Testing a Cirrus Radiation Scheme with In Situ Microphysical and Radiometric Measurements from a Tropical Cirrus Anvil

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Experimental Design and Objective

The only successful microphysics/radiation experiment to date in tropical anvil cirrus was the 4 April 1993 mission during the Central Equatorial Pacific Experiment (CEPEX). The National Aeronautics and Space Administration (NASA) ER-2 aircraft flew repeated transects over a tropical anvil roughly parallel to stepped leg constant altitude transects within the anvil by the AEROMET Lear jet, with measurements from both aircraft occurring during the same time period (75 min.). Ice particle size distributions were measured within the anvil via a two-dimensional cloud (2DC) probe and a video ice particle sampler (VIPS), while multichannel solar reflectances were measured aboard the ER-2 by the moderate-resolution imaging spectroradiometer (MODIS) Airborne Simulator (MAS). The VIPS detects ice crystals down to 5-10 gm, based on the smallest crystals that can be resolved in VIPS images (McFarquhar and Heymsfield 1996). The objective of this study was to compare visible and near infrared reflectances predicted from the observed microphysics with MAS reflectances, thereby testing a recently developed treatment of ice cloud radiative properties (Mitchell et al. 1996, henceforth M96).

Analysis Approach

Ice particle size spectra and reflectances were averaged over coincident sampling time into six longitude bins covering 1.5°, corresponding to the flight transects. Seven ER-2 transects were made, giving a mean and standard deviation for each reflectance bin. Concentrations of small ice crystals having maximum dimension $D < 100$ μm were estimated at the National Center for Atmospheric Research (NCAR) using the parameterization of McFarquhar and Heymsfield (1997) for size distributions in tropical cirrus, based on CEPEX VIPS measurements made between -40 °C and -500 °C.

The lowest anvil region near cloud base (-5.0 km) was sampled over only two longitude bins, and most of the total ice water path (IWP) was contained between this leg and the adjacent transect above. Hence, radiation calculations could be performed only for these two longitude bins, containing seven legs. These legs defined boundaries for six cloud layers, having mean properties of the legs. Layer IWP, optical depth (τ) and single scatter albedo (ω_o) were calculated from the relations in M96, assuming planar polycrystals. This assumption is supported by the 2DC images, of which 80% were classified as compact or branched spatial crystals (mostly compact) at all levels for both longitude bins. The median area dimension of the size distribution, D_a, was estimated from the 2DC images and spectra. Scattering phase functions were matched with D_a values within 5 μm resolution (M96). The radiation scheme in M96 was modified to integrate over bins of the measured size spectra, and τ and ω_o were weighted by solar fluxes across each MAS channel. An example of microphysical and radiative properties calculated for one of the two longitude bins (178.625°) is given below.

Table 1. Mean layer altitudes and depths, mean dimensions $(\overline{D})$, median area dimensions (D_a), IWP, τ and ω_0 for each layer of longitude bin 178.625°, for the MAS channel centered at 1.62 µm.

Layer Altitude (km)	Layer Depth (km)	$(\overline{D})$ (µm)	D_a (µm)	IWP (g/m^{-2})	τ	ω_0
12.84	0.950	22	40	4.9	0.45	0.9513
12.18	0.362	24	55	3.5	0.32	0.9502
11.68	0.639	26	60	7.6	0.66	0.9475
11.14	0.468	27	65	7.4	0.57	0.9418
10.36	1.082	33	90	34.6	2.13	0.9285
7.40	4.850	30	80	140.1	7.99	0.9245

Scattering phase functions were based on hexagonal columns, since phase functions for complex spatial crystals common in cirrus are not well understood. Solar flux weighted values for the real and imaginary index of refraction were calculated for each MAS channel used, and phase functions were based on these refractive indexes.

A Monte Carlo multiple scattering model, developed by Andreas Macke (Macke et al. 1995), was initialized with phase functions, τ, and ω_0 for each cloud layer for a given MAS channel and longitude. The solar zenith angle was 30°, and surface albedo in the visible and near infrared (IR) spectrum was 3.5% and 0%.

Tropical anvil systems evolve rapidly in time, and the microphysical properties along a given leg may change considerably during the 75 min. of sampling. Also, while the 3.50 km region below cloud top (13.3 km) was well sampled, the 4.85 km layer below this (lowest layer in Table 1) contained two-thirds of the total optical depth. Because the greatest uncertainty results from this lowest layer, predicted uncertainties were based on varying τ for this layer by ±1/3.

Results

Reflectances for the visible MAS channel centered at 0.66 µm and the near infrared MAS channels centered at 1.62 µm and 2.14 µm are plotted in Figures 1 and 2. These are contrasted with predicted reflectances assuming planar polycrystals, denoted "x." Vertical lines give standard deviations regarding the MAS data, and uncertainties as described above regarding predicted reflectances. Predicted uncertainties in the near IR were generally too small to see when plotted. Also, predicted reflectances for bullet rosettes (*) were plotted for comparison. The polycrystal reflectances tend to agree with observations within the estimated uncertainties, although appearing to underestimate them somewhat. Bullet rosettes overestimate reflectances in the near IR. It is quite possible that the ice crystals dominating this anvil had mass and area characteristics

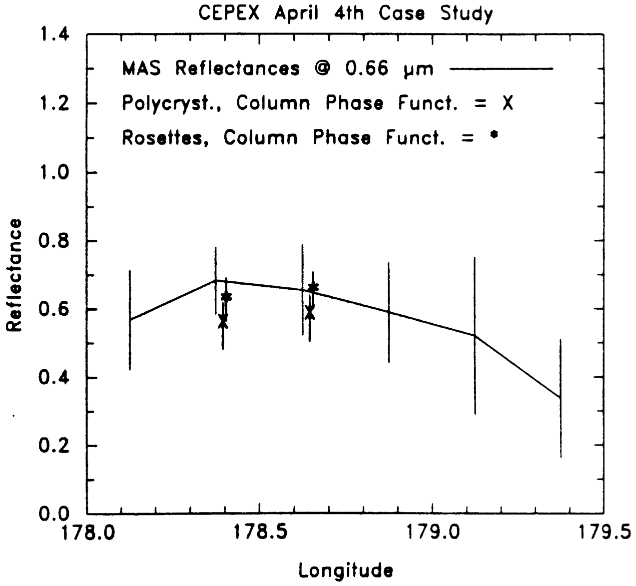

Figure 1. Comparison between predicted and measured reflectances for the 0.66 µm channel, for the two longitude binds. Optical depths and ω_0 were calculated for both planar polycrystals and bullet rosettes, while hexagonal column phase functions were used for both shapes.

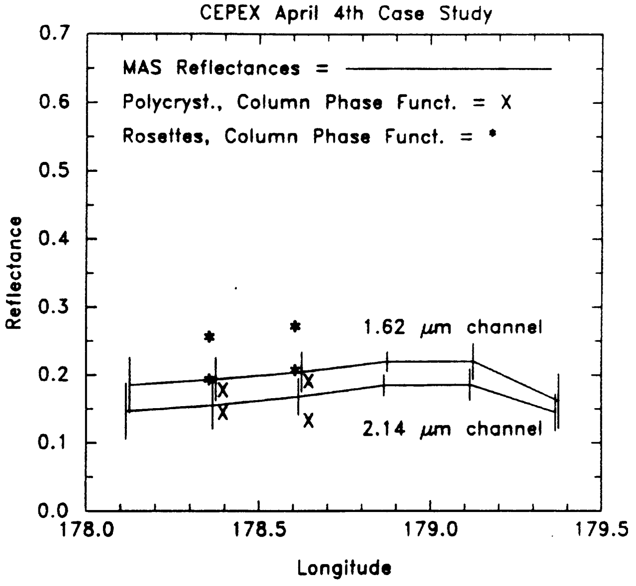

Figure 2. As in Figure 1, but for MAS channels centered at 1.62 µm and 2.14 µm.

intermediate between those assumed for planar polycrystals and bullet rosettes.

Since VIPS analyses were only made between -40 °C and -50 °C, over limited spatial domain, and may undercount the smallest ice crystals, the concentrations of crystals (N) with D < 100 µm were assumed to follow an exponential distribution, with $N = N_{observed}$ for $D \geq 100$ µm, and $N = 2.5\ N_{observed}$ at 15 µm (bin 2). An example of this modification is shown in Figure 3 (dashed histogram). Based on these modified size spectra, reflectances were recalculated for planar polycrystals in Figures 4 and 5. Significantly better agreement with MAS reflectances is evident.

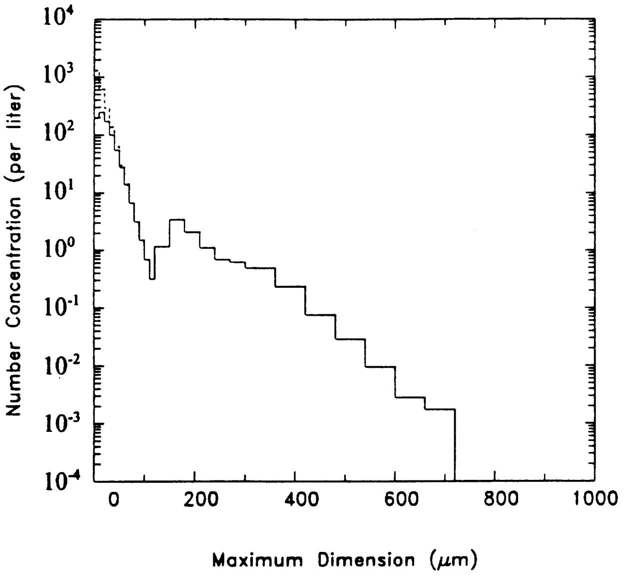

Figure 3. An arbitrarily selected size distribution for the 11.7 km layer of Table 1. Solid histogram gives the original size distribution based on the 2DC and VIPS data, while the dashed histogram (D < 100 µm) describes the changes made to produce better agreement with the MAS data.

Conclusions

The objective of this study was to test whether a scheme for predicting ice cloud radiative properties could explain the reflectances observed over a tropical cirrus anvil in the visible and near infrared, based on the ice particle size distributions measured during the period of radiometric sampling. Favorable agreement between theory and measurements were obtained by assuming planar polycrystals with reasonable concentrations of small ice crystals. Such crystals may have dominated the cloud, since 80% of the 2DC images were classified as compact or branched spatial crystals. However, it also appears that all observed reflectances could be explained well without the modest adjustment in small ice crystal concentrations, if crystal shapes were characterized by mass- and area-dimensional relationships intermediate to those assumed for planar polycrystals and bullet rosettes.

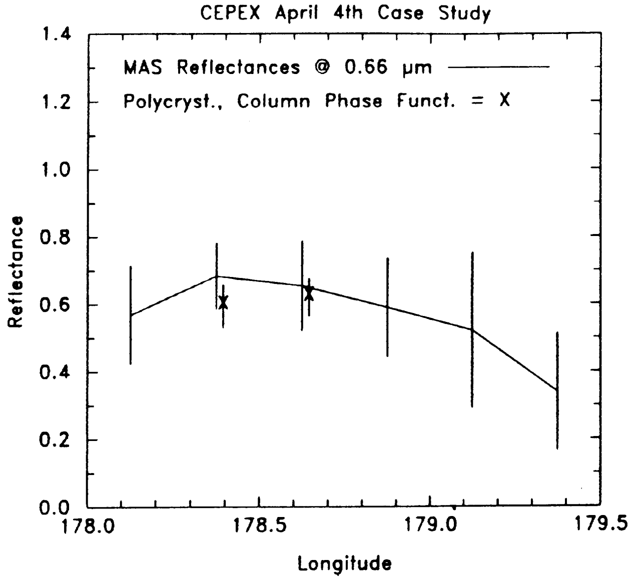

Figure 4. As in Figure 1, but for τ and ω_0 based on planar polycrystals and the modified size distribution in Figure 3, which shows higher concentrations of small ice crystals.

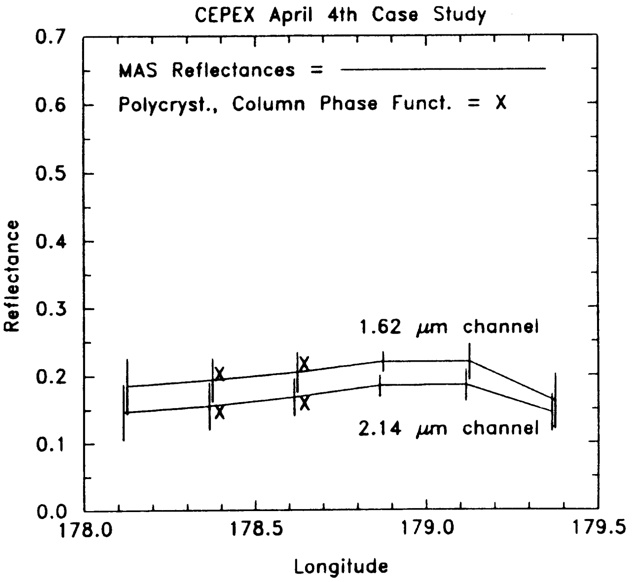

Figure 5. As in Figure 4, but for the MAS channels centered at 1.62 µm and 2.14 µm.

Other significant findings are listed below:

- Hexagonal column phase functions, having asymmetry parameter (g) values around 0.79 in the visible and between 0.80 and 0.85 in the near IR, were best for explaining the reflectances. Phase functions for hexagonal plates and randomized fractals (Macke 1993) were not as successful.

- Predicted reflectances were sensitive to modest increases in the concentrations of small crystals (i.e., factor of 2.5 at D = 15 μm), as well as assumptions for ice crystal shape.

- No evidence for "excess" solar absorption was found for the two near infrared MAS channels.

References

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