Sensitivities of SCMs to New Parameterizations of Cloud-Radiative Interactions

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Introduction

Ice clouds have a major effect on the earth's radiation balance and climate as a result of the significant contribution they make to diabatic heating in the upper troposphere. The relationship between cloud microphysical and optical properties is especially important after examining the response of specific General Circulation Models (GCMs) to changes in the representation of such properties. The connected description of microphysical and radiative characteristics is the weakest physical link for the parameterization of microphysical and radiative processes in clouds and for larger scale models. This does not need to be an explicit physically predictable system, but can be a diagnostic approach depending upon measured relationships.

Although a number of parameterizations for the microphysical and single-scattering properties of cirrus have been developed, most have not adequately considered the role of smaller ice crystals and realistic distributions of different sizes and habits of ice crystals. Parameterizations of the mean single-scattering properties (e.g., single-scatter albedo, extinction coefficient, and asymmetry parameter) are developed for ice crystal distribution in tropical and mid-latitude cirrus using in situ measurements of ice crystal sizes and habits. These are combined with a library of single-scattering properties derived for various idealized shapes calculated with an improved geometric ray-tracing method (Yang et al. 2000). Improvements over past parameterizations are accomplished by using observed mixtures of crystal shapes and sizes rather than a single crystal habit, and by using observations of ice crystals smaller than 100 μm in calculations of single-scattering properties.

Parameterizations of Tropical Cirrus

Parameterizations of tropical cirrus are derived using microphysical measurements obtained during the Central Equatorial Pacific Experiment (CEPEX). During CEPEX, two-dimensional (2D) images of ice crystals larger than 100 μm were obtained using 2D optical array cloud probe (2DC), and of crystals smaller than 100 μm using a video ice particle sampler (VIPS) (McFarquhar and Heymsfield 1997). From the 2D image of each 2DC crystal, the shape is defined using McFarquhar et al. (1999) self-organized neural network that defines shape based on simulations of particle maximum dimension and area ratio variances for random orientations of different idealized shapes (e.g., columns, bullet rosettes, and rough aggregates). Images of smaller ice crystals obtained during CEPEX showed the majority were quasi-circular, meaning they have area ratios close to unity, but not exactly circular in shape. Therefore, for this study small crystals are represented as deformed spheres with shapes determined by eighth degree Chebyshev polynomials. Because calculated radiative properties of Chebyshev particles are not available in the Yang et al. (2000) library, the radiative properties of these particles are calculated by the geometric optics approximation accounting for diffraction occurring at circular aperture (Macke 1993). The calculated phase functions for these merged sized distributions are rather flat and featureless, resembling those phase functions previously used (Macke et al. 1996, Baran et al. 2000).

Figure 1 shows how the asymmetry parameter, g, calculated for the habit-dependent size distributions varies as a function of effective radius (r_e), for the four solar broadbands commonly used in climate models. The dots represent values from size distributions and the solid lines represent best fits to the data. A single dependence on r_e adequately characterized the data. The other line types show other parameterizations previously used in climate modeling studies, namely those of Ebert and Curry (1992), Wyser and Yang (1998), and Kristjansson et al. (1999). Agreement between schemes is not expected since these other schemes all assume different crystal habits, whereas the new scheme represents cumulative properties. These differences can be rather significant. A similar procedure was followed to derive the dependence of single-scatter albedo, ω_0, on r_e (Figure 2). Again, a single dependence on r_e adequately described the data, and there were substantial differences from previous parameterization schemes. The differences were primarily caused by the use of deformed spheres to characterize the small crystals rather than the more pristine habits used in prior studies.

The relationship between extinction coefficient, β_{ext}, ice water content (IWC), and r_e is also needed. Ebert and Curry (1992) and others have used relationships of the form $\beta_{ext} = \mathrm{IWC}\,(a_0+a_1/r_e)$ to characterize these interactions, where a_0 and a_1 are wavelength-dependent coefficients. However, because r_e is defined as proportional to the ratio of volume divided by cross-sectional area (Fu 1996), the extinction coefficient is represented by $Q_{ext}\,\mathrm{IWC}/(3^{1/2}\,\rho\, r_e)$. Q_{ext} is the extinction efficiency averaged over the distribution of particles weighted according to scattering cross section and ρ_i is the bulk density of ice. Q_{ext} is equal to 1.989, 1.986, 2.000, and 2.000 over the four wavelength bands used to develop the parameterization. Hence, it is assumed $Q_{ext} = 2$, and β_{ext} is directly obtained from the IWC and r_e for this parameterization.

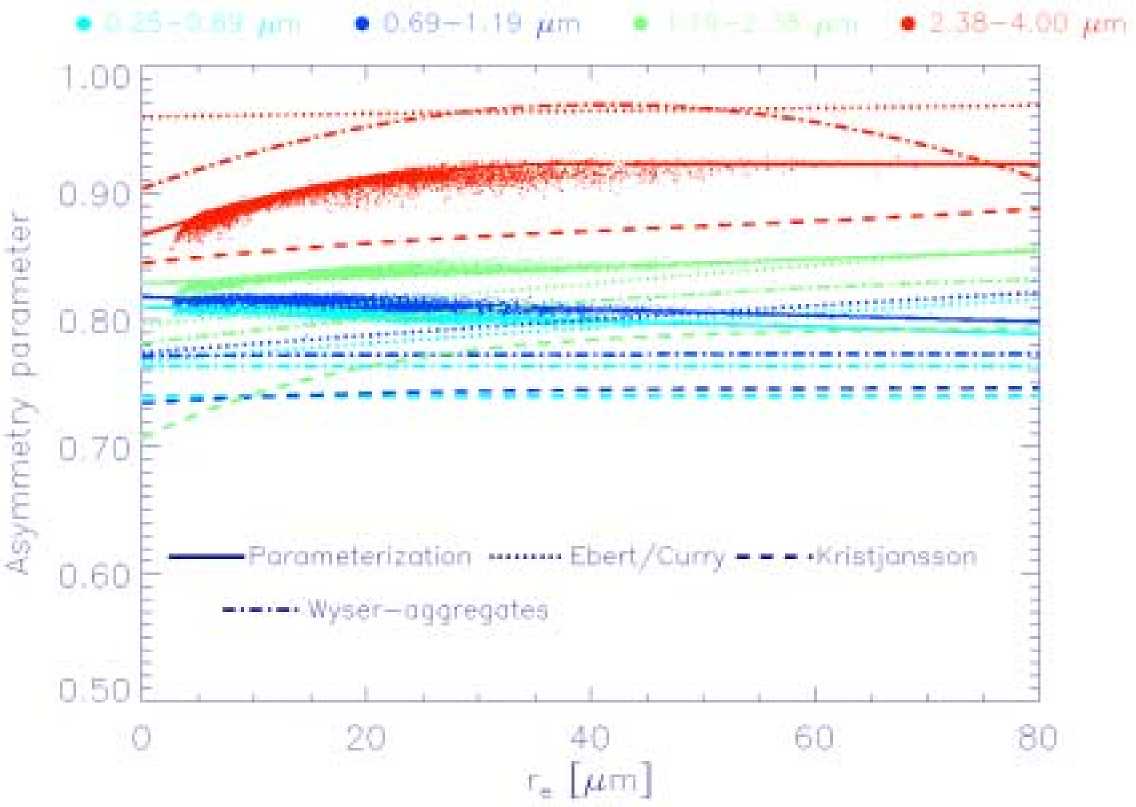

Figure 1. Asymmetry parameter as a function of r_e for four different wavelength bands for tropical cirrus. Dots represent g calculated by combining measured size and habit distributions with results of an improved geometric ray-tracing method. Solid lines represent best fits to data, and other line types represent other parameterizations used in climate modeling studies.

Mid-Latitude Parameterizations

Parameterizations of the mean-scattering properties of mid-latitude clouds are derived in similar ways, using data collected by the University of North Dakota (UND) Citation aircraft during the 1997 Atmospheric Radiation Measurement (ARM) intensive operational period (IOP). Large crystals were measured by the 2DC probe and smaller crystals were measured by the Forward Scattering Spectrometer Probe (FSSP). Because there is still debate in the literature about the reliability of the FSSP when large ice crystals are present, only the large crystal data are used for the preliminary parameterizations presented here. Further, there is no evidence that small ice crystals can be represented as deformed spheres for mid-latitude cirrus.

Figure 3 shows g as a function of r_e for the same four wavelength bands for data collected during the 1997 IOP. The dashed lines represent the Ebert and Curry (1992) parameterization scheme commonly used in climate models. Differences are again associated with use of different crystal habits

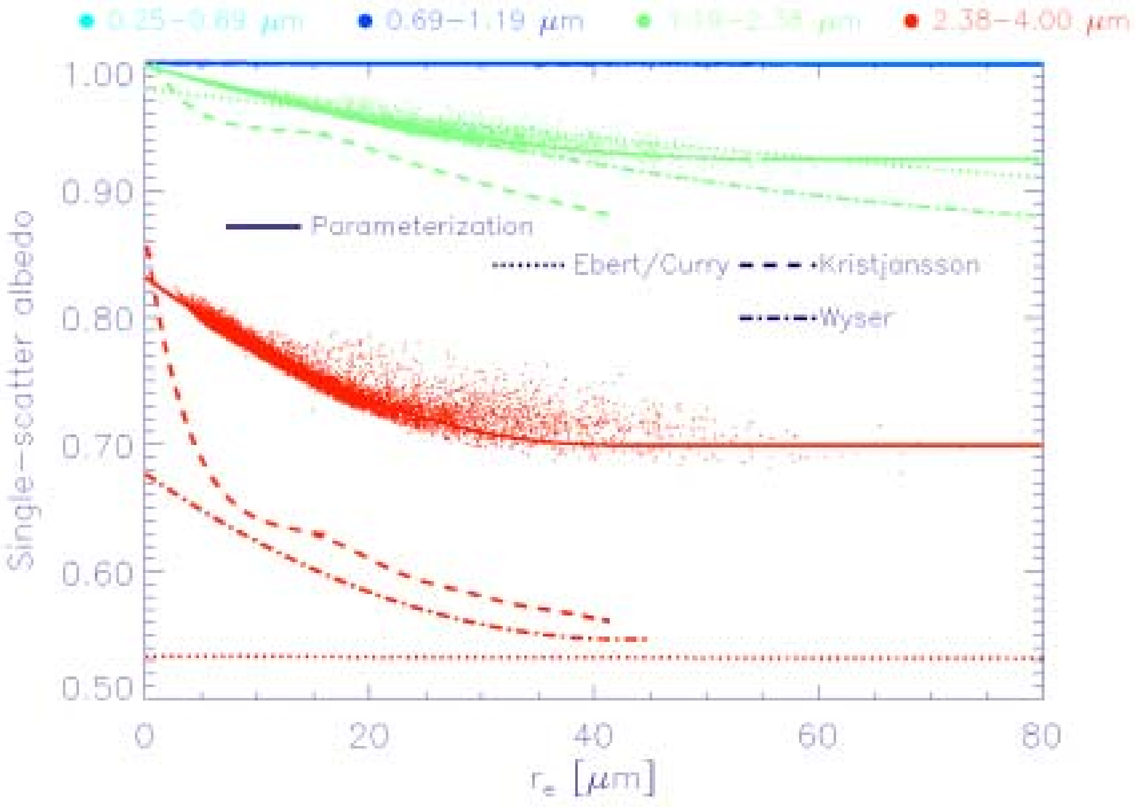

Figure 2. Same as Figure 1, except for single-scatter albedo as a function of r_e.

to describe the measured ice crystals, but scheme differences are not as large because no small crystals are characterized by deformed spheres in this new parameterization scheme. Similarly, Figure 4 shows the variation of single-scatter albedo as a function of r_e.

SCM Simulations

Some preliminary tests have been performed with the tropical parameterization in the Scripps single-column model (SCM). The initial and boundary conditions Iacobellis and Somerville (2000) used to simulate the 1992/1993 Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA COARE) IFP were used to drive the simulations. The effects of varying single-scattering radiative parameterizations on radiative and heating properties were studied. Figure 5 shows the temporal evolution of the shortwave cloud forcing at the top of the atmosphere calculated using different parameterizations. Calculations with the Ebert and Curry (1992) scheme are compared against two new versions of the parameterization; McFarquhar 1 and 2 represent sensitivity studies on the use of different polynomial expansions of Chebyshev polynomials to describe the deformed spheres. There can be significant differences in radiative forcing depending on which parameterization is used. Ongoing studies further quantify the effects of differing parameterizations on this and other calculated radiative and heating rates.

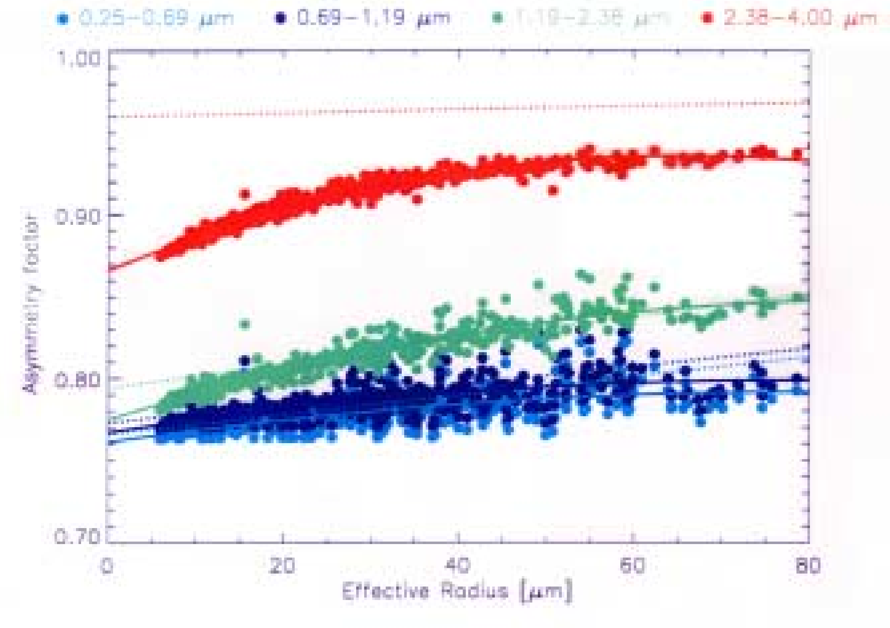

Figure 3. Same as Figure 1, except asymmetry parameter calculated for mid-latitude cirrus using data collected by the UND Citation during the 1997 IOP.

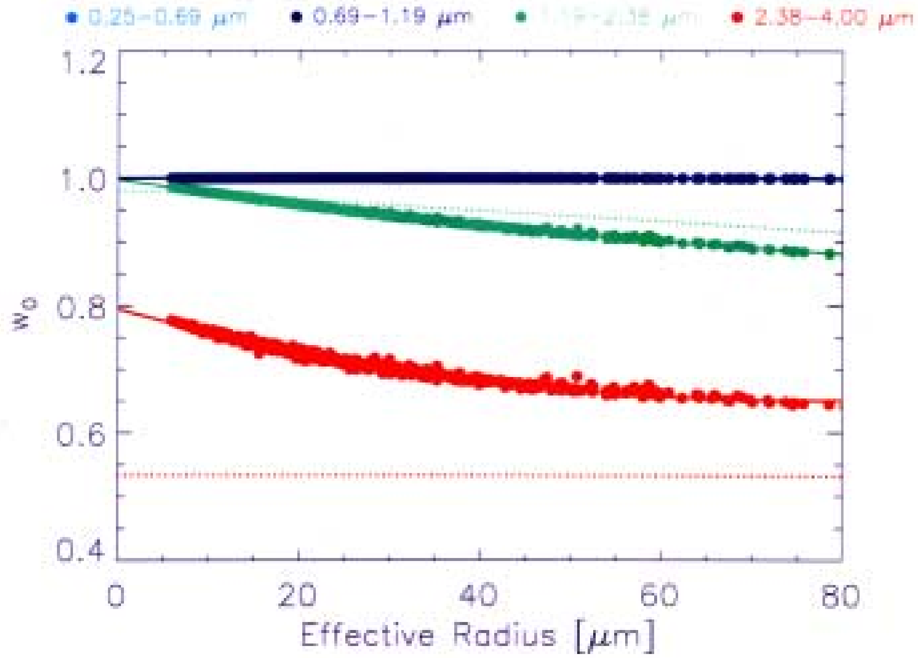

Figure 4. Same as Figure 3, except for single-scatter albedo as a function of r_e for mid-latitude cirrus.

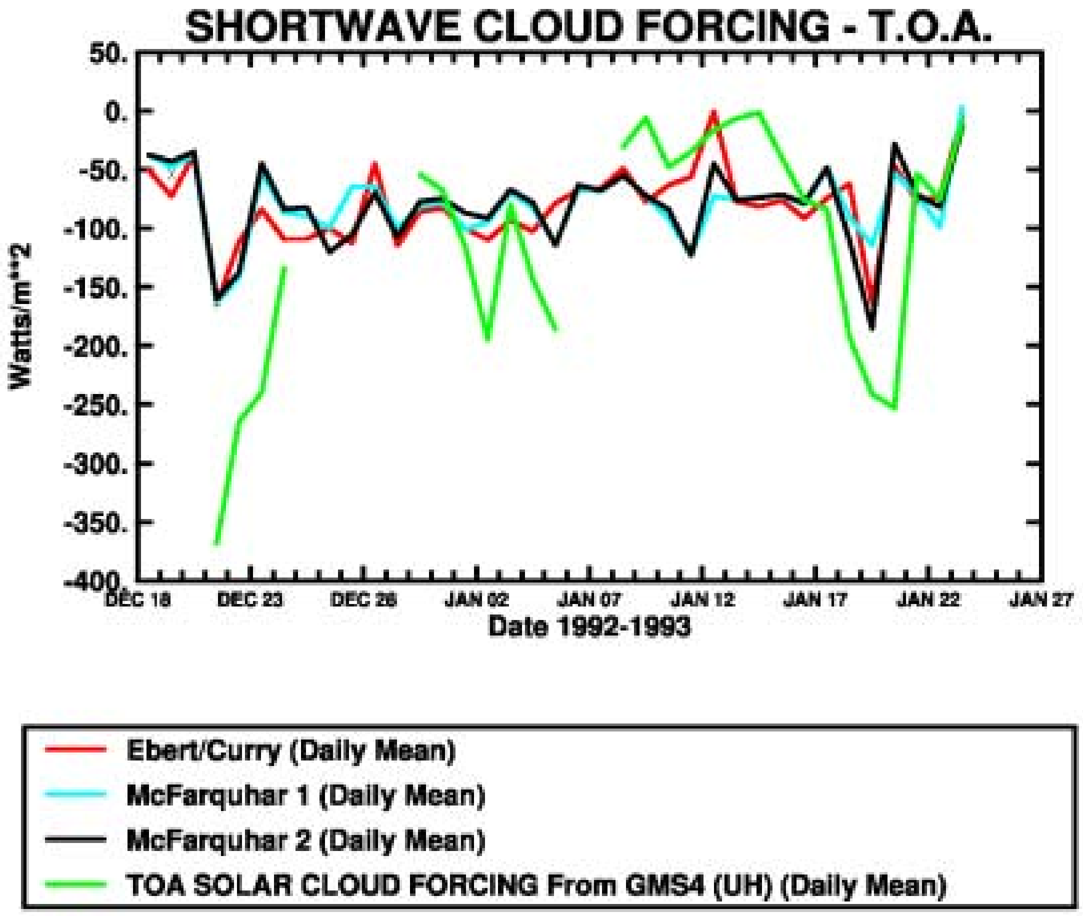

Figure 5. Temporal evolution of shortwave cloud forcing at the top of the atmosphere calculated using different parameterizations for the single-scatter properties. See text for details.

Summary

New parameterizations of single-scattering radiative properties for distributions of ice crystals have been developed using the results of an improved geometric optics code together with in situ observations of the sizes and shapes of ice crystals. Separate schemes have been developed for tropical and mid-latitude clouds. It is also possible that other schemes will have to be developed for clouds forming in other geographical regimes or having different formation mechanisms. Preliminary tests with the Scripps SCM during the TOGA COARE IOP show that the use of the tropical parameterization can cause differences in the radiation at the surface and top of the atmosphere. Sensitivity studies are currently under way to determine why and when these differences occur and how uncertainties in the microphysics scale up to uncertainties in the radiative budgets.

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