The Impact of Small Ice Crystals and Bimodal Size Spectra on Cloud Radiative Forcing in Tropical Cirrus

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Introduction

Addressing the question of the presence of large concentrations of small ice crystal particles (< 50 μm in diameter) in cirrus clouds has been hampered by the inability to routinely measure crystals of such sizes. Recent in situ measurements of cirrus-size distributions during a U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) intensive operational period (IOP) of Hurricane Nora, using a Desert Research Institute (DRI) Cloudscope collocated with a Forward Scattering Spectrometer Probe (FSSP), show a comparable peak ice crystal concentrations between the two probes for maximum crystal dimension D < 50 μm (Arnott and Hallet 1998). These measurements gave bimodal size spectra for cirrus, with peak concentrations for D < 100 μm often 3 orders of magnitude greater than peak concentrations for D > 100 μm.

Tropical cirrus pose even greater measurement difficulty due to the extreme height and cold of the cloud environment. Observations from two recent experiments have given more evidence of small particles and bimodal size distributions. First, ground-based lidar-radiometer (LIRAD) measurements made during the ARM Pilot Radiation Observation Experiment (PROBE) in the tropical western Pacific produced estimated "α" ratios of visible (0.532 μm) extinction to infrared (10.84 μm) absorption efficiency (Platt et al. 1998). For temperatures < -45 °C, α ratios exceeded 4. Whereas size spectra measured by the two-dimensional cloud (2DC) probe will more typically yield α's near 2.0. Mitchell and Platt (1998) showed that large concentrations of small particles could partially account for α > 2 by using the cirrus radiation treatment of Mitchell et al. (1996a).

Secondly, results from the Central Equatorial Pacific Experiment (CEPEX) give bimodal size distributions showing size spectra inferred from a 2DC probe to be bimodal with a minimum or shoulder near D = 100 μm where D is the maximum particle dimension (McFarquhar and Heymsfield 1996, 1997). Mitchell et al. (1999) describe the analysis of these measurements and the subsequent development of parameterizations relating to them appropriate for implementation into general circulation models (GCMs). This paper explores the radiative effect of these parameterizations in terms of the radiative cloud forcing differences between the tropical cirrus clouds with and without the bimodal size spectra using the Mitchell et al. (1996b) non-spherical ice optical property parameterizations.

Particle Size Distributions

To treat bimodal size distributions within tropical cirrus clouds, it is assumed that these distributions can be represented according to

$$N(D)_{bim} = N(D)_{sml} + N(D)_{lrg} \quad (1)$$

where N(D) is a gamma size distribution of form

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

and D is the maximum crystal dimension and N_o, ν, and λ are constants characterizing the distribution. Following Mitchell et al. (1999), a large particle mode distribution, $N(D)_{lrg}$, for D > 90 µm is fit to the 2DC microphysical measurements from CEPEX using Eq. (2) with $\nu = 0$. A small particle mode distribution for D < 90 µm was inferred from Modis Airborne Simulator (MAS) radiances and microphysical observations, using the Mitchell et al. (1996) ice cloud radiation scheme and a Monte Carlo radiative transfer model (Macke et al. 1995). The distribution, $N(D)_{sml}$ also assumes $\nu = 0$, but has a slope equivalent to increasing the first usable 2DC size bin (30 µm to 60 µm) concentration (known for its uncertainty) by a factor of 1.5. This distribution gives particle concentrations for D < 90 µm very similar to those reported using the video ice particle sampler (VIPs) by McFarquhar and Heymsfield (1997) and also similar to concentrations inferred from FSSP measurements from previous studies. Mitchell et al. (1999) noted a correlation between the small and large particle slopes as

$$\lambda_{sml} = 1.49\, \lambda_{lrg} + 583. \quad (3)$$

An ice water content (IWC) partition relationship between $N(D)_{lrg}$ and $N(D)_{sml}$ was developed by integrating the observed size spectra in the form of Eq. (2) from the 2DC probe observations excluding the first two usable size bins and assuming planar polycrystal particle mass relationships to determine $(IWC)_{lrg}$ (see Mitchell et al. 1996). Thus, a normalized relationship between $N(D)_{lrg}$ and $N(D)_{sml}$ becomes

$$IWC_{sml,n} = 0.025 + 0.975 \exp(-\,(\overline{D}_{lrg}/80)^2) \quad (4)$$

such that $IWC_{lrg,n} = 1 - IWC_{sm,n}$, $\overline{D}_{lrg}$ is the mean maximum dimension for the large particle distribution, and $\overline{D} = 1/\lambda$ using Eq. (2) when $\nu = 0$.

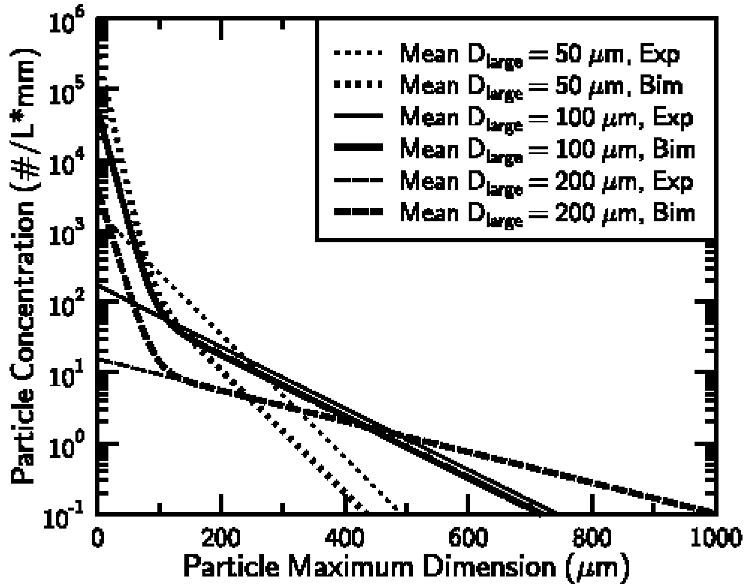

Figure 1. Examples of three particle size distributions for the indicated $\overline{D}_{lrg}$ sizes for both the bimodal (Bim) and the pure exponential (Exp) distributions.

Using these relationships, we now explore the radiative effects of the bimodal size distributions compared to a simple exponential distribution of the form Eq. (2) with $\nu = 0$ normalized to the same IWC. Examples of these distributions are shown in Figure 1 for $\overline{D}_{lrg}$ = 50 µm, 100 µm, and 200 µm.

Cloud Radiative Properties

To understand the radiative implications of these bimodal size spectra, we have performed radiative transfer calculations for two idealized cold tropical cirrus clouds, both 2 km deep having a mean temperature of 210.5 °C, IWC = 5 mg m^{-3}. The first of these clouds assumes a bimodal size spectra and the second a purely exponential size spectra, as noted in the previous section. A two-stream radiative transfer model described in Stackhouse and Stephens (1991) was used with a McClatchy tropical atmosphere (McClatchy et al. 1972). The model is used for computing the fluxes in both the shortwave (SW; 0.28 µm to 3.8 µm) and longwave (LW; 3.8 µm to 500 µm). For both cirrus types, $\overline{D}_{lrg}$ is varied from 3 µm to 200 µm, covering a broad range of cirrus size spectra. The surface albedo for these cases is spectrally fixed to 0.04 and the surface emittance is 1. The solar zenith angle is fixed at 50.46°. This value represents the daytime averaged solar zenith angle at the equator during equinox characteristic of the CEPEX period. Since daylight lasts 12 hours at this location and time, the solar irradiance at the top of (the) atmosphere (TOA) is reduced by a factor of 2 to approximate a daily averaged solar flux.

Figure 2 gives the difference between the bimodel and exponential distributions (bimodal-exponential) for the effective albedo and emittance of the clouds as a function of $\overline{D}_{lrg}$ for a set of ice water paths (g m^{-2}). Towards small mean particle sizes, the differences between the bimodal and exponential distributions decrease in both albedo and emittance due to the reduction of weight of the large mode. Toward large mean particle sizes, the small mode is reduced, reducing the effects of the small particles. The peaks then represent the mean size at which the effect of the small particle mode of the distribution is most important to the radiative properties of the cloud. The peaks are observed to shift to larger mean sizes as the ice water path (IWP) of the cloud increases.

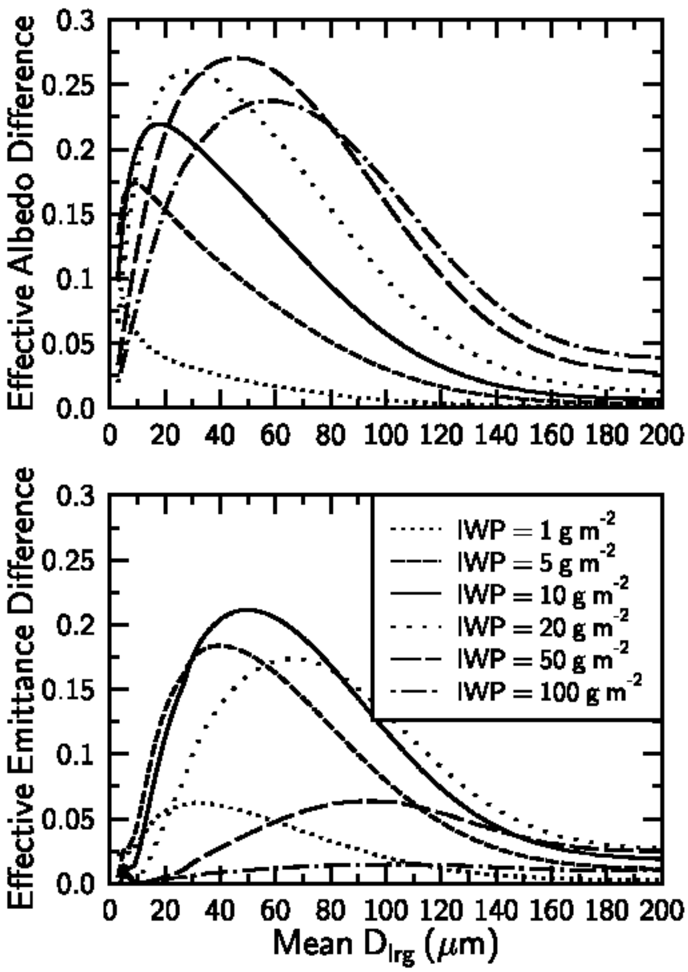

Figure 2. The difference (bimodel-exponential) between the effective albedo (top) and emittance (bottom) as a function of $\overline{D}_{lrg}$ for a series of ice clouds with IWP g m^{-2} as labeled.

Note also that the peak albedo difference increases to 0.275 with IWP to 50-g m^{-2}, then decreases to 0.24 at 100-g m^{-2}. Similarly, the emittance difference increases to 0.22 at 10-g m^{-2}, then decreases to 0.02 at 100-g m^{-2}. These effects are due to the albedo and emittance approaching their asymptotic limits with increasing cloud thickness. The fact the maximum differences reach their peak values at different IWPs implies that any errors due to the underestimation of small particles affect the albedo differently from the emittance depending upon the mean cloud particle size and thickness.

Figure 3 shows the LW radiative heating differences of the entire cloud layer between the clouds with a bimodal distribution and with the pure exponential size distribution. This plot very closely resembles the emittance plot of Figure 2, but we note that for these clouds the LW heating dominates at cloud base and the differences reach a maximum of 4.5 K/day at 10-g m^{-2}. The daytime averaged SW heating rate differences (not shown) are generally less than 1.5 K/day.

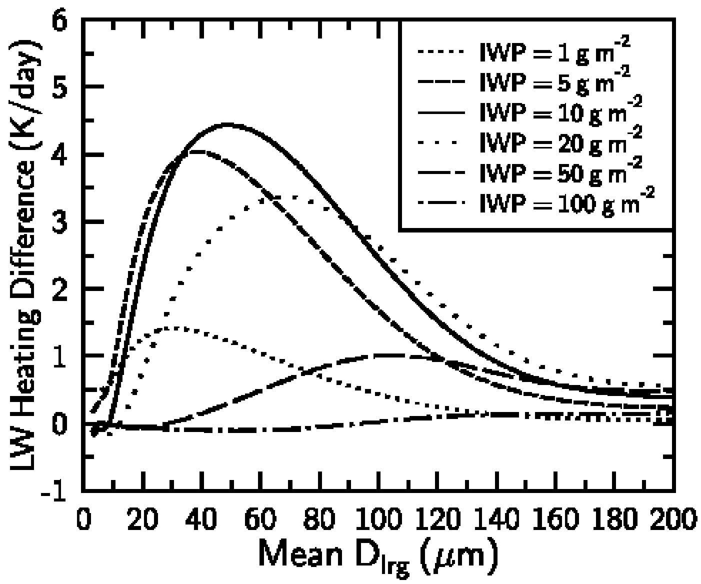

Figure 3. Same as Figure 2 except for the LW heating difference (K/day) for the entire cloud layer.

SW, LW, and Net Cloud Forcing

Figure 4 presents the difference in the TOA cloud radiative forcing between the clouds with and without a bimodal size distribution for SW, LW, and net radiative fluxes as a function of $\overline{D}_{lrg}$. A family of curves for the IWPs of Figures 2 and 3 are also shown. The TOA radiative forcing is defined as

$$C_{sw,lw,net} = F_{clear\text{-}sw,lw,net} - F_{cloudy\text{-}sw,lw,net}, \quad (5)$$

where F is upward flux at TOA.

Figure 4 gives relationships that mirror the albedo and emittance properties of the clouds, but the flux differences are indicative of the average daily flux for the SW, LW, and net fluxes. As noted in Section 3, the fact that the peak differences between the SW and LW occur at different mean particle

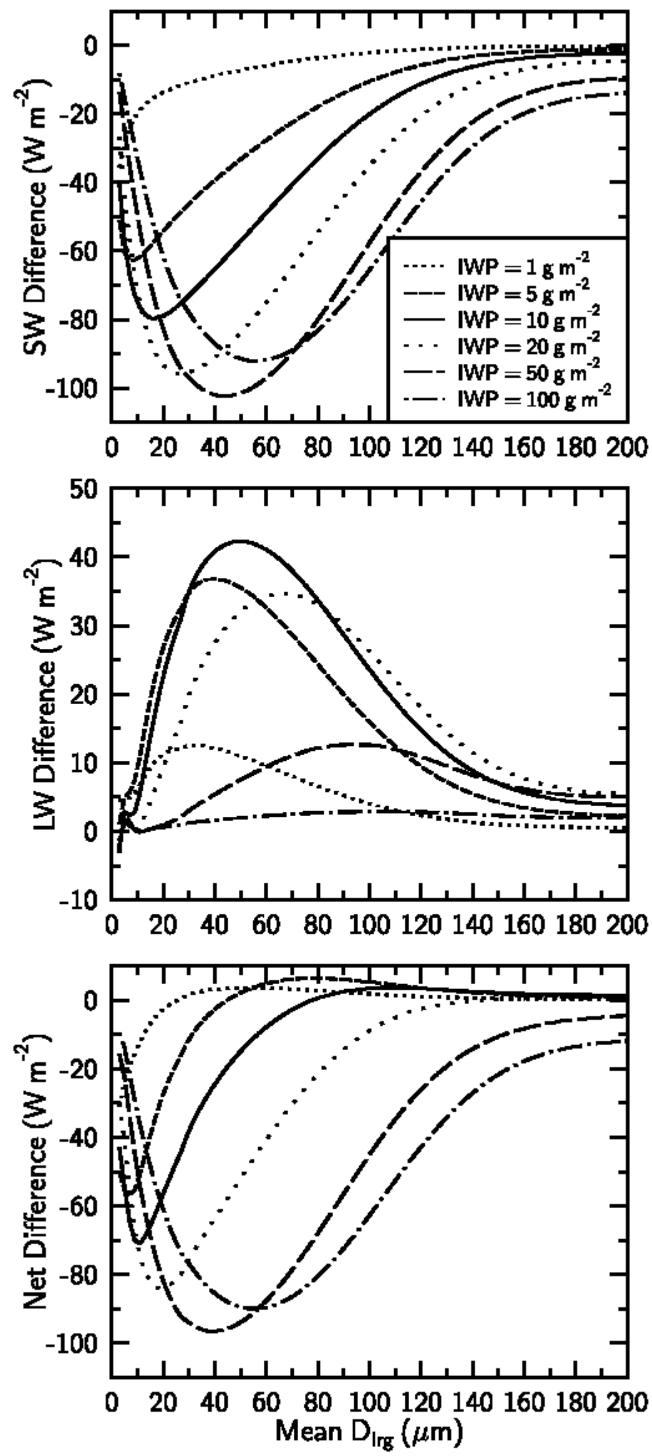

Figure 4. TOA radiative cloud forcing differences between clouds with and without a bimodal size distribution for the SW (top), LW (middle) and Net (bottom) as a function of for the IWP's indicated.

sizes and water paths means that these differences are complimentary in the net forcing for only certain conditions. Therefore, in most cases, the use of bimodal distributions has enhanced the cloud albedo relative to clouds with exponential size spectra more greatly than using bimodal spectra has reduced the emitted flux. Thus, net cloud forcings is more negative using the bimodal spectra. The peak enhanced albedo effect is increasingly dominate over the enhanced emittance effect for IWPs between 10 g m^{-2} and 50 g m^{-2}, but begins to lessen for thicker clouds. Thus, we find that the inclusion of small particles in the size distributions is important for an optimal range of mean particle sizes. The extent to which tropical cirrus clouds are prevalent and persistent at these sizes and thicknesses determines the relative importance of treating the microphysical properties with the more complex bimodal distributions. Future work in this research will focus upon comparing these simulated radiative properties with actual radiative observations, as well as GCMs to look at the possible climatic implications of these results.

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