A Trimodal Size Distribution Parameterization for Tropical Cirrus Clouds

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Abstract

The role of small ice crystals in cirrus and the use of the Forward Scattering Spectrometer Probe (FSSP) to characterize the concentration and sizes of small crystals continues to be controversial, although new evidence in recent studies indicate that the FSSP may approximate the size distributions (SD) of small ice crystals (D <100 micrometers). Efforts to parameterize the SD in tropical anvil cirrus should thus take advantage of existing FSSP data to evaluate the potential impact of small ice crystals. This study describes a parameterization for trimodal size spectra in tropical cirrus, based on 5,546 SD taken from three flights on April 1, April 4, and March 17 1993, during the Central Equatorial Pacific Experiment (CEPEX). FSSP and two-dimensional cloud (2DC) probe measurements were used to parameterize the SD. This parameterization provides three gamma SD parameters for each mode of the trimodal distribution: very small, small, and large. The parameters are expressed in terms of cloud ice water content (IWC) and/or temperature (T). Size distribution behavior in the tropical cirrus is quite different from the SD behavior in the mid-latitude cirrus. This leads to differences in the cloud radiative properties. The resulting parameterization predicts the full trimodal SD in terms of three gamma functions, based on knowledge of T and total IWC. The simple inputs make the parameterization useful for Global Climate Models.

Introduction

Recent analysis of microphysical data from cirrus clouds observations suggests that the SD seen in mid-latitude clouds and tropical anvils belong to distinct populations and significant differences in SD behavior and concentration N(D) of small ice crystals exist between tropical and mid-latitude cirrus. Previous tropical cirrus parameterizations (McFarquhar and Heymsfield 1997; Mitchell et al. 1999) and recent parameterizations of effective ice particle sizes (Boudala et al. 2002; Donovan 2003) show evidence that the shapes of the mid-latitude SDs substantially differ from those of tropical SDs and small particles may contribute significantly to the optical properties of ice clouds. These indications suggest that ice crystals in tropical anvils and in mid-latitude cirrus are best parameterized separately. Our mid-latitude Global Climate Model parameterization (Ivanova et al. 2001) provides a Global

Climate Model parameterization for bimodal size spectra in mid-latitude cirrus clouds. Here we present our preliminary results toward a new trimodal SD tropical cirrus parameterization. This is still a work in progress, but the main data analysis and parameterization results have been obtained and checked for consistency.

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 FSSP may, given some criteria, at least approximately measure the small ice crystal mode for D <50 μm. In a cloud chamber at the 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-100, where the accuracy of SD measurements is unclear for non-spherical particles. 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 (extinction coefficient = 20 km^{-1}), corresponding to a number concentration of about 60 cm^{-3} (exceeding FSSP concentrations in natural cirrus). Errors due to non-spherical effects appear marginal, since the FSSP and CS spectra are in relatively good agreement. Moreover, the two SDs produce virtually identical radiative properties (Mitchell et al. 2001). Similar good agreement was found when hexagonal plates were sampled, using the same experimental design (Mitchell et al. 1999).

The two probes were also compared when collocated on the Citation aircraft during and 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 the Particle Measuring System's 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 Gardiner and Hallett (1985), the FSSP and replicator were intercompared, with concentration differences reported up to a factor of 300. Since 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. For more details on intercomparisons between the CS, FSSP, replicator, and 2DC see Arnott et al. (2000).

In addition, Twohy et al. (1997) found that IWCs measured by the cloud virtual impactor and FSSP in wave clouds were in good agreement. Recently, Lawson et al. (2001) found that when the cloud particle imager (CPI) SD were scaled with the help of OAP-2DC measurements, SDs in arctic cirrus measured by the CPI, FSSP, and 2DC were in relatively good agreement. The CPI size range includes the FSSP size range.

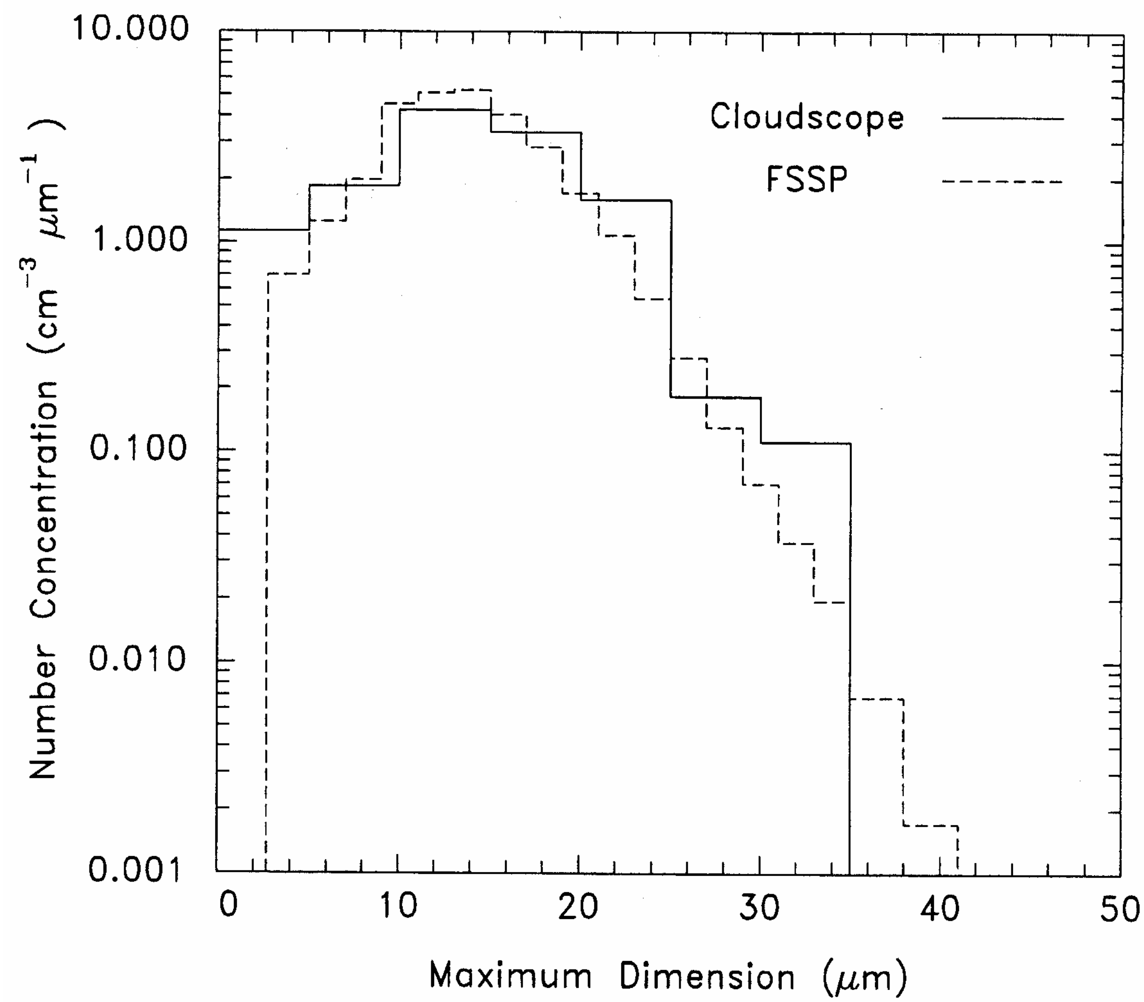

Figure 1. Comparison of size spectra measured by the CS and FSSP for hexagonal columns in a laboratory grown ice cloud.

The FSSP and 2DC were intercompared by Gayet et al. (1996), who found good agreement in the overlap region near 50 μm when SD 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. The criteria used for accepting FSSP data was that the extrapolated FSSP SD had to intersect the measured 2DC SD in either the first or second usable bin. This acceptance criteria, resulted in discarding only 7% of the SDs, suggesting the FSSP and 2DC size spectra were reasonably continuous for this large dataset.

Another acceptance criteria was also applied, SDs must have a large particle mode from the 2DC and a small mode from the FSSP, with at least four bins in each mode having concentrations >0.0008 l^{-1} μm^{-1}. The data suggested this threshold was needed for adequate statistics on bin concentration. Moreover, at least four bins were needed for the gamma fitting procedure to produce meaningful SD parameters.

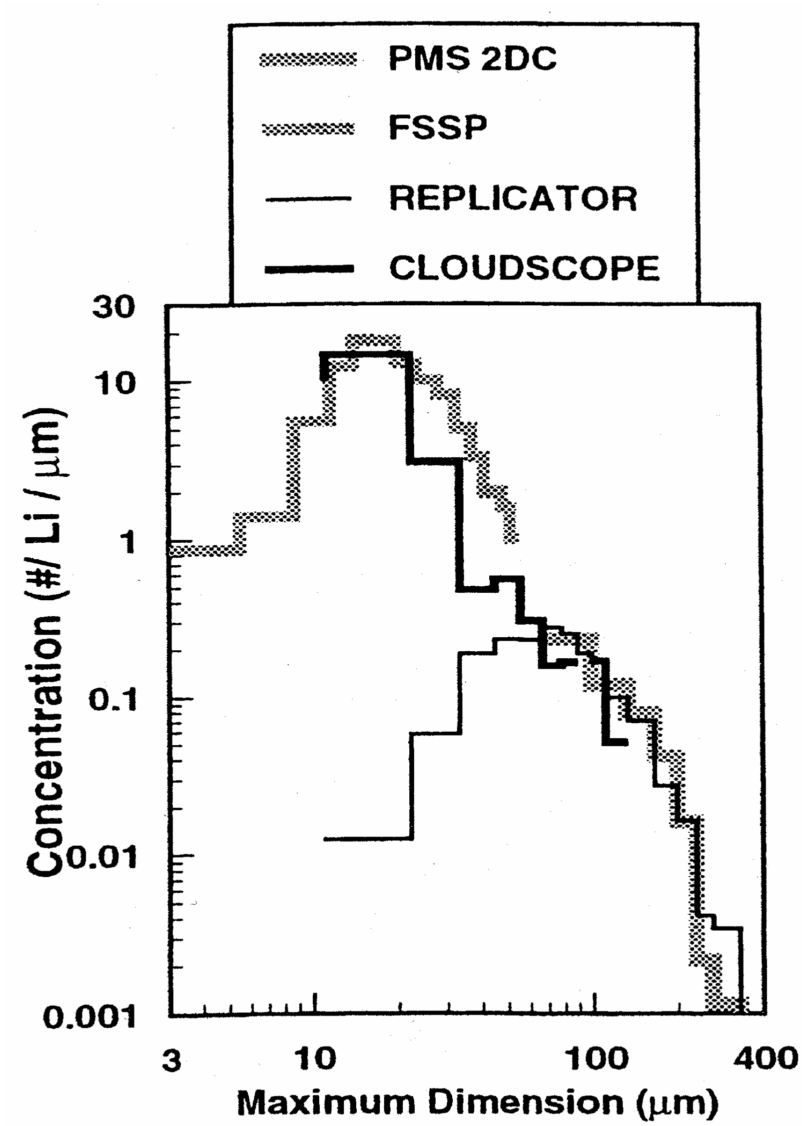

Figure 2. Size spectra from September 26, 1997, U.S. Department of Energy (DOE)-ARM Program IOP, Hurricane Nora outflow, 19:09:15 - 19:11:00 Universal Time Coordinates, -48.3°C to -50.3°C, 11.95 km to 12.18 km, T.A.S. = 118.5 m/s.

Datasets

The most comprehensive available observations of tropical anvil cirrus that include data from colder temperature range (less than -55°C) were made during the field experiment CEPEX. This study employs data from all three case studies during CEPEX: March 17, April 1, and April 4, 1993.

Based on recent work (Arnott et al. 2000) and the discussion in Section 2, the FSSP appears to be a viable instrument for approximating the concentration and sizes of small ice crystals for the cirrus clouds. Therefore, the small particles of the SD ($\overline{D} \leq 100$ µm) in this study were characterized using the FSSP. The large ice particles were characterized from laser imaging 2DC probe measurements.

Recent studies (Donovan 2003) strongly support the notion that in general ice-cloud SDs can not be adequately characterized by monomodal distributions. Previous tropical cirrus parameterizations (McFarquhar and Heymsfield 1996; 1997; Mitchell et al. 1999) represented CEPEX measured size spectra as bimodal with a minimum or shoulder near 100 µm. Comparison of FSSP – CEPEX SD (in black), plotted together with Mitchell (2000) tropical parameterization (in blue) and McFarquhar (1997) CEPEX VIPS tropical small mode parameterization (in red) are shown in Figure 3 for a temperature range -60°C to -50°C.

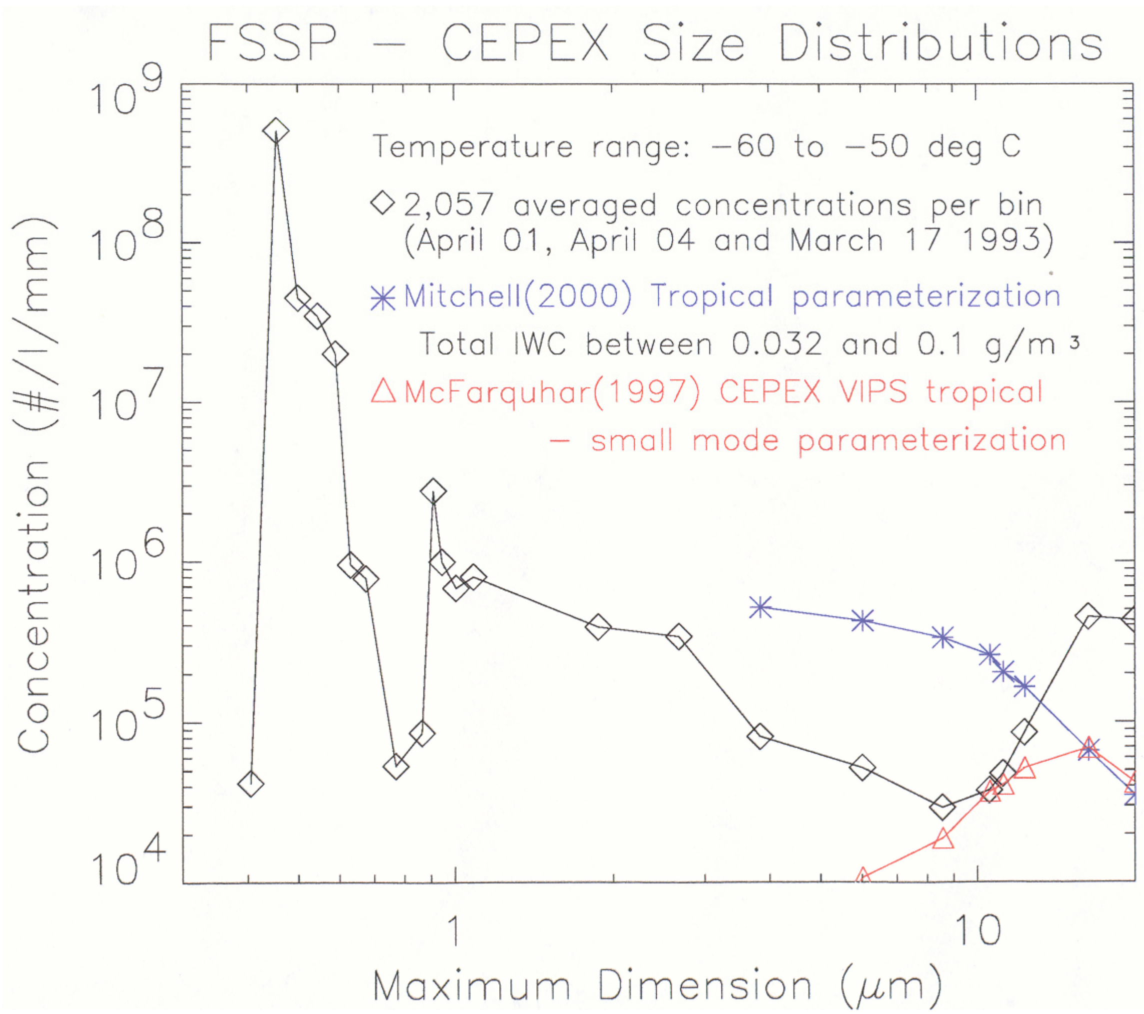

Figure 3. Comparison of FSSP - CEPEX SD (in black), plotted together with Mitchell (2000) tropical parameterization (in blue) and McFarquhar (1997) CEPEX VIPS tropical small mode parameterization (in red).

However, careful examination of the FSSP and 2DC probe spectral data from all three cases (March 17, and April 1 and 4, 1993) shows the trimodality (Figures 4, 5, and 6) of the tropical cirrus spectra. The most natural way is to follow what the data already suggest and to incorporate the new – very small particle mode in our parameterization efforts. In this paper, we use the term bimodal and trimodal not in a strict sense mandating that two peaks or three peaks must be evident in a SD, but simply to indicate that two, respectively three distinct populations of ice particles are evident, although in all three case studies three peaks in the SD were present. Thus, we define three distinct populations – three modes: (1) very small (from 0.77 μm to 8.7 μm), (2) small (from 8.7 μm to 105 μm), and (3) large (from 105 μm to 3000 μm).

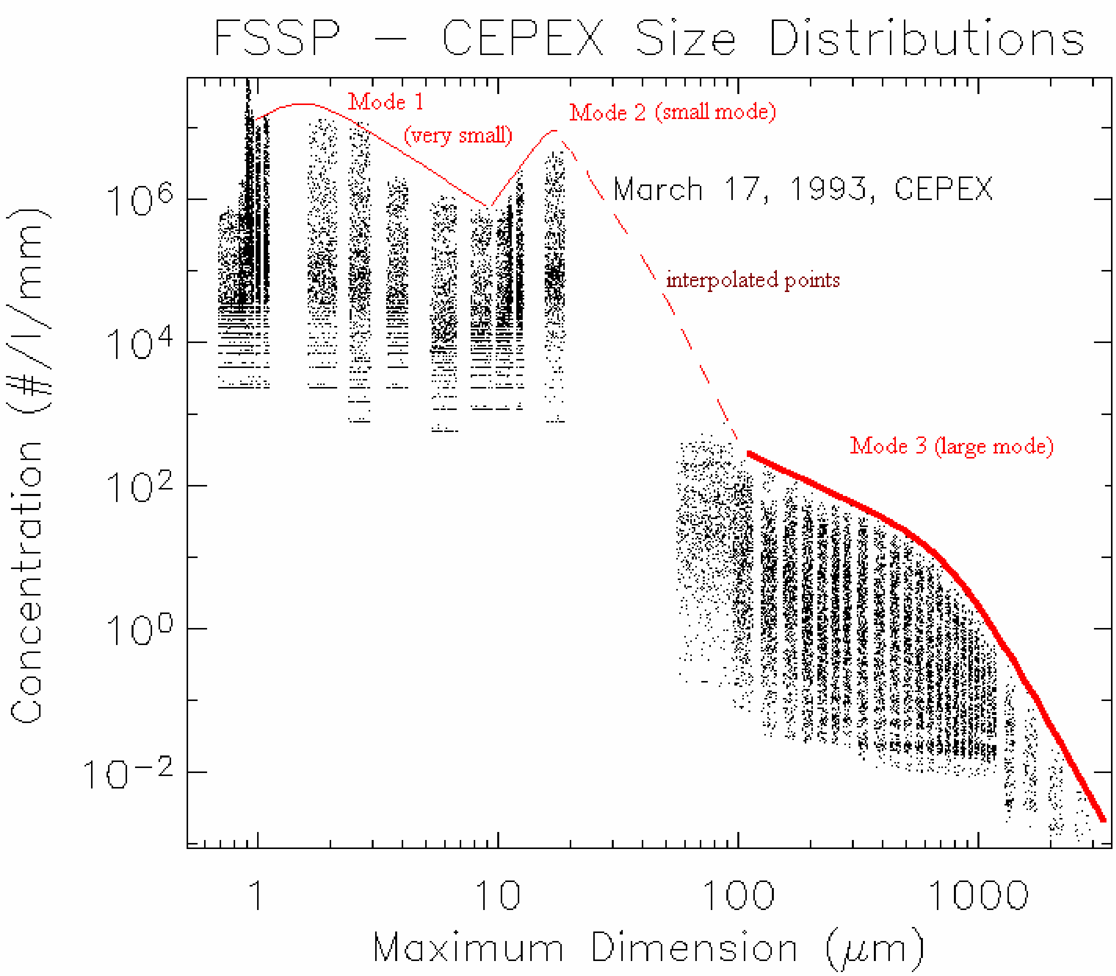

Figure 4. CEPEX FSSP and 2DC data for March 17, 1993. Naturally, the three modes: (1) very small, (2) small, and (3) large are present. Mode 1 (very small) has been ignored in the previous parameterization studies.

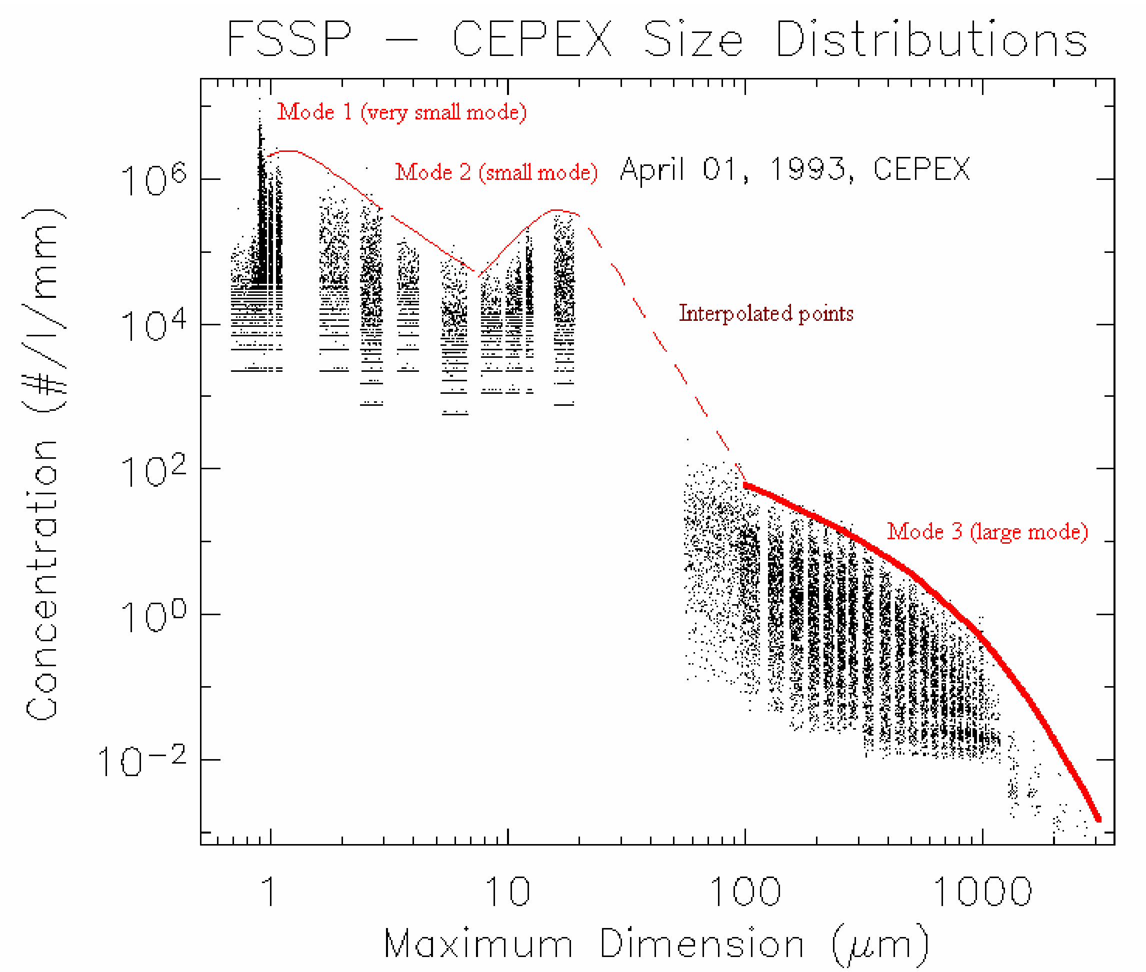

Figure 5. Same as Figure 3-2, but for CEPEX April 1, 1993. The three modes are present.

Parameterizing the Very Small, Small and Large Modes

5,546 SDs were used in this parameterization. The size range of the FSSP-300 used was 0.77 μm to 21 μm, while the usable size range for the 2DC probe was 60.0 μm to 3,000.0 μm. We use linear interpolation between the last FSSP and the first usable 2DC bins and approximate the Mode 2 in that matter. Ten additional data points for each of the 5,546 SD were created, allowing FSSP data to be considered continuous with 2DC spectra and used for determining SD parameters.

We parameterize SDs as trimodal (see Figures 4, 5, and 6) with all three modes: (1) very small, (2) small, and (3) large mode, expressed as a gamma distribution having the form:

$$N(D) = N_o D^{\nu} \exp(-\lambda D) \qquad (1)$$

Every SD analyzed in this study exhibited three distinct populations as illustrated in Figures 4, 5, and 6. The SD parameters D, λ, and ν in Table 1 were determined from the probe measurements, using the formulas, given in Mitchell (1991) and also used in Ivanova (2001).

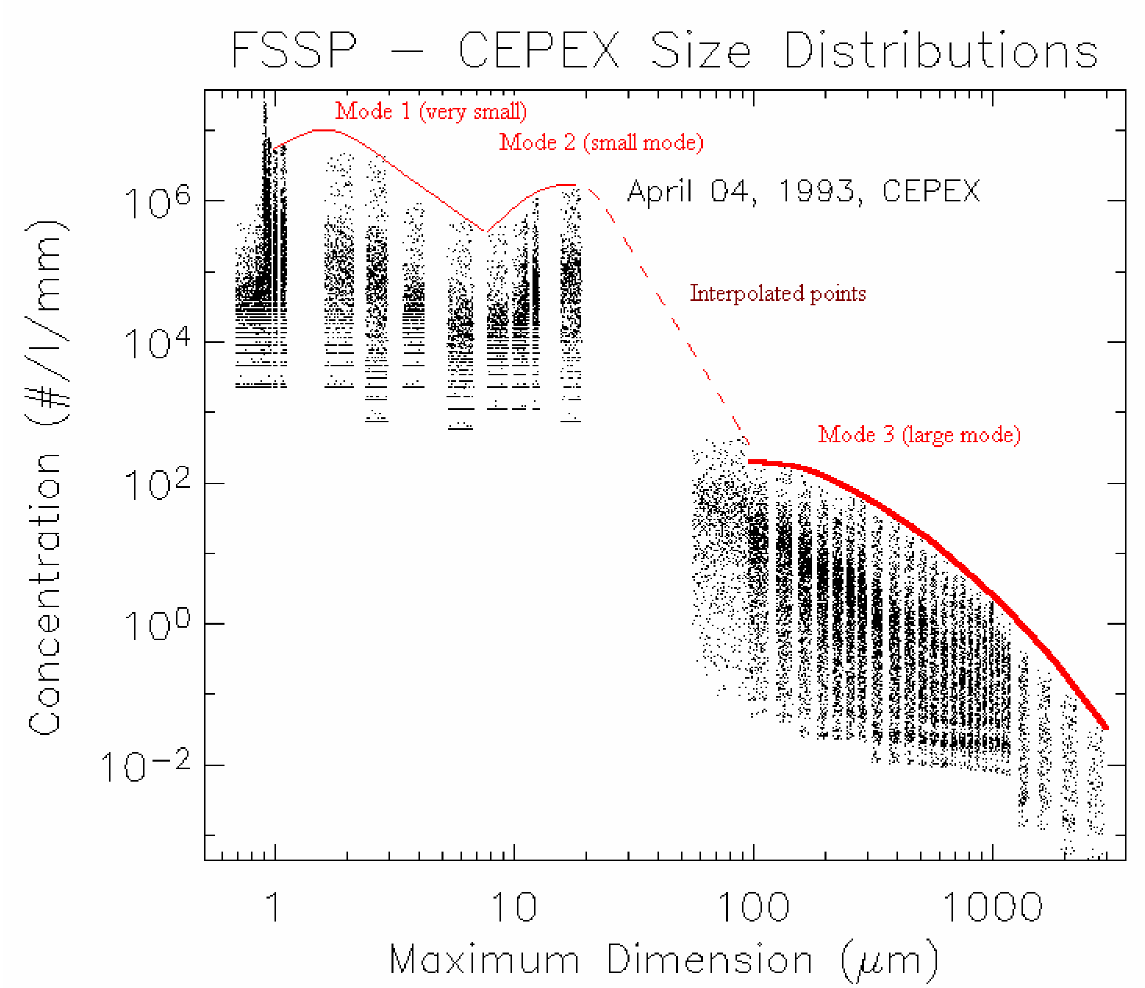

Figure 6. Same as Figure 3-2, but for April 4, 1993. The three modes are well distinguished.

Table 1. Trimodal distribution parameters, which are approximated as constants. The crystal shape assumed is Planar polycrystals.

Parameter	Value	Standard Deviation
$\overline{D}_{-1}$	2.4738	1.1672
λ_1	28130.41	13093.315
υ_1	6.0212	3.6783
$\overline{D}_{-2}$	18.06	4.3218
λ_2	2779.81	754.508
υ_2	4.02	1.3814

The SD parameterization resulted in the finding that the standard deviations associated with the mean values of the SD parameters in Table 1 are sufficiently small(for practical purposes) to regard these parameters as constants. This leaves the SD parameters of the large mode. They can be estimated in terms of cloud temperature T, because $\overline{D}_3$ was correlated with sampling temperature T as shown in Figure 7. The resulting best fit equation is:

$$\overline{D}_3 = 332.58 \exp(0.0335\ T), \tag{2}$$

where T and D_3 are in Celsius and micrometers, and the correlation coefficient is 0.94.

$N_{o,1}$, $N_{o,2}$, and $N_{o,3}$ can be estimated through the manner in which IWC is partitioned between the large, small and very small modes (named here as mode 3, 2, and 1).

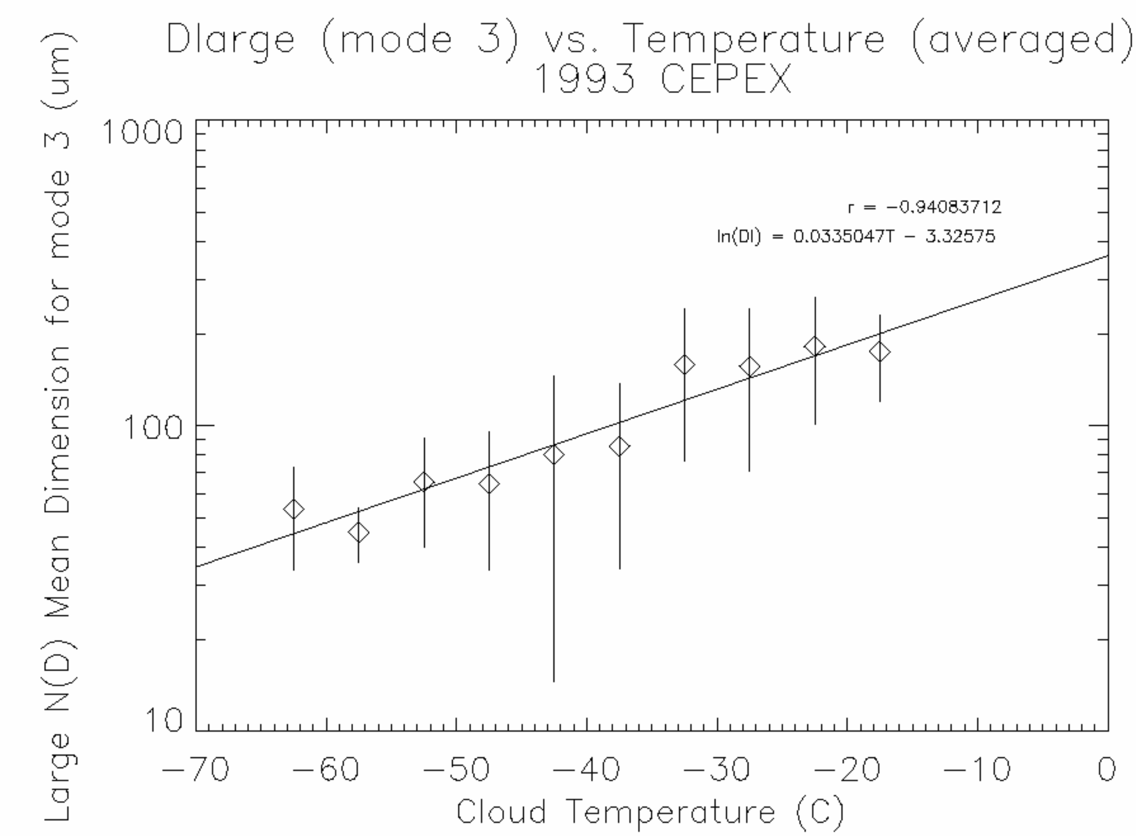

Figure 7. Mean dimension measured by the 2DC vs. temperature for this study (CEPEX). Vertical bars are standard deviations. Note the high correlation coefficient r = - 0.9408.

A flow chart summarizing this methodology is shown in Figure 8, illustrating the procedure for acquiring all nine of the gamma parameters for trimodal size spectra. The SD constant values were obtained directly from measurements, and are listed in Table 1. We assume planar polycrystals for modes 2 and 3 (small and large) and spheres for the very small Mode 1.

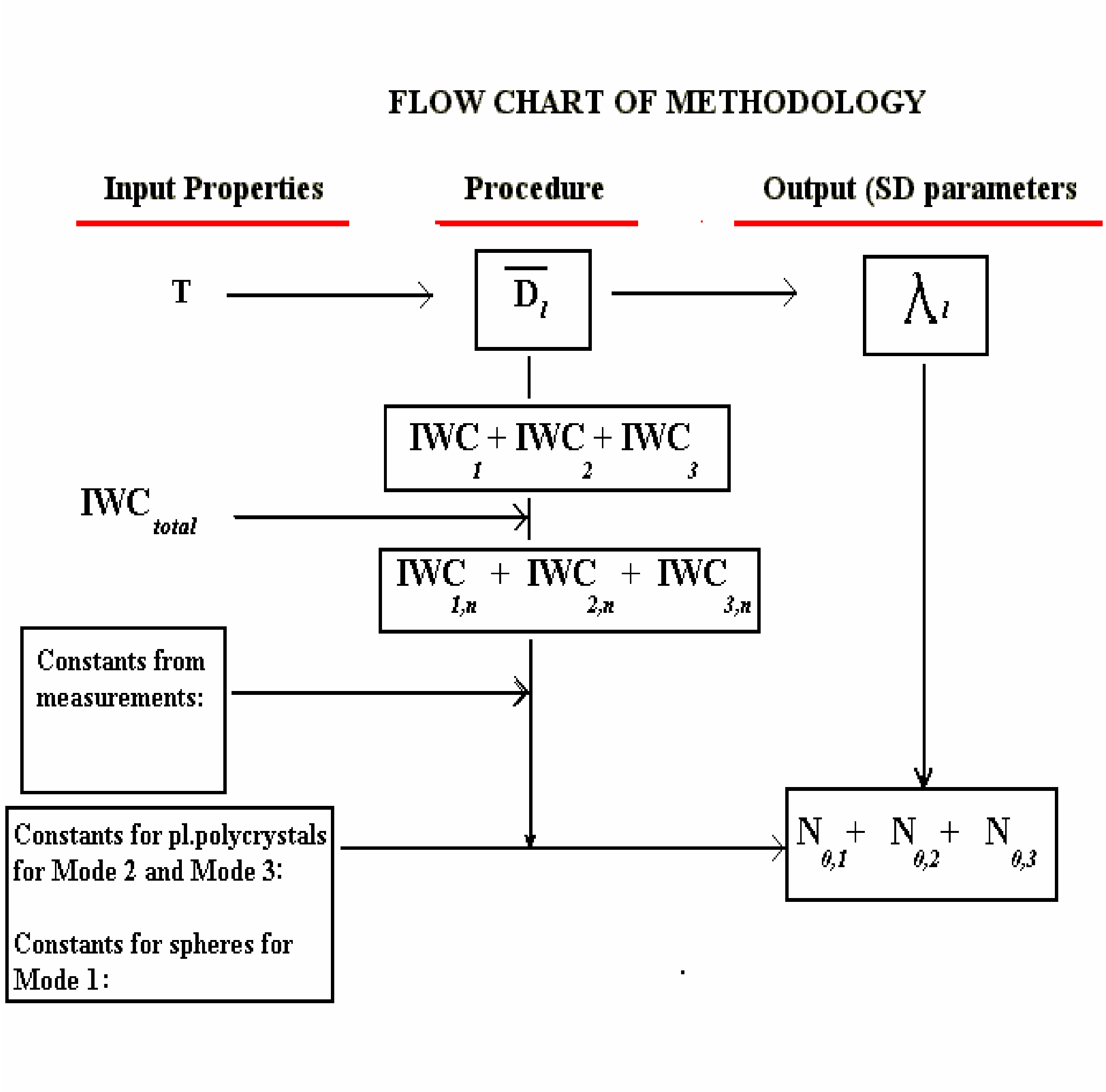

Figure 8. Flow chart describing the methodology used to parameterize tropical trimodal size spectra. Note: Planar polycrystals are assumed for the shape of Mode 2 and Mode 3 ice crystals and spheres are assumed for the very small Mode 1 crystals. This methodology illustrates the procedure for acquiring all nine of the gamma parameters for trimodal size spectra. SD constant values were obtained directly from measurements and are listed in Table 1.

After the IWC partitioning is done and the three modes, (1) very small, (2) small, and (3) large are normalized to total IWC. Relationship, describing the dependence of $IWC_{1,n}$ (for the very small mode) is given here, following some assumptions:

$$F_{iwc} = -1.633x10^{-4}T - 0.005453 \tag{3}$$

$$IWC_{1,n} = F_{iwc} (IWC_{tot}),$$

where $F_{iwc} > 0.0001$.

This relationship and the relationships for Mode 2 and Mode 3 are shown in Figure 9. Mode 1(very small) $IWC_{1,n}$ partitioning is depicted with the black dots, Mode 2 (small) with the red triangles, and Mode 3 (large) with the blue diamonds.

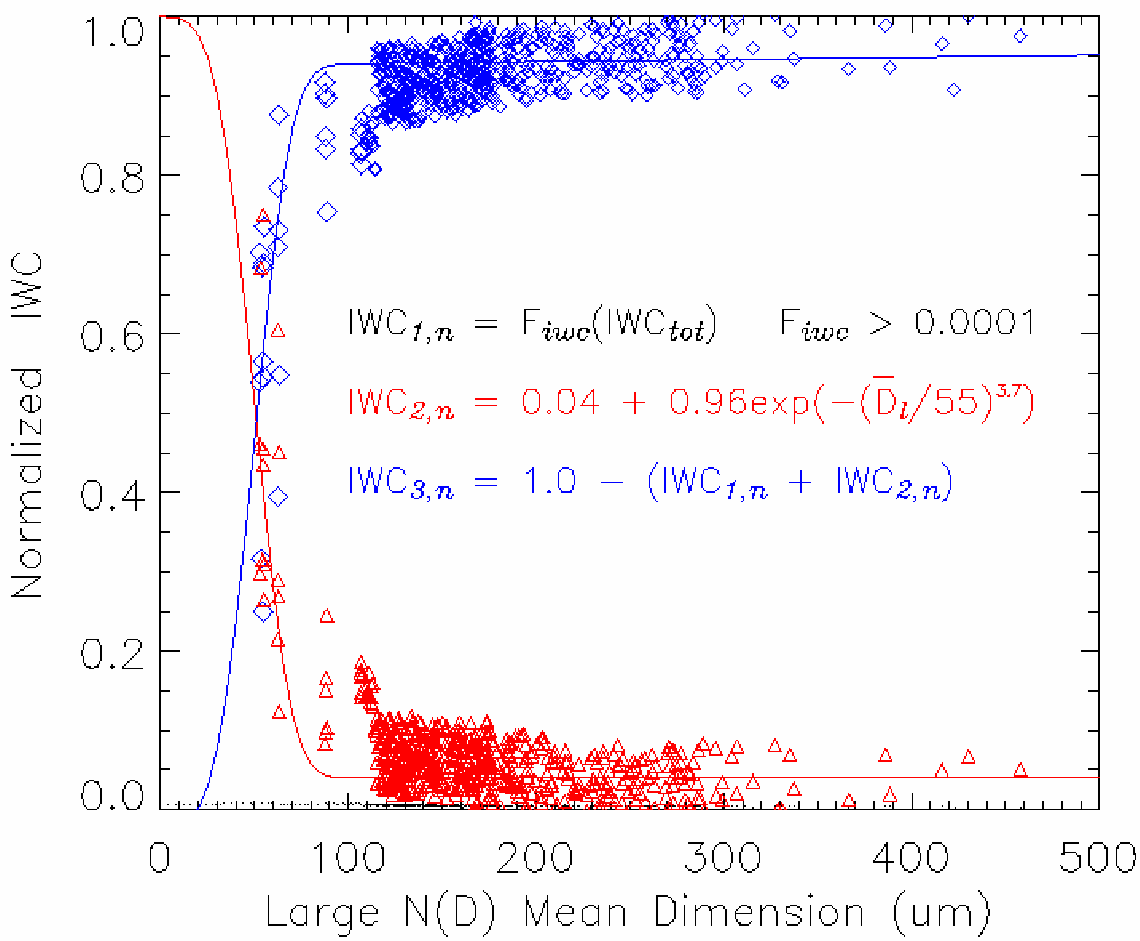

Figure 9. Normalized IWC calculated from the FSSP and 2DC related to the large mode (Mode 3) mean size D.

This is a work in progress and we plan to extend our research looking at the degree of variation between the SD parameters, the temperature T and the variations of the IWC observed at any given temperature range. We are going to repeat the parameterization process with different crystal shape assumptions: hexagonal columns, bullet rosettes, etc.

Main Findings and Conclusions

A new trimodal tropical SD parameterization is introduced. The general behavior of this scheme is demonstrated in Figure 10, where three trimodal SDs are predicted for the same IWC, but different temperatures T. The trend shown is different from the one which characterizes our mid-latitude scheme (Figure 11).

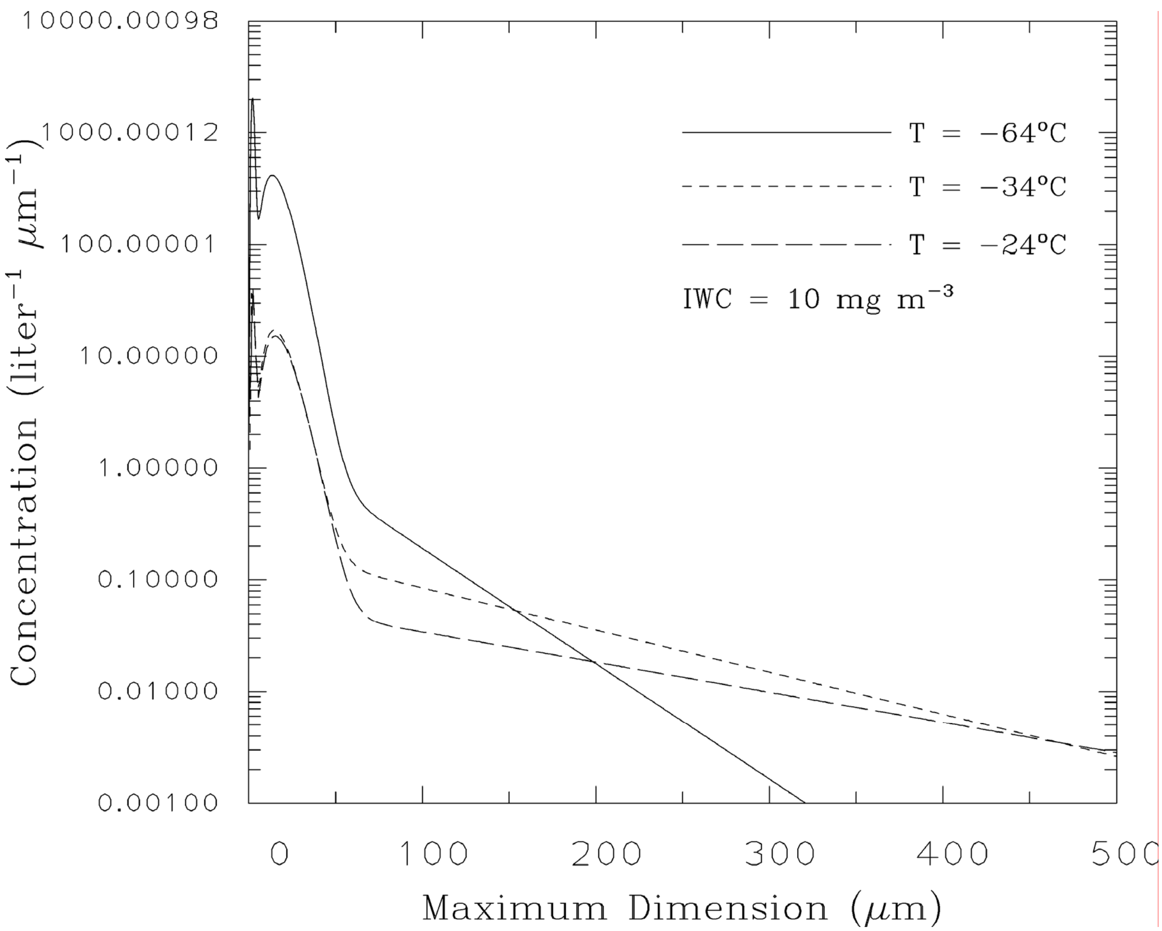

Figure 10. Size spectra predicted by the new trimodal tropical parameterization.

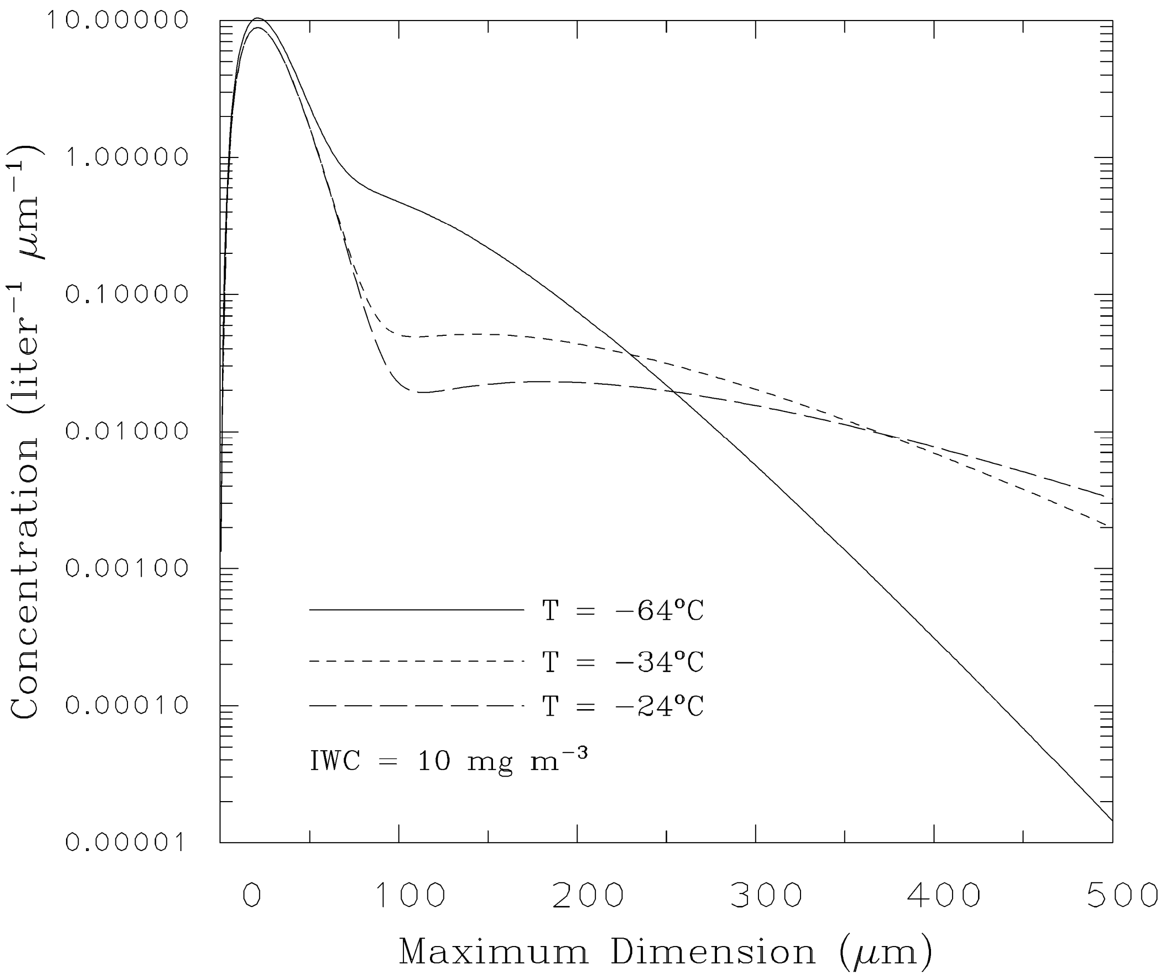

Figure 11. Size spectra predicted by our mid-latitude scheme. Note that not only the concentration of the small ice crystals (D <100 μm) is much higher for the tropical cirrus there are other significant differences in the particles SD behavior.

The concentration values of the very small mode and the small mode in the tropical cirrus is about two magnitudes higher than the concentrations of the small mode in the non-convective cirrus and as temperature decreases beyond -35°C, the magnitude of the small mode is enhanced with the tropical scheme, but the opposite occurs with the mid-latitude scheme. This is a fundamental finding, and indicates that the radiative properties of tropical and mid-latitude cirrus are considerably different for the same IWP. For example, tropical cirrus should reflect more sunlight at colder temperatures for the same IWP.

This finding may also point to the different mechanisms by which convective and non-convective cirrus are generated. The temperature dependence of their size spectra may yield important clues for unraveling the underlying physics that determine the evolution of size spectra in these different cloud systems.

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