Preliminary Parameterization for Effective Radius for SCMs

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Introduction

Using a single-column model (SCM), Somerville et al. (1999) showed that different parameterizations of effective radius, r_e, could result in variations in the outgoing longwave radiation (OLR) and down-welling shortwave flux (DSWF) on the order of 20 W m^{-2} and 30 W m^{-2}, respectively, and differences in solar and longwave radiative heating rates of 0.3°C day^{-1}. Because many cloud radiative properties for both ice and water clouds (e.g., extinction coefficient, single-scattering albedo, asymmetry parameter) are parameterized in terms of water content and r_e, the representation of r_e is critical for an accurate estimate of cloud forcing.

The weakest physical link for the parameterization of microphysical and radiative processes in cloud and for larger scale models is the connected description of microphysical and radiative characteristics. This does not need to be an explicit, physically predictable system, but can be a diagnostic approach depending upon measured relationships. As part of our newly funded Atmospheric Radiation Measurement (ARM) research effort, we are developing improved parameterizations of relations between r_e, ice water content (IWC), temperature (T), and mean single-scattering cloud radiative properties, which can be incorporated into cloud resolving models (CRMs) and SCMs. Past studies (e.g., McFarquhar and Heymsfield 1997; Ebert and Curry 1992) have shown considerable promise for developing such relationships.

McFarquhar and Heymsfield (1998) reviewed several different definitions of r_e that have been used for distributions of ice crystals for remote sensing and climate studies. They concluded that Fu's (1996) definition of generalized effective radius, given by

$$r_e = \frac{1}{2} D_e = \frac{\sqrt{3}\,IWC}{3\rho_i A_c} \quad (1)$$

where ρ_i is the density of ice, was best suited for the development of subsequent parameterizations because the ratio of ice mass to cross-sectional area, A_c, is a physically meaningful quantity.

Tropical Ice Cloud Studies

McFarquhar and Heymsfield (1997) parameterized average ice crystal size distributions as a function of T and IWC based on cirrus observations made during the Central Equatorial Pacific Experiment (CEPEX). Large ice crystals (D > 100 μm, measured by optical array probes, were characterized by a lognormal distribution, whereas small ice crystals (5 < D < 100 μm), measured by a Video Ice Particle Sampler, were represented by a first-order gamma function. The function coefficients were chosen to match the observed data as closely as possible while conserving mass; uncertainty estimates were based on variations in the observations. Because the parameterization gives accurate estimates of mass, area, and number contained in different size ranges, a simple application of the formulae can be used to produce a parameterization of r_e as a function of IWC and T.

Figure 1 shows the temperature-dependent variation of r_e with IWC. The variation is parameterized by the family of curves

$$r_e = 10^{a_i + b_i \log(IWC) + c_i \log(IWC)^2 + d_i \log(IWC)^3} \tag{2}$$

where the coefficients depend on temperature. Because small and large crystals are represented separately in the parameterization, their contributions to r_e can also be calculated separately, which is useful for models with multiple categories of ice. There is a slight increase of r_e with temperature for a

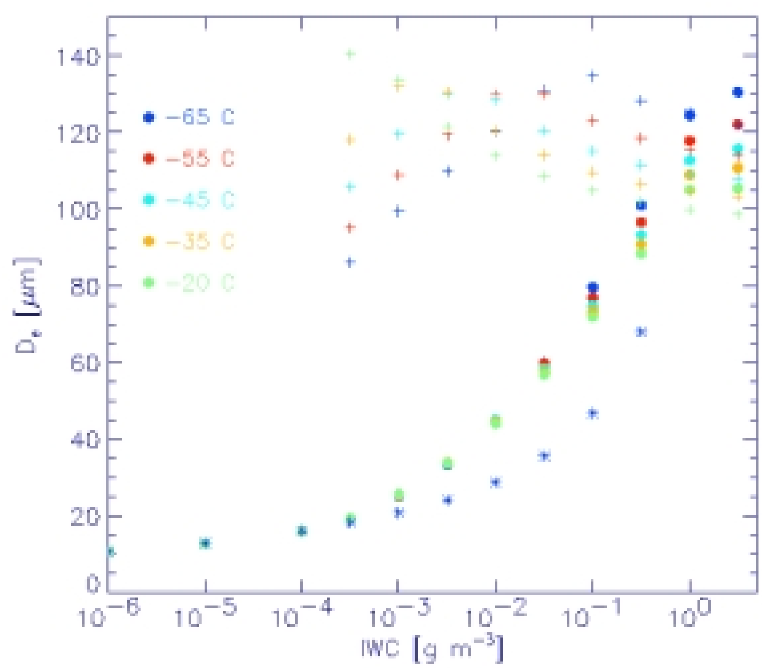

Figure 1. D_e as function of IWC for different temperatures for tropical outflow anvils as derived from McFarquhar and Heymsfield (1997). Circles represent D_e from complete size range; pluses, only large mode of parameterization; asterisks, only small mode (no temperature dependence).

given IWC, which is produced by more compact particles at colder temperatures. However, r_e actually decreases with T because of a substantial decrease of IWC with temperature, as shown by McFarquhar and Heymsfield (1997). This shows that application of the formulae requires proper consideration of multi-dimensional dependencies. Equation (2) was developed considering the observed mixture of crystal habits in blow-off anvils, which consisted mainly of aggregates and side-planes for larger crystals, and quasi-circular crystals for smaller sizes. Attempts to extrapolate these formulae to distributions of ice crystals having substantially different shapes or acquired under different conditions should be avoided.

Parameterization of Single-Scattering Properties

Although parameterizations of the shortwave radiative properties of distributions of ice crystals have been developed (e.g., Ebert and Curry 1992), none have taken into account the complexity of cirrus clouds in terms of both the shapes and sizes of ice crystals. Many have assumed that cirrus crystals can be represented as hexagonal columns, and the representation of ice crystals smaller than 100 μm has not been adequate.

Here, improved parameterizations for distributions of ice crystals that reflect the variety of sizes and shapes of ice crystals that are observed in cirrus clouds are developed. First, the single-scattering properties of commonly occurring shapes (hexagonal columns, bullet rosettes, quasi-spheres, and polycrystals represented as Koch fractal particles (see Macke et al. 1996) and sizes of ice crystals are calculated at several visible and near-infrared wavelengths using Macke et al.'s (1996) ray-tracing algorithms that account for reflection and transmission processes of a bundle of incoming rays to the particles randomly oriented in space (note, preferred orientation of hexagonal columns are considered). The detailed morphometric information about the particle shapes (aspect ratios, pyramid angles, deformation parameters) was chosen to replicate the measured ice crystals as closely as possible. Second, the mean single-scattering properties using observed mixtures of different sizes and habits of ice crystals derived from a neural network classification scheme (McFarquhar et al. 1999) are determined by weighting the single-scattering properties by scattering cross section and number density using observations obtained in a blow-off anvil during CEPEX. This allows a parameterization of the mean single-scattering properties in terms of IWC, r_e and T.

Figure 2 shows the asymmetry parameter (g) calculated from the CEPEX data for four different wavelengths (0.664 μm, 0.875 μm, 1.621 μm, and 2.142 μm) chosen to represent different channels on the recently launched moderate imaging resolution spectroradiometer (MODIS) as a function of r_e. The different symbols represent different IWCs. Although lower g always occur for larger IWC, the variation of g can be accounted for by a single dependence on r_e. The solid lines represent the Ebert and Curry (1992) parameterizations, given by $g = e_i + f_I\, r_e$, where e_i and f_i depend on wavelength, λ, for a broadband encompassing the narrow wavelength for which the CEPEX calculations were performed. Exact comparison of the broadband and narrow channel wavelengths is not possible because broadband g integrate contributions of many narrow bands weighted by the fraction of solar radiation in the appropriate interval. However, closer agreement than that observed in Figure 2 would be expected; the broadband asymmetry parameters should occur between narrowband results of different λ if all other

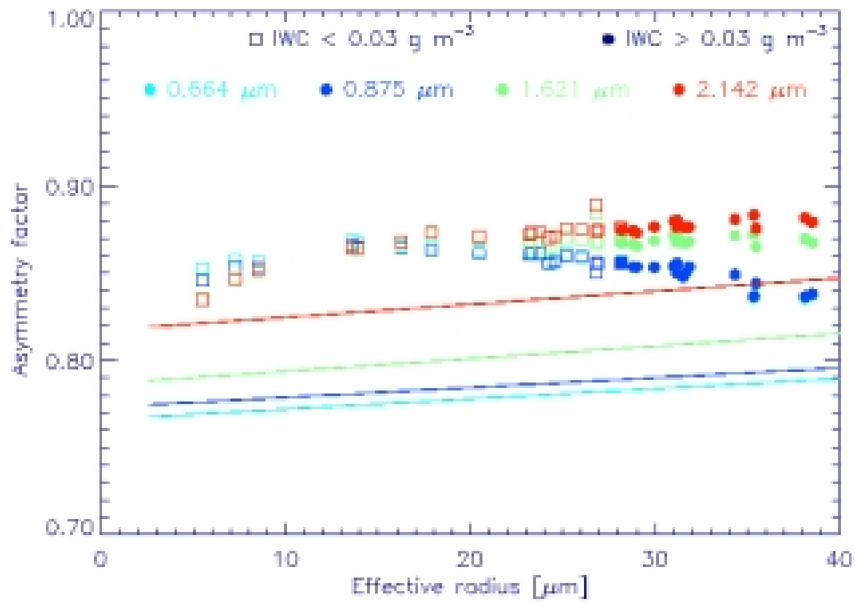

Figure 2. Variation of asymmetry parameter calculated from CEPEX data versus r_e for indicated wavelengths. Squares represent cases where IWC < 0.03 g m^{-3}; circles, IWC > 0.03 g m^{-3}. Solid lines represent Ebert and Curry (1992) broadband parameterization for similar wavelengths (0.2 μm to 0.7 μm, light blue; 0.7 μm to 1.3 μm, dark blue; 1.3 μm to 1.9 μm, green; 1.9 μm to 2.5 μm, red.

factors were similar. Other reasons, namely different weighting of crystal shapes, might explain the differences. Similar calculations and parameterizations were performed for single-scattering albedo (paper in preparation).

The relationship between extinction coefficient, β_{ext} IWC, r_e and temperature was also examined. Figure 3 shows the dependence of β_{ext} on r_e. As r_e increases, β_{ext} also increases even though r_e is derived as inversely proportional to A_c (or 0.5 β_{ext}). This occurs because of the additional dependence of r_e on IWC. In fact, Eq. (1) and Eq. (2) can be combined to give the relationship between r_e and β_{ext}. Ebert and Curry (1992) parameterized the relationship between β_{ext}, IWC and r_e as $\beta_{ext} = IWC\ (a_i + b_i\ r_e)$. In this study, a_i is automatically equal to zero because of the differing definitions of r_e.

Because the McFarquhar and Heymsfield (1998) parameterization was developed for tropical anvils, it does not apply to clouds sampled in different geographical regimes (e.g., mid-latitudes) or associated with different formation mechanisms (e.g., large-scale lifting rather than deep convection). Data from other projects, especially those at the Southern Great Plains site, are currently being used to investigate the relationship between r_e, IWC, T, and mean single-scattering properties. These studies will be presented at next year's ARM meeting.

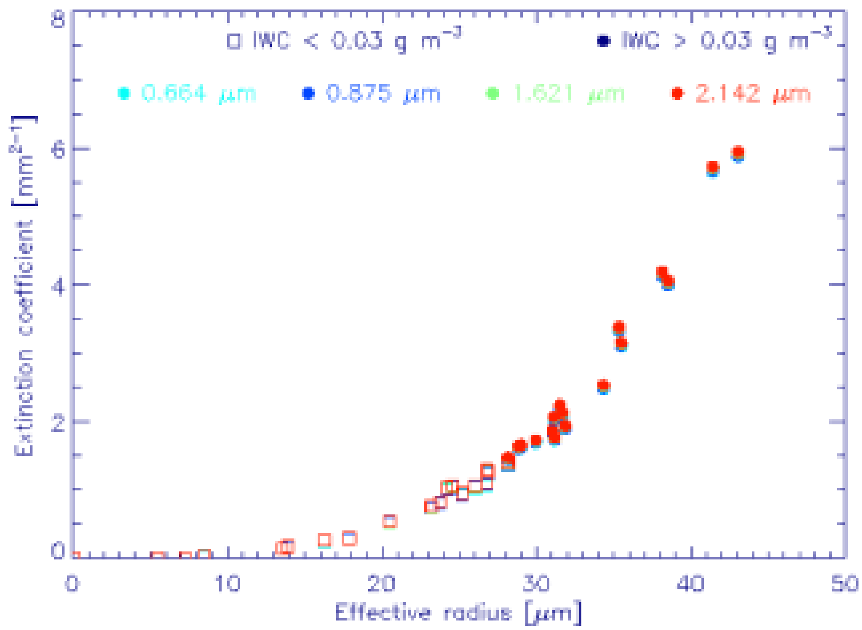

Figure 3. As in Figure 1, except for variations of extinction coefficient against r_e.

Parameterization of r_e for Stratus

Not only are parameterizations of r_e needed for ice clouds, but also for water clouds. Many recent studies have parameterized r_e as a function of the cube root of the ratio of cloud liquid water content (LWC) to total cloud droplet concentration (N_{tot}). A shape parameter (k), depending on the skewness and dispersion of the cloud droplet size distribution, determines the proportionality constant, and hence

$$r_e = \left(\frac{3LWC}{4\rho_w{}^k N_{tot}} \right)^{1/3} \tag{3}$$

where ρ_w is the density of water. Using observations of cloud microphysical properties acquired during the Indian Ocean Experiment (INDOEX) in both pristine and polluted cloud masses south and north of the Intertropical Convergence Zone (ITCZ), k is found to depend on the observed number of condensation nuclei, with k ranging from 0.73 ± 0.07 in polluted clouds to 0.84 ± 0.07 in pristine clouds. Figure 4 shows r_e^3 plotted as a function of LWC/ N_{tot}. The thick solid line represents the k = 1 line, which corresponds to a monodisperse-size distribution, and lower k values are associated with a larger r_e^3 for a given LWC/N_{tot}. The blue and red dots represent the 1-Hz INDOEX cloud data in pristine and polluted clouds, respectively, and a distinct separation between the two cloud types is noted with higher k values for the pristine clouds. Relationships such as Eq. (3) show considerable promise for use in SCMs and GCMs because even though proportionality coefficients differ considerably depending on the degree of pollution and on typical drop sizes, the non-varying format of the parameterization suggests that it might be applied universally.

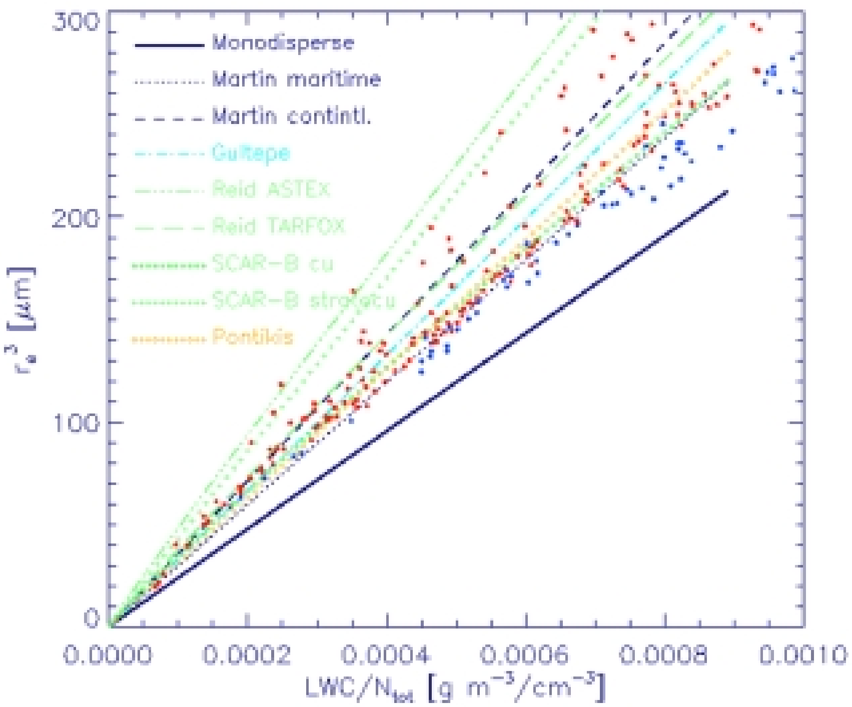

Figure 4. Relationship between r_e^3 and LWC/N_{tot} observed or parameterized during various projects. Slope of line gives k, shape parameter. Red and blue circles represent INDOEX cloud data for pristine and polluted clouds, as classified by measured CN values (k is 0.84 ± 0.07 for pristine, and 0.73 ± 0.07 for polluted clouds during INDOEX.

Summary

A multitude of parameterizations have been and are currently being developed to describe the variation of r_e in terms of variables such as IWC, T, and LWC. Although the relationships between r_e and other variables can vary substantially depending on cloud type (e.g., convective versus stratiform, liquid versus ice) and geographical location (e.g., mid-latitude versus tropical), there is promise that relationships with non-varying forms (but varying coefficients) can be applied universally.

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