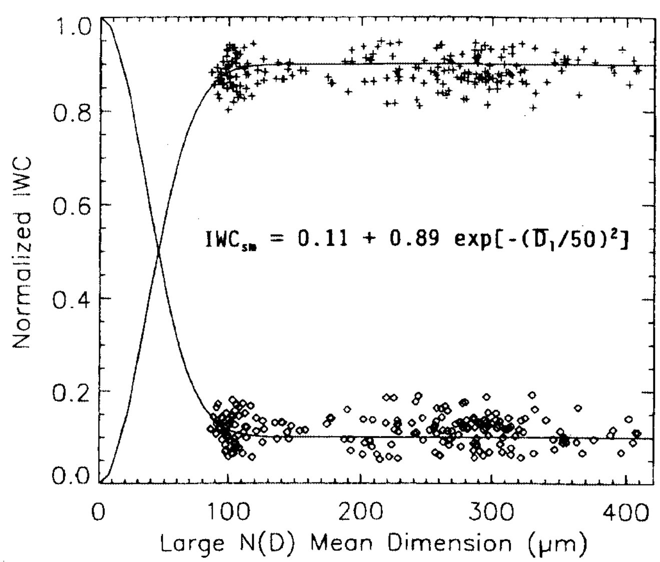

Figure 6. Normalized IWC calculated from the FSSP (◊) and 2DC (+), related to $\overline{D}_1$. The IWC partitioning between the large and small SD modes is described by the equation.

Given cloud temperature T and total IWC, we now have expressions for $\overline{D}_1$, IWC_{sm}, and IWC_{lg}. For closure, we still need expressions for $\overline{D}_{sm}$, ν_{sm}, and ν_{lg}. Most fortuitously, the standard deviations associated with the mean values of these quantities are sufficiently small to regard them as constant: $\overline{D}_{sm}$ = 27.4 ± 2.9 μm, ν_{sm} = 3.24 ± 1.41 μm, ν_{lg} = 2.64 ± 1.65 μm. Based on the first few bins of the

2DC, Mitchell et al. (1996a) also found $\overline{D}_{sm}$ was constant. To calculate λ and N_o for each mode, Eqs. (4) and (5) may be used for a given ice crystal shape (which effects only N_o).

Equations (6) and (7) and the findings above provide closure for estimating bimodal size spectra as a function of total IWC and temperature. Moreover, D_{eff} can be determined from Eq. (1) by noting $P_t = P_{sm} + P_l$, and that

$$P_x = \frac{\sigma_x \Gamma(\delta_x + \nu + 1)}{\alpha_x \Gamma(\beta_x + \nu + 1)} IWC_x \lambda_x^{\beta_x - \delta_x}, \tag{8}$$

where x refers to either the "l" or "sm" subscript, Γ denotes the gamma function, and σ and δ refer to the projected are of an ice crystal, given as

$$P = \sigma D^{\delta}. \tag{9}$$

Values of σ, δ, α, and β for different crystal shapes corresponding to $N(D)_{sm}$ and $N(D)_l$ are given in Mitchell (1996) and Mitchell et al. (1996b).

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