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ISSUES RELATED TO PARAMETERIZATION OF THE RADIATIVE PROPERTIES OF ICE CLOUDS IN GCMs

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1. INTRODUCTION

Recent efforts in the GCM community in developing a physically-based parameterization of cloud processes have been remarkable. Numerous GCM modelers now include a prognostic equation to compute cloud water/ice content. Many of them also recognize the importance of incorporating in the GCM a physically-based radiative parameterization that is compatible with the predicted water and ice contents.

In this report, we should confine the presentation to the issues that are pertinent to parameterization of the radiative properties of ice clouds for use in GCM simulation studies. We base our discussions on physical principles and available cloud microphysics observations. Although these discussions are for clouds containing ice crystals, the fundamental principles presented herein should be applicable to water clouds and mixed clouds as well.

In Section 2, we discuss the importance of developing the physical relationships between ice water content (IWC) and mean effective size and temperature on the basis of cloud microphysics observations and model simulations. Four scientific issues associated with parameterization of the radiative properties of ice clouds are identified in Section 3. These include determination of the scattering and absorption properties of nonspherical ice crystals, parameterization of the single-scattering properties in terms of mean effective size and variance of the size distribution, potential effects of the cloud macroscopic heterogeneity on the radiation field, and validation of the radiation parameterization program using spectral and broadband radiometric measurements from the ground, the air, and space.

2. THE DEPENDENCE OF ICE MICROPHYSICS ON TEMPERATURE

Two fundamental variables determine the radiative properties of ice clouds: IWC and ice crystal size distribution. Based on the aircraft measurements of midlatitude cirrus clouds, the ice crystal size distribution and IWC are both dependent on temperature. Heymsfield and Platt (1984) determined that ice crystal size distribution can be represented by a general power form in terms of length (L, maximum dimension) and IWC as follows:

$$n(L) - A\, L^{B} \cdot IWC, \tag{1}$$

where IWC is in units of g/m^3 and A and B are empirical coefficients determined from the measured data. All of these variables are functions of temperature.

Figure 1 shows values of the averaged IWC derived from the dataset presented by Heymsfield and Platt for a temperature range from -20 to -60° C with the vertical bars denoting the standard deviation. The steepest increase of the average IWC occurs from -42 to -37° C. Liou (1986) presented a parameterization of IWC as a function of temperature based on this dataset in the form

$$\left[\ell n(\mathrm{IWC}) + a\right]/b = \exp\left[c(|T_c| - 20)^d\right] \tag{2}$$

for $T_c < -20°$ C, where a = 7.6, b = 4, c = 2.443 x 10^{-4}, and d = 2.455. This parameterization (the solid curve) is shown in Figure 1.

Because ice crystals scatter an amount of light in proportion to their cross-section areas, we can define a mean effective size (D_e) to represent the mean properties of ice crystals size distribution for the purpose of radiative transfer parameterization in the form (Liou et al. 1990)

$$D_e = \int_{L_{min}}^{L_{max}} D^2 L n(L) dL \Big/ \int_{L_{min}}^{L_{max}} D L n(L) dL, \tag{3}$$

where D is the width. Based on laboratory and field experiments, L and D of an ice crystal can be related by a power form: $D = aL^b$, where a and b are coefficients determined from measurements (Auer and Veal 1970; Heymsfield 1972; Hobbs et al. 1975). Thus D_e can be determined from Eq. (1). The lower limit L_{min} is set at 20 μm based on the limitations of optical probes that were used in collecting the ice particles. The upper limit L_{max} is prescribed by using the observed maximum crystal length. Figure 2 shows the D_e value determined from the dataset presented in Heymsfield and Platt as a function of temperature. Using a statistical procedure, we have derived the following parameterized polynomial relationship (Ou and Liou 1995):

$$D_e = \sum_{n=0}^{3} C_n T_c^n, \tag{4}$$

where C_0 = 326.3, C_1 = 12.42, C_2 = 0.197, and C_3 = 0.0012. In the fitting, the root-mean-square difference between the parameterized and observed mean D_e values is about 12.5 μm. It is clear that D_e increases with increasing T_c, as is also evident from recent aircraft microphysics measurements (Heymsfield et al. 1990). The definition of D_e is significant in that the radiative properties of ice clouds depend not only on ice water path, the product of IWC and cloud thickness, but also on D_e (Liou et al. 1990).

We have developed simple models for the diffusion and accretion growths of ice crystals to understand from a theoretical perspective the dependence of IWC and D_e on temperature. For the diffusion growth we begin with the growth equation for ice crystal mass m as follows:

$$\frac{dm}{dt} = \frac{4\pi C}{A+B}(S_i - 1), \tag{5}$$

where C is the shape factor; A and B are thermal and mass diffusion coefficients, respectively; and S_i is the supersaturation over ice, which can be solved by using the mass balance equation that involves IWC. Assuming that the ice crystals have the same size and shape and employing a time marching numerical

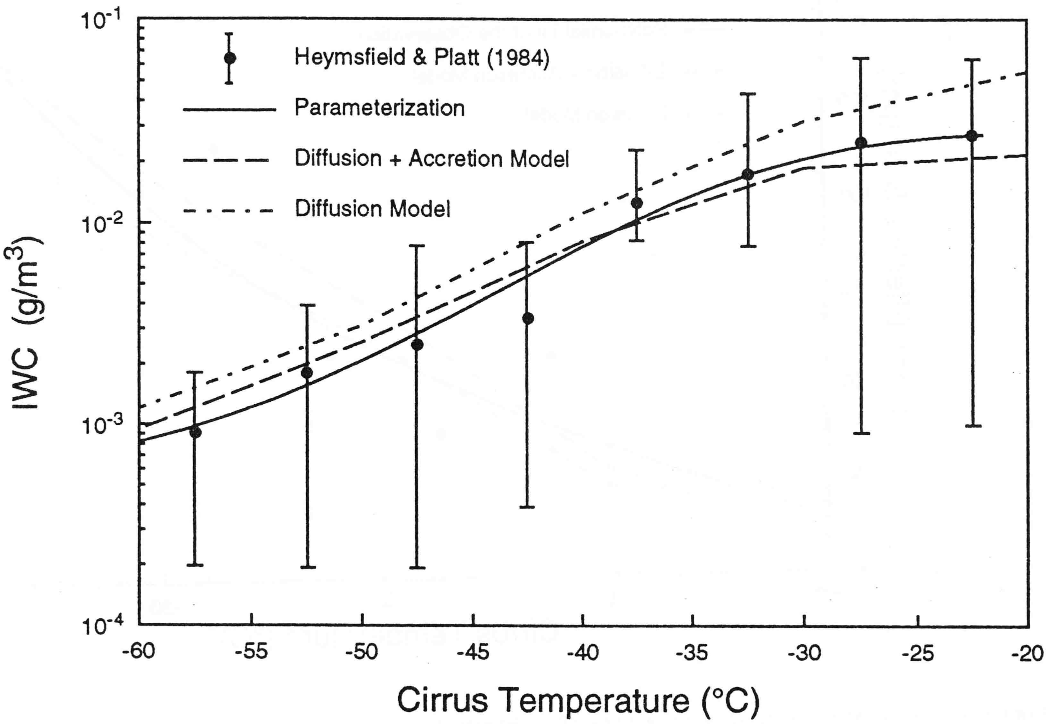

Figure 1. IWC derived from aircraft measurements for midlatitude cirrus clouds as a function of temperature. The solid curve denotes the best-fit polynomial parameterization. The dashed and dashed-dot curves represent results computed from a diffusion plus accretion model and a diffusion model, respectively.

procedure, the IWC results are illustrated by the dashed line in Figure 1. The diffusion growth clearly shows that IWC is a function of temperature. The systematically higher IWC values from diffusion growth calculations as compared with parameterization results are due to the fact that gravitational settling initiated by accretion has not been accounted for.

The accretion growth for ice crystals due to collision and coalescence is modeled by using the conventional growth equation in the form

$$\rho_i \frac{dv}{dt} \cong A \bar{E}\ IWC(\omega_T - \omega), \tag{6}$$

where ρ_i is the ice density, V is the ice crystal volume, A is the ice crystal cross section area, $\bar{E}$ is the mean collision efficiency which is assumed to be 1 in this model, ω_T is the crystal terminal velocity, and ω is the updraft velocity which for simplicity is assumed to be zero in the calculation. From laboratory and field experiments, the ice crystal volume, cross section area, and terminal velocity can be related to length as follows: $V = aL^3$, $A = bL^2$, $\omega_T = cL^d$, where a, b, c, and d are coefficients determined from measured data. Numerical solution can be obtained by performing the integration over time in terms of the crystal length.

The total ice water mass settled out of cloud can be obtained from the vertical divergence of the ice mass flux integrated over the time of ice crystal growth as follows (Heymsfield and Donner 1990):

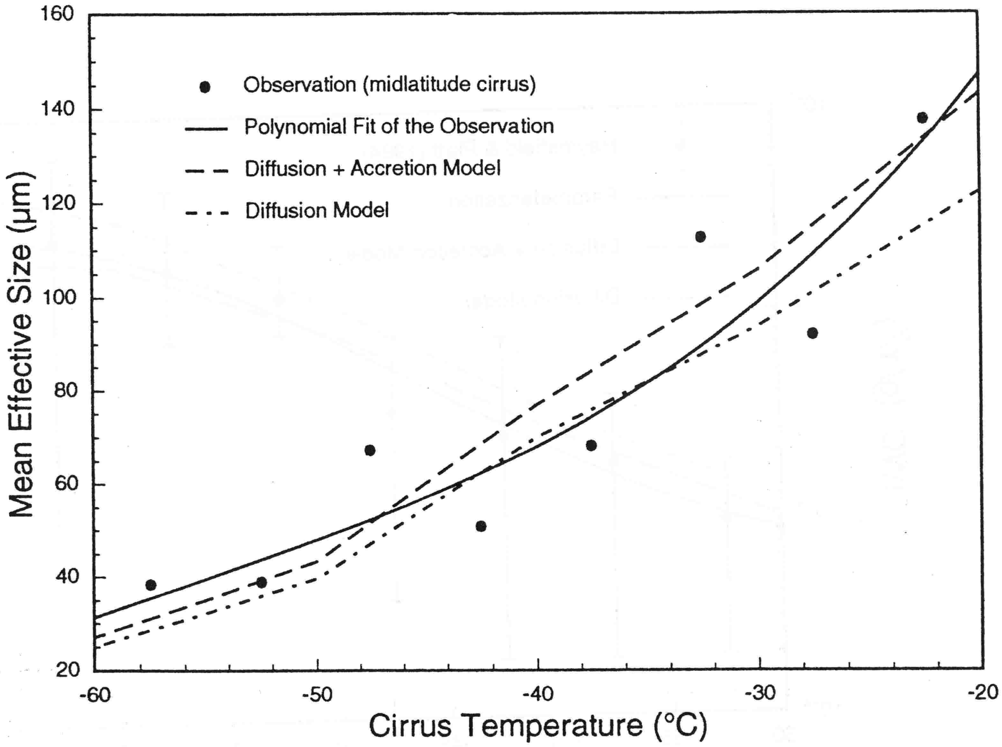

Figure 2. Ice crystal mean effective size (D_e) obtained form aircraft measurements for midlatitude cirrus clouds as a function of temperature. The solid curve denotes the best-fit polynomial parameterization of the observation. the dashed and dashed-dot curves represent results computed from a diffusion plus accretion model and a diffusion model, respectively.

$$IWC = -\int_0^t \frac{\partial}{\partial z}(IWC \cdot \omega_T)dt' . \tag{7}$$

The terminal velocity ω_T is dependent on the ice crystal length which in turn is governed by accretion.

To solve Eq. (6) in terms of the crystal length, we use the length determined from diffusion growth as the initial condition and assume that IWC remains constant during this growth; a reasonable assumption because gravitational settling normally occurs after the onset of accretion. The total time before the ice crystal fallout is given by $\Delta z/\omega_T(L_0)$, where Δz is a prescribed cloud thickness (1 km) and L_0 is the initial crystal length.

The results of the mean effective ice crystal size defined in Eq. (3) for diffusion growth only and for diffusion plus accretion growths are illustrated in Figure 2. With the inclusion of accretion, ice crystals become larger. For larger ice crystal sizes associated with warmer temperatures in diffusion growth, the accretion process further enhances their growth. In Figure 1, IWC is reduced by the incorporation of gravitational settling which follows accretion growth.

As pointed out in the Introduction section, there has been significant progress in incorporating a fully prognostic cloud scheme to evaluate cloud ice/water content in GCMs following the pioneering work of Sundqvist (1978). To be fully interactive with a radiation parameterization program, information on the mean effective cloud particle size is required. It is unlikely that cloud particle size distribution will be predicted in GCMs in the near future. In the preceding discussion we have demonstrated that the mean effective ice crystal size is dependent on temperature based on some aircraft microphysics measurements in midlatitude cirrus cloud systems, as well as from the theoretical analyses for diffusion and accretion growths. Jakob and Morcrette (1995) have illustrated that the ECMWF model is sufficiently sensitive to the use of an interactive mean effective ice crystal size driven by temperature in respect to the radiation budgets at the top and the surface. Analyses of numerous ice crystal size distribution data sets that have been obtained during FIRE II (midlatitude) and CEPEX and TOGA-COARE (tropics) are important in order to narrow down the uncertainty in the representation of ice crystal size distribution using grid parameters such as temperature generated in GCMs. In addition, more detailed theoretical analyses should be carried out for the simulation of ice crystal size distributions using the one-dimensional parcel method to understand the critical parameters, in addition to temperature, that may affect the growth of ice crystals.

3. RADIATIVE PROPERTIES OF ICE CLOUDS

3.1 Light scattering and absorption properties of ice crystals

The first issue in parameterization of the radiative properties of ice clouds involves the basic scattering and absorption properties of nonspherical ice particles.

The shapes of ice crystals that occur in the atmosphere vary greatly. Laboratory experiments show that the shape and size of an ice crystal are governed by temperature and supersaturation. In the atmosphere, if the ice crystal growth involves collision and coalescence, shape can be extremely complex. Ice crystals generally have a basic hexagonal structure. As illustrated in subsection 3.2, observations based on replicator sonde from FIRE-II-IFO shows that midlatitude cirrus clouds are largely composed of bullet rosettes, solid and hollow columns, plates, and aggregates with sizes ranging from about 5 to 600 μm.

The significance of using reliable phase function, single-scattering albedo, and polarization properties for nonspherical ice crystals in remote sensing and climate research has been demonstrated by and articulated in a number of recent papers. In particular, interpretation of the observed solar albedo of cirrus clouds must use the scattering and absorption properties of hexagonal ice particles (Kinne et al. 1992; Stackhouse and Stephens 1991; Fu and Liou 1993). There are also sufficient sensitivities of the scattering and absorption properties of hexagonal ice crystals in the climatic investigation concerning the competition of solar albedo and IR greenhouse effects associated with cirrus clouds (Liou and Takano 1994) and in parameterization of the radiative properties of ice clouds in a GCM (Donner 1994).

Unlike the scattering of light by spherical water droplets which is governed by the exact Mie solution, an exact scattering theory for the solution of hexagonal ice crystals covering all shapes and sizes does not exist in practical terms. In recent years, our research group has developed light scattering programs for use in radiation/climate modeling and remote sensing applications based on a Monte Carlo/geometric ray-tracing method (Takano and Liou 1989, 1995; Liou and Takano 1994). We can determine the scattering, absorption, and polarization properties of plates, solid and hollow columns, dendrites, bullet rosettes, and aggregates whose sizes are much larger than the incident wavelengths. For small quasi-spherical ice crystals notably frozen droplets, we can approximate them by spheroids whose scattering and absorption properties can be computed exactly (Takano et al. 1992).

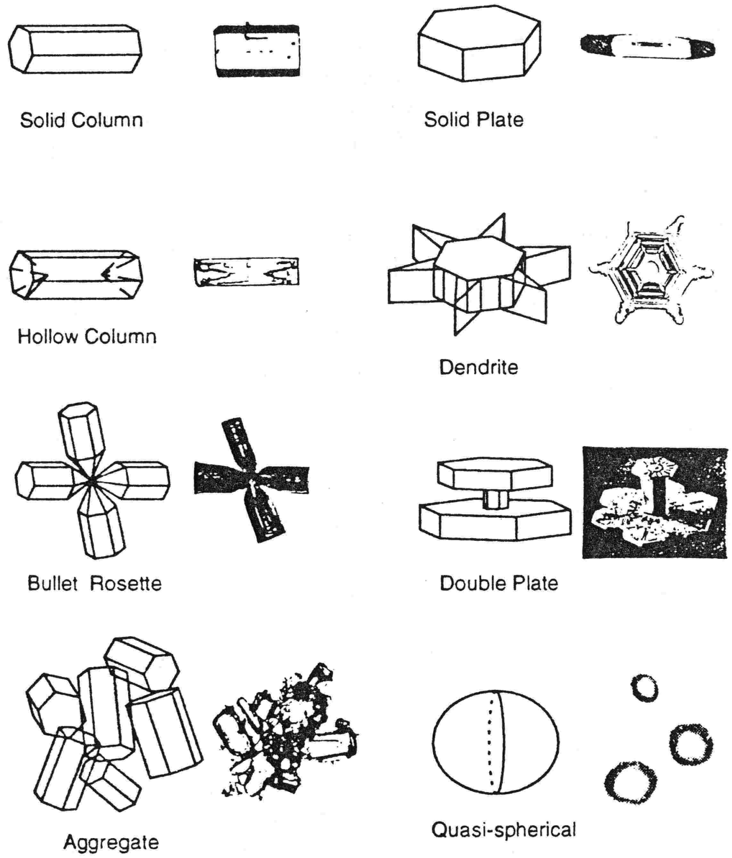

Figure 3.Display of ice crystal shapes observed in cirrus clouds (second and fourth columns). The first and third columns illustrate the shapes simulated from a geometric model for ray-tracing calculations. Our current capability of solving light scattering and absorption of ice crystals includes all the shapes.

Our present capability for solving the scattering of light by large ice crystals based on the geometric optics principle is illustrated in Figure 3 in terms of the display of ice crystal shapes. The second and fourth columns display the commonly occurring ice crystal shapes observed in cirrus clouds, while the first and third columns represent the shapes that are simulated from a geometric model from which photons can be traced by the Monte Carlo method. This geometric ray-tracing technique requires the localization of geometric rays, while the scattering field is equally partitioned into the contribution from diffraction and Fresnelian rays. It is valid for large ice crystals with size parameters greater than about 30-40 (Liou and Takano 1994) and may not be applicable to small ice crystals, particularly involving infrared wavelengths.

An extensive data collection of the ice crystal size distribution for midlatitude and tropical cirrus has been made from 2D-c and 2D-p probes onboard aircraft and replicator sonde (Heymsfield and Miloshevish 1993; Heymsfield and McFarquhar 1995). These data show that small ice crystals on the order of 5-20 μm exist in cirrus clouds. The assessment of the impact of these small ice crystals on the radiative properties of midlatitude and tropical cirrus is an important subject with respect to the understanding and determination of the energy budget in cirrus cloudy atmospheres.

To tackle the problem involving light scattering by small ice crystals, we have developed a novel geometric ray-tracing method (GOM2) and a finite

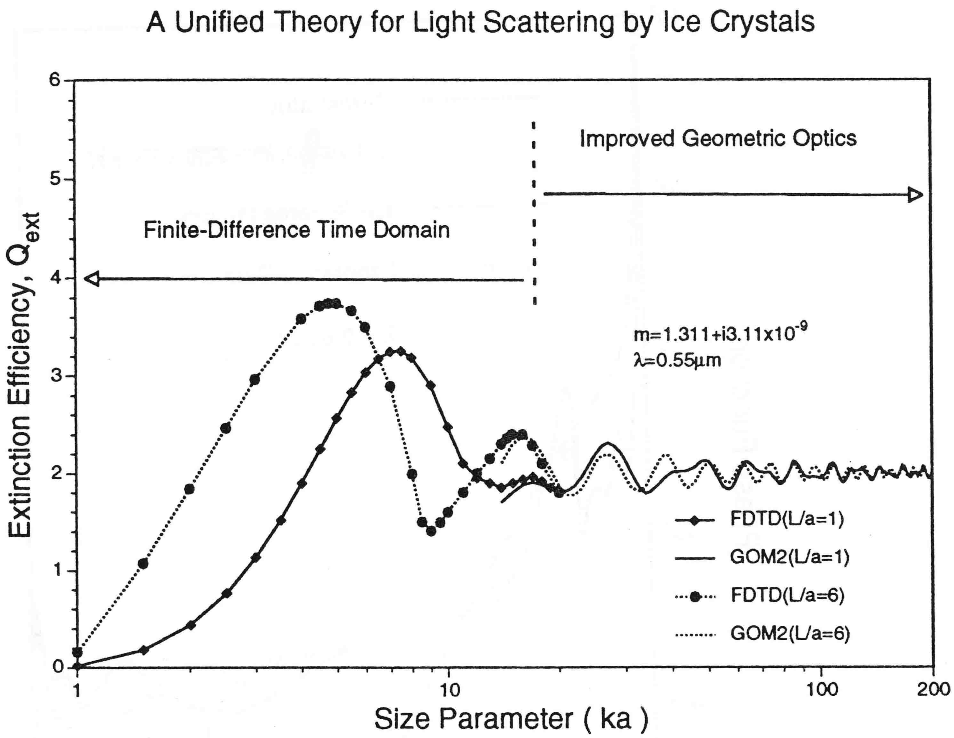

Figure 4. Presentation of a unified theory for light scattering by ice crystals using the extinction efficiency as a function of size parameter as an example. The improved geometric optics method (GOM2) breaks down at the size parameter of about 15, whereas the finite-difference time domain (FDTD) is not applicable to size parameters larger than about 15 because of numerical and computational limitations. The extinction efficiency is shown for two ice crystal shapes: L/a = 1 for plates and L/a = 6 for columns. By unifying the GOM2 and FDTD methods and in reference to Figure 3, computations for light scattering, absorption, and polarization properties of ice crystals of all shapes and sizes can be made, similar to the exact Mie scattering theory for water droplets.

-difference time domain (FDTD) method (Yang and Liou 1995). In the improved ray-tracing model, we invoke the principle of geometric optics to evaluate the reflection and transmission of localized waves from which the electric and magnetic fields at the particle surface (near field) can be computed. The near field can subsequently be transformed to the far field based on the equivalence theorem in which the phase interferences are fully accounted for. This innovative method improves the scattering and absorption results, as compared with the exact FDTD method, and can be adequately applied to size parameters as small as ~ 15 for three-dimensional random orientation conditions. Pioneered by the electrical engineers for the identification of irregular objects, the FDTD method is a numerical technique for the solution of the Maxwell equations using appropriate absorbing boundary conditions. It is considered to be the "exact" numerical solution for light scattering by particles, as verified by the exact Mie solutions for long circular cylinders and spheres. Because of numerical instability and required computer time, the FDTD method can only be applied to size parameters smaller than ~ 10-15.

Combining the improved geometric ray-tracing and FDTD methods, we have developed a unified theory for light scattering by ice crystals for all sizes and shapes. An example of this theory is illustrated in Figure 4 in terms of the extinction efficiency as a function of size parameter. Two ice crystal types involving plate (L/a = 1) and column (L/a = 6) are shown. The extinction coefficient reaches about 2 for the size parameter of ~ 30-40. The size parameter at which both the GOM2 and FDTD methods breakdown is at ~ 15. The

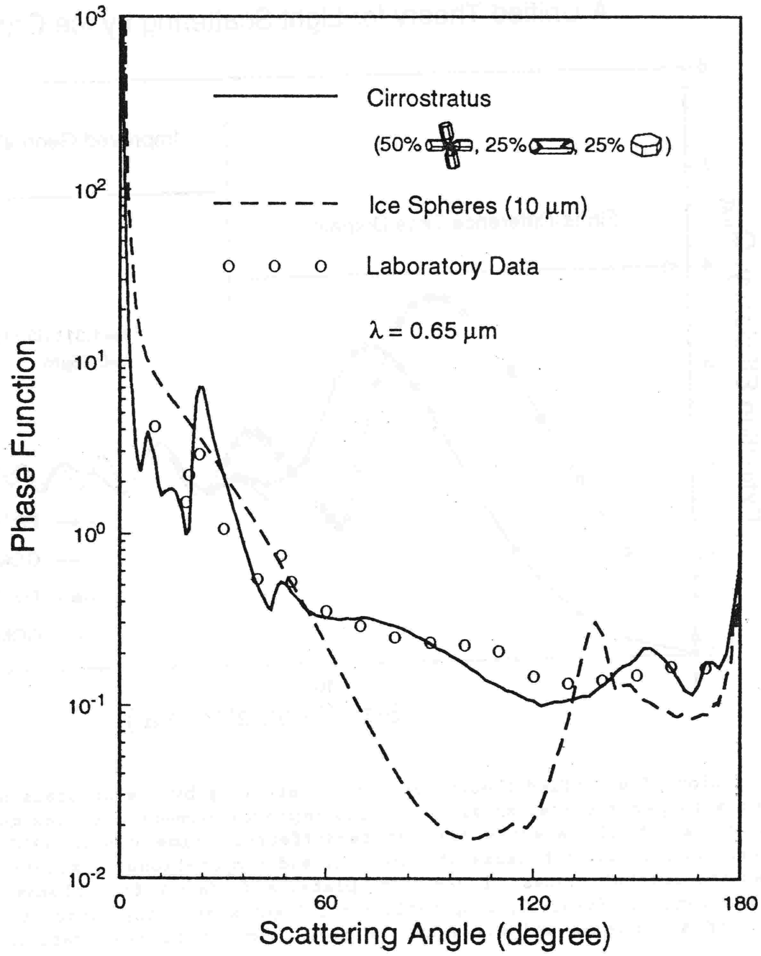

Figure 5.An example of the unified theory for light scattering by ice crystals in terms of phase function as a function of scattering angle. the theoretical results are presented for a cirrostratus composing of 50 % bullet rosettes, 25 % hollow columns, and 25 % plates. Also shown are results form laboratory experiment data and Mie scattering calculations for ice spheres.

former is due to the assumption involved in the geometric optics method to determine the field, while the latter is caused by the numerical and computational limitations. Figure 5 shows another example of the applicability of the unified theory for the computation of phase function as a function of scattering angle. We have constructed a typical cirrostratus model containing 50 % bullet rosettes, 25 % hollow columns, and 25 % plates. Also shown are the laboratory experimental data for ice particles generated in a cold chamber and Mie scattering results for ice spheres. The phase function calculated from the cirrostratus model compares reasonably well with laboratory data for all scattering angles, including the 22° and 46° halo features. Ice spheres scatter more light in the forward directions and much less light in the side directions in comparison with ice crystals. These differences are critical in the interpretation of satellite data and in the analysis of solar albedo effects involving cirrus clouds.

At this point, we have the theoretical tools to provide the basic scattering and absorption data required for a reliable parameterization of the radiative properties of ice clouds. For application to GCMs we can employ the mean ice crystal size spectra and typical shapes, preferable with a classification of geographical regions (tropics, midlatitude, arctic/antarctic)

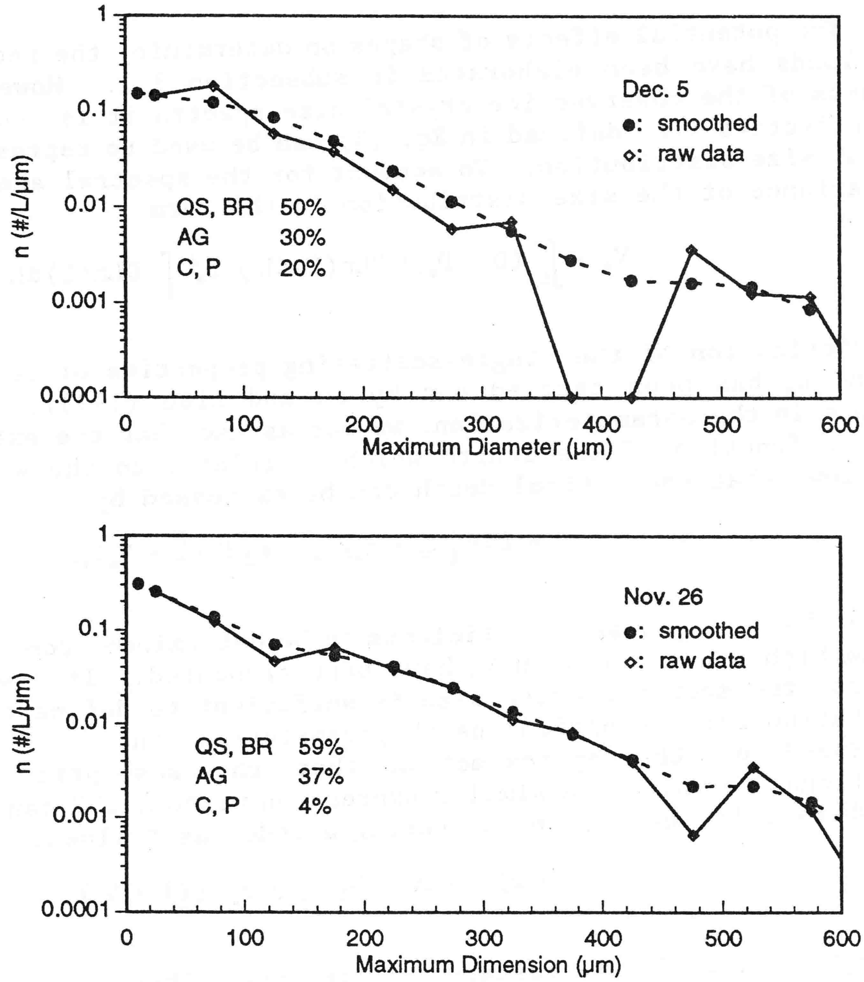

Figure 6.Averaged ice crystal size distributions (and their smoothed curves) derived from the replicator sounding datasets for the 5 December and 25 November cases during FIRE-II-IFO, Kansas, 1991. The percentages of shapes for each distribution are also shown: QS, BR, AG, C, and P denotes quasi-spherical particles, bullet rosettes, aggregates, column, and plate, respectively.

for light scattering calculations (see below for further discussion). Computations are required to cover the necessary and sufficient wavelengths in the solar and infrared regions the details of which are yet to be worked out.

3.2 Parameterization in terms of mean and variance involving ice crystal size distribution

From the observed ice crystal size spectra, we find that there are significant spatial and temporal variabilities in terms of sizes and shapes produce by various stages of the ice crystal growth. For applications to GCM studies, mean properties of the ice crystal size distribution are the quantities that are required in parameterization and in determining the bulk radiative properties of a cloud field. Examples of the ice crystal size spectra are shown in Figure 6. These spectra were obtained by averaging over a number of spectra derived from the replicator data at different levels within cirrus clouds that were sampled at Coffeyville, Kansas on 26 November and 5 December 1991 during FIRE-II-IFO. The ice crystal sizes range from 5 to 600 μm, while the shapes span from bullet rosettes, solid and hollow columns, plates, to aggregates.

The potential effects of shapes on determining the radiative properties of ice clouds have been elaborated in subsection 3.1. However, in view of the skewness of the observed ice crystal size spectra it is not clear whether the mean effective size defined in Eq. (3) can be used to represent properly the ice crystal size distribution. To account for the spectral skewness, we can define the variance of the size distribution in the form

$$V_e = \int_L (D - D_e)^2 \, DLn(L)dL \, / \, D_e^2 \int_L DLn(L)dL. \tag{8}$$

Parameterization of the single-scattering properties of ice clouds in terms of IWC and D_e has been carried out by Fu and Liou (1993). To incorporate the variance in the parameterization, we may assume that the extinction coefficient (Q) is a function of the length which is related to the width by a power law. It follows that the optical depth can be expressed by

$$\tau = \mathrm{IWP}\left[a_0 + a_1/D_e + a_2 \, D_e(1 + V_e)\right], \tag{9a}$$

where $a_1(i = 0, 1, 2)$ are coefficients to be determined from "exact" calculations and the high order terms in V_e have been truncated. If $Q = 2$, then $a_2 = 0$. In this case the mean effective size is sufficient to define the ice crystal size distribution for the optical depth parameterization.

Based on the approximation that the absorption cross section is proportional to volume, a similar expression without IWP can be derived for $(1 - \tilde{\omega})^{-1}$, where $\tilde{\omega}$ is the single-scattering albedo, as follows:

$$(1 - \tilde{\omega})^{-1} \cong b_0 + b_1/D_e + b_z \, D_e(1 + V_e), \tag{9b}$$

where $b_i(i = 0, 1, 2)$ are certain coefficients. There appears to be no physical foundation for the parameterization of the asymmetry factor, because parameterization of the phase function does not exist in the case of ice crystals. However, we may postulate that the phase function must be determined by ice crystal size distribution and that the form presented in Eq. (9b) may be used for parameterization purpose, viz,

$$g = c_0 + c_1/D_e + c_2 \, D_e(1 + V_e), \tag{9c}$$

where again $c_i(i = 0, 1, 2)$ are certain constants. The high order moments in the phase function can also be parameterized in a likely manner for application to the delta-four-stream scheme for use in numerical models.

For application to GCMs that predict IWC only, D_e and V_e can be prescribed according to three regions: tropics, midlatitude, and arctic/antarctic. Alternately, we may also derive physical equations relating D_e and V_e to temperature (see Section 2). For future GCMs that simulate ice crystal spectra offline, the radiation program will be driven by IWC, D_e, and V_e.

3.3 Cloud inhomogeneity and finiteness

From the mapping of optical depth using satellite data, cirrus clouds are shown to exhibit substantial horizontal variability (Minnis et al. 1993; Ou et al. 1995). This variability is also evident from the time series of backscattering coefficients constructed from lidar returns (Sassen 1991; Spinhirne and Hart 1990). Moreover, within a GCM grid, partial cloudiness generated by either diagnostic or prognostic means frequently occurs. Thus, in addition to the issues associated with the microscopic properties of ice clouds involving particle shapes and sizes, the macroscopic characteristics of these clouds in terms of horizontal inhomogeneity and finite geometry could also be important in determining their radiative properties.

The subject of radiative transfer in finite clouds has been reviewed by Liou (1992, Section 5.4). In particular, the diffusion approximation for 3-D radiative transfer is introduced and some results from Monte Carlo simulations are shown. The importance of the spatial inhomogeneity of clouds on the radiation field, especially on the question of cloud absorption, has been discussed by Stephens and Tsay (1991) and pointed out by Liou (1992, p. 300). More recent works on these subjects have been made by Evans (1993) based on the spherical harmonics method, Gabriel et al. (1993) using a Fourier-Riccati approach, and Cahalan et al. (1994) employing Monte Carlo simulations. The first two authors applied the methods to radiative transfer in 2-D inhomogeneous clouds, while the last investigated the assumption of plane-parallel pixel-by-pixel calculations on the visible albedo for marine stratocumulus clouds.

We are still in the embryonic stage in understanding the significance of the inhomogeneous and finite effects on the cloud radiative properties. From the computational perspective, we require a 3-D radiative transfer program that includes variation of the single-scattering properties as functions of position to simulate the cloud radiation field and to study the deviation of the conventional plane-parallel calculations. Unfortunately, the 3-D inhomogeneous radiation transfer program is extremely intricate and requires formidable computational efforts to achieve reliable results, even for a single wavelength. At the present, the Monte Carlo method appears to be the best tool for investigating the effect of the macroscopic structure on the radiative properties of clouds in general and ice clouds in particular. Optimization of the 3-D radiative transfer program so that computations can be carried out to cover the entire solar and IR spectral regions with the inclusion of gaseous absorption is a research task that requires further theoretical and numerical efforts. Until a reliable and efficient 3-D inhomogeneous radiative transfer program has been developed, we would not be in a definitive position to resolve the contemporary cloud absorption problem. Finally, the 3-D radiative transfer program is also required for a reliable interpretation of spectral and broadband radiometric measurements in the atmosphere containing clouds with finite extends.

3.4 Validation of radiation parameterization programs

Parameterizations of radiative transfer for broadband flux and heating rate calculations for application to GCMs are subject to assumptions and approximations. Consequently, their general accuracies must be checked and verified, the so-called validation procedure. Many scientific programs and field experiments have been carried out for this particular purpose. From the theoretical perspective, validation can be made by comparing the results calculated from parameterizations with those from the "exact" method. For example, radiative transfer parameterizations based on the δ-Eddington, δ-two-stream, and δ-four-stream approximations have been checked with the "exact" adding or discrete-ordinates methods from which the accuracies of these approximations are known. Radiation parameterizations based on the band model, broadband emissivity, or correlated k-distribution method for IR flux and cooling rate calculations can also be checked with the "exact" line-by-line (LBL) calculations using the same input data. Some progress has been made in this area through the international intercomparison efforts.

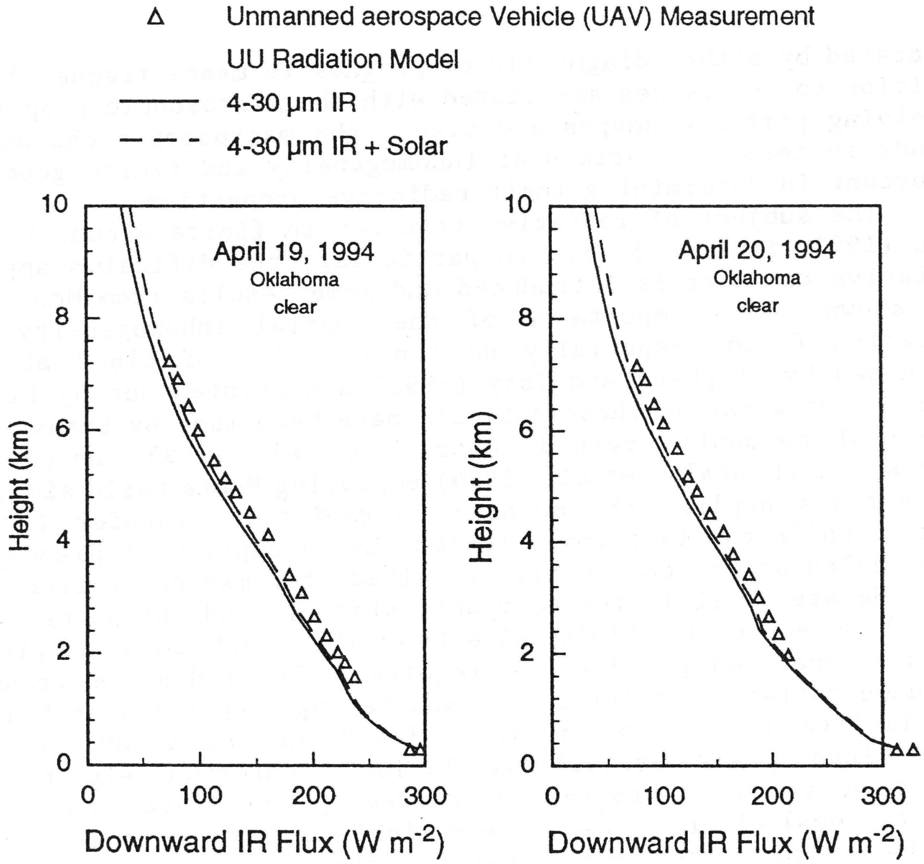

Figure 7. Downward IR fluxes as a function of height measured from radiometers onboard the unmanned aerospace vehicle (UAV) in clear atmospheres over the DOE-ARM-CART cite, Oklahoma on April 19 and 20, 1994 (Valero et al. 1995). Theoretical results computed from the correlated k-distribution method are shown for two cases with and without the inclusion of the solar contribution in the IR broadband radiometer measurements.

Even with LBL calculations, the radiance and flux results are subject to uncertainties in the input line parameters, including line strength, half-width, and line position. For atmospheric applications, it is essential to compare the theoretical results with the radiometric measurements. An example of the comparison between results computed from a model and derived from aircraft broadband radiometric measurements are show in Figure 7. The measurements were made over the Department of Energy ARM CART cite, Oklahoma on April 19 and 20, 1994, using the unmanned aerospace vehicle (UAV). Flux measurements covered from about 2 to 7 km. The two points at the surface denote the IR radiometric measurements at the onset and completion of the UAV flux profile operation which lasted for about 1-2 hours. The data were obtained from the precision radiometers (4 - 30 μm) developed by Francisco Valero (private communication). Using the correlated k-distribution program developed by Fu and Liou (1992, 1993) and the collocated temperature and humidity profiles obtained during the UAV operation as inputs to this program, the computed downward fluxes are shown in Figure 7 for two cases: one includes the solar contribution in the spectral radiometer interval while the other does not incorporate this contribution, which accounts for about 13 W m^{-2}. For the former, the theoretical results closely match the observed downward IR flux profile with deviations within about 5 - 10 W m^{-2}. For the upward fluxes not shown here, comparison between theory and measurement becomes more complicated because of the uncertainties in the surface temperature and surface emissivity. Uncertainties in the solar flux comparisons involve not only the atmospheric (including aerosol) and surface input parameters to the model but also the solar insolation, solar zenith angle, and the actual distance between the sun and the earth that are used in the calculations.

Validation of radiation model calculations by means of radiometric measurements is currently a contemporary research program. However, the model validation efforts even for clear column solar and IR fluxes have not been completely satisfactory at this point. Validation of the radiation parameterization models involving ice clouds employing spectral and broadband radiometric measurements in cirrus cloudy atmospheres would be much more complicated and would require the collocated and concurrent measurements of ice crystal size distributions. With a number of field experiment programs that are planned, we have the excellent opportunity to narrow down the uncertainties in parameterization of the radiative properties of ice clouds and to improve our modeling capability for use in GCMs.

4. ACKNOWLEDGMENTS

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