Microphysical Interpretation of LIRAD Extinction/Absorption Ratios Using a Microphysics-Radiation Scheme

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Introduction

The role of undetected small ice crystals (D < ~ 70 μm maximum dimension) in ice clouds still represents a major uncertainty to understanding their radiative properties. Ice crystal impaction devices such as replicators (Arnott et al. 1994) and video imaging samplers (McFarquhar and Heymsfield 1996) have provided important information, but because the data analysis is labor intensive, climatological information remains elusive. The ice cloud-radiation scheme of Mitchell et al. (1996a) has been revised somewhat to include bimodal size spectra and photon tunneling processes. This work gives an example of how this radiation treatment can be combined with remote measurements to infer information on ice particle size spectra, N(D), or, more specifically, on the sizes and relative concentrations of ice crystals contained in the small particle mode of inferred bimodal size spectra.

Ground Based Remote Sensing

The Commonwealth Scientific and Industrial Research Organization (CSIRO) lidar-radiometer (LIRAD) system was used in the Tropical Western Pacific (TWP) during the ARM Pilot Radiation Observation Experiment (PROBE), as described in Platt et al. (1998). Extensive cirrus clouds were observed at various periods over 3 days, with shorter-term cirrus on another 2 days, over a 3-week period in January through February 1993. None of the cirrus observed were associated directly with convective outflow, but appeared to form in deep moist layers often present in the upper troposphere. The moisture in which this cirrus formed was invariably supplied through convective transport at some earlier time. Cirrus ranged in depth from 0.7 km to 7.5 km, and in temperature from -7° C to -82° C. Maximum cloud top was 17.6 km. In total, 1120 lidar profiles were obtained in over 18 hours of observation. The LIRAD instrument measures the cloud backscatter coefficient at 0.532 μm and the cloud infrared radiance at 10.84 μm. Cloud height and depth were retrieved by lidar and cloud temperatures were retrieved with radiosonde data. One property derived from these is the ratio of visible extinction to infrared absorption efficiency, or α, measured at wavelengths of 0.532 μm and 10.84 μm, respectively. An excerpt from Platt et al. (1998) is shown in Table 1, giving α values over various temperature intervals. While uncertainties are large, there is a distinct shift toward larger α at temperatures < -45° C. The large number of measurements would suggest the trend is real.

Table 1. Measured temperature dependence of α during PROBE. Uncertainties are in ( ).

Temperature interval (°C)	α
-75 to -65	4.83 (2.00)
-65 to -55	5.26 (1.90)
-55 to -45	4.29 (1.40)
-45 to -35	1.77 (0.51)
-35 to -25	2.22 (0.55)
-25 to -15	2.67 (0.80)

Theoretical Evaluation of α

More traditional radiation treatments for ice clouds suggest α should be near 2.0 for strong absorption, with Q_{ext} and Q_{abs} being near 2 and 1, respectively. An attempt was made to explain the α values in Table 1 for T < -45 C by using the above radiation scheme. In deep cirrus, previous in situ measurements indicate large particles are bound to be present. Given this, the only way to explain these α ratios was to assume a small ice crystal mode of the size distribution, as illustrated in Figure 1, which peaks about 3.5 orders of magnitude above the large particle maximum, with a mean crystal length of about 10 μm. The ice radiation scheme was revised to produce these bimodal spectra by partitioning the ice water content (IWC) between the small and large particle distribution modes as a function of $\overline{D}_1$, the mean maximum dimension of the large particle mode. This is shown in Figure 2. This assumes that all the IWC resides in the small N(D) for $\overline{D}_1$ < 10 μm, while when $\overline{D}_1$ > 150 μm, only about 10% of the IWC resides in this mode. IWCs derived from observed small and large N(D) support this partitioning scheme (Mitchell et al. 1996b, Heymsfield and McFarquhar 1996, Knollenberg et al. 1993). Mean ice particle lengths corresponding to the small N(D) can be denoted $\overline{D}_{sm}$. Assuming $\overline{D}_{sm}$ = 10 μm, bimodal size spectra predicted by the scheme are shown in Figure 1 for four $\overline{D}_1$ values: 10, 50, 100 and 200 μm. Bimodality disappears ($\overline{D}_1 = \overline{D}_{sm}$) when $\overline{D}_1 \leq 10$ μm.

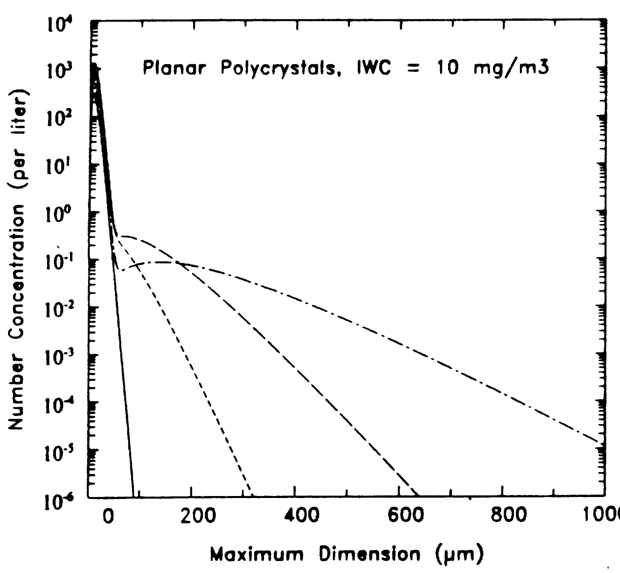

Figure 1. Examples of bimodal size spectra predicted in the ice cloud radiation scheme. From left-to-right, spectra refer to $\overline{D}_1$ = 10, 50, 100 and 200 μm.

Size spectra similar to these ($\overline{D}_{sm}$ near 10 μm, small N(D) peaking ~ 10^3 higher than the large N(D) peak) have been measured in mid-latitude cirrus [e.g., Platt et al. 1989; Platt 1997; Heymsfield and Platt 1984; unpublished ARM '94 Cloud Intensive Observation Period (IOP) results] using a

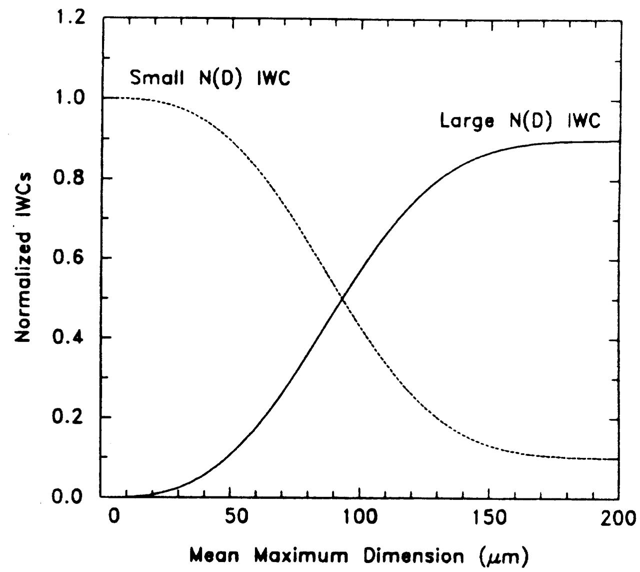

Figure 2. Assumed partitioning of IWC between the large and small N(D) in the radiation scheme.

forward scattering spectrometer probe (FSSP), which is unreliable for ice, but which may under some circumstances be accurate to within a factor of 2 or 3 (Platt et al. 1989). Such spectra have also been measured in tropical cirrus with the DRI ice particle replicator (Pueschel et al. 1997), and with an ASSP probe (Heymsfield and McFarquhar 1996).

The α ratios resulting from this formulation of the ice radiation scheme (assuming no tunneling except for spheres) are plotted in Figure 3 as a function of the size distribution median mass dimension (D_m) for various crystal shapes. It is seen that for D_m commonly found in cirrus (30 μm to 100 μm), α can be 4 or higher. Crystal shapes at T < -45 C are poorly understood, and α values plotted for rosettes or plates could easily apply to such shapes. Very similar results were obtained when photon tunneling processes were included, with slightly lower α values. Tunneling here can be viewed as processes by which photons beyond the area cross-section of a particle can be transmitted through the particle or absorbed, as predicted by Mie theory (Mitchell 1998). Although the role tunneling plays in ice crystal scattering/absorption processes is uncertain, this uncertainty does not have a large effect on α.

If $\overline{D}_{sm}$ is increased to 20 μm or larger, α ratios generally range between 2 and 3, even though the IWC partitioning relationship between the small and large N(D) remains the same. Hence, α > 3 appears to be a sensitive indicator of $\overline{D}_{sm}$.

Extinction and absorption efficiencies (Q_{ext} and Q_{abs}) corresponding to α in Figure 3 for planar polycrystals are plotted in Figure 4, with and without tunneling. A very different picture emerges regarding Q_{abs}, generally assumed to be near 1.0. This is due to the large contribution very small crystals make to the total size distribution projected area, P_t. These crystals allow radiation to pass through them, making absorption more dependent on IWC at 10.84 μm instead of only a function of P_t. In spite of the lower Q_{abs} values, absorption coefficients are relatively large (for a given IWC) due to higher P_t.

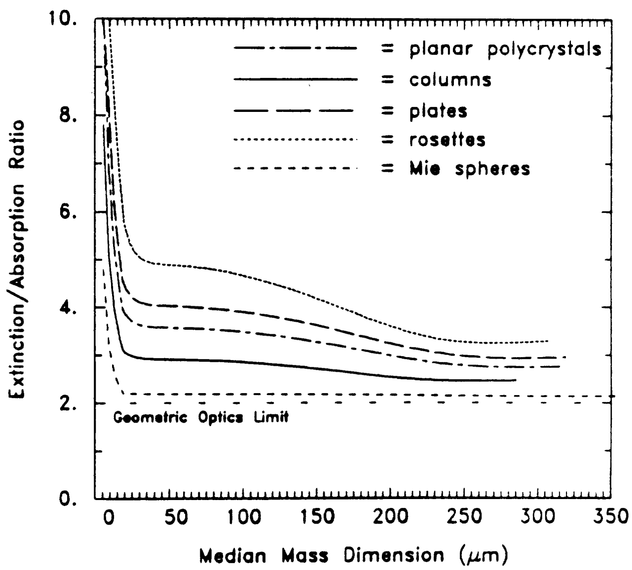

Figure 3. Ratios of visible extinction (0.532 μm) to IR absorption (10.8 μm) efficiency (α) in terms of D_m of size spectra similar to those plotted in Figure 1. Except for spheres, no tunneling is assumed.

Implications of High α

To explore how size spectra inferred from α > 3 might effect cirrus cloud albedo and emissivity, these properties were calculated using the scheme described here (version 2), and the scheme used previously in GCM work (version 1; Mitchell et al. 1998). The main difference between these schemes is the treatment of bimodal size spectra, where version 1 assumes $\overline{D}_{sm}$ = 40 μm and lower IWCs in the small particle N(D). Hence, crystals having D < 70 μm make a minor contribution to cloud radiative properties in version 1. Also, version 1 assumes phase functions or asymmetry parameters (g) based on randomized fractals for planar polycrystals. To emphasize the role of the small crystals, we assumed g values for hexagonal plates in version 2. Assuming an IWP of 15 g m^{-2}, a solar zenith

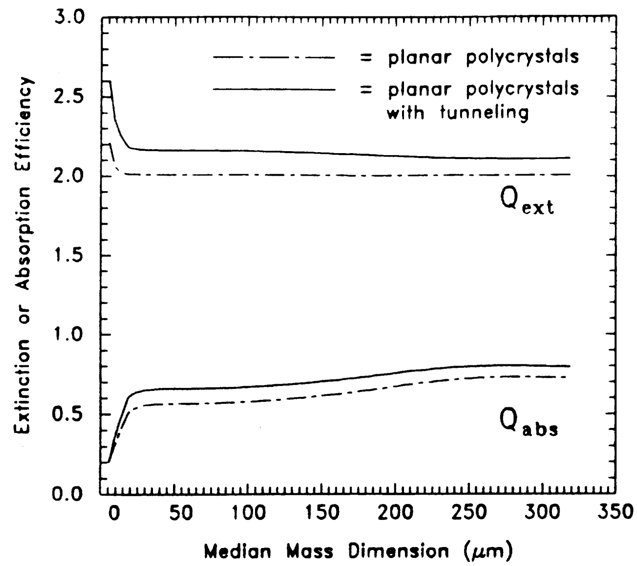

Figure 4. Absorption and extinction efficiencies corresponding to the planar polycrystal α values in Figure 3, along with values for full tunneling added.

angle of 55°, and a mean cloud temperature of 213°K, cloud albedos and emissivities are shown in Figures 5 and 6. Clearly one need not assume g 0.75 (i.e., fractals) to get high albedos. The implications of much brighter and blacker clouds at solar and terrestrial wavelengths for high

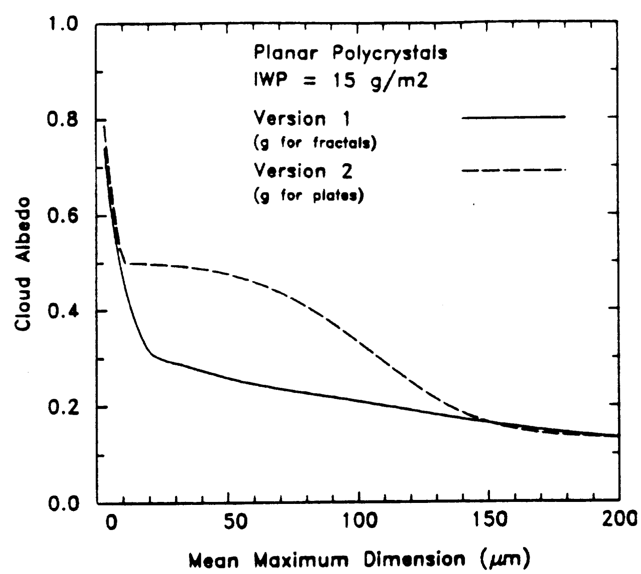

Figure 5. Comparison between versions 1 and 2 of the radiation scheme, illustrating the effect of small ice crystals in version 2. Mean dimension refers to $\overline{D}_1$.

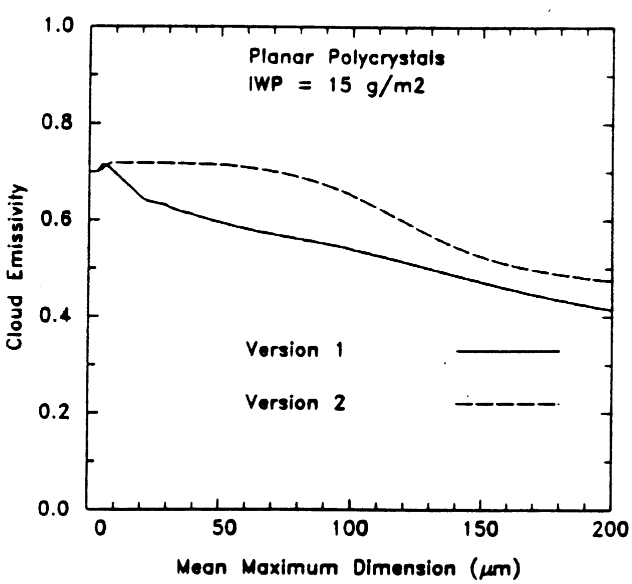

Figure 6. Same as Figure 5, but for emissivity.

α values underscores the need for in situ validation of LIRAD measurements and improved measurements of small ice crystals.

If size spectra inferred from LIRAD α values for T < -45 C are characteristic of tropical cirrus at these temperatures, it could have a significant impact on GCM predictions.

References

Arnott, W. P., Y. Dong, J. Hallett, and M. R. Poellot, 1994: Role of small ice crystals in radiative properties of cirrus: A case study, FIRE II, November 22, 1991. *J. Geophys. Res.*, **99**, 1371-1381.

Heymsfield, A. J., and C. M. R. Platt, 1984: A parameterization of the particle size spectrum of ice clouds in terms of ambient temperature and the ice water content. *J. Atmos. Sci*., **41**, 846-855.

Heymsfield, A. J., and G. M. McFarquhar, 1996: High albedos of cirrus in the tropical Pacific warm pool: Microphysical interpretations from CEPEX and from Kwajalein, Marshall Islands. *J. Atmos. Sci.*, **53**, 2424-2451.

Knollenberg, R. G., K. Kelly, and W. C. Wilson, 1993: Measurements of high number densities of ice crystals in the tops of tropical cumulonimbus. *J. Geophys. Res*., **98**, 8639-8664.

McFarquhar, G. M., and A. J. Heymsfield, 1996: Microphysical characteristics of three anvils sampled during the Central Equatorial Pacific Experiment. *J. Atmos. Sci.*, **53**, 2401-2423.

Mitchell, D. L., A. Macke, and Y. Liu, 1996a: Modeling cirrus clouds. Part II: Treatment of radiative properties. *J. Atmos. Sci.*, **53**, 2967-2988.

Mitchell, D. L., S. Chai, Y. Liu, A. J. Heymsfield, and Y. Y. Dong, 1996b: Modeling cirrus clouds. Part I: Treatment of bimodal size spectra and case study analysis. *J. Atmos. Sci.*, **53**, 2952-2966.

Mitchell, D. L., J. M. Edwards, and P. N. Francis, 1998: General circulation model sensitivity of globally averaged albedo and outgoing longwave radiation to ice crystal shape. In *Proceedings of the Seventh Atmospheric Radiation Measurement (ARM) Science Team Meeting*, CONF-970365, pp. 253-256. U.S. Department of Energy.

Platt, C. M. R., 1997: A parameterization of the visible extinction coefficient of ice clouds in terms of the ice/water content. *J. Atmos. Sci.*, **54**, 2083-2098.

Platt, C. M. R., J. D. Spinhirne, and W. D. Hart, 1989: Optical and microphysical properties of a cold cirrus cloud: Evidence for regions of small ice particles. *J. Geophys. Res.*, **94**, 11,151-11,164.

Platt, C. M. R., S. A. Young, P. J. Manson, G. R. Patterson, S. C. Marsden, R. T. Austin, and J. H. Churnside, 1998: The optical properties of equatorial cirrus from observations in the ARM Pilot Radiation Observation Experiment. *J. Atmos. Sci.*, in press.

Pueschel, R. F., J. Hallett, A. W. Strawa, S. D. Howard, G. V. Ferry, T. Foster, and W. P. Arnott, 1997: Aerosol and cloud particles in tropical cirrus anvil: Importance to radiation balance. *J. Aerosol Sci.*, **28**, 1123-1136.

Other Publications in Progress

Mitchell, D. L., 1998: Parameterization of the Mie extinction and absorption coefficients for water clouds: A process oriented approach. *J. Atmos. Sci.*, submitted.