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Effect of particle size distributions on the retrieval of ice cloud properties

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[1] Various measured size distributions obtained from aircraft measurements at different regions and seasons are used in the retrieval algorithms for ice cloud properties by several major satellite instruments such as MODIS, CERES and VIIRS. These measured size distributions are characterized by one parameter: effective size (diameter or radius). This study shows that the adoption of such measured size distributions leads to inconsistent results in retrieved cloud properties because neglecting the effect of effective variances causes non-monotonic relations between crystal size and single scattering properties. We also show that single scattering properties of most observed size distributions of hexagonal columns can be adequately characterized by effective radius and effective variance. Therefore, in remote sensing of ice cloud properties, theoretical size distributions with explicitly assumed effective variances should be used, similar to the practice adopted for water clouds. **Citation:** Han, Q., J. Zeng, K.-S. Kuo, H. Chen, and E. Smith (2005), Effect of particle size distributions on the retrieval of ice cloud properties, *Geophys. Res. Lett.*, *32*, L13818, doi:10.1029/2005GL022659.

1. Introduction

[2] Cloud microphysical parameterizations are important due to their effect on cloud radiative properties and cloud-related hydrological processes in large-scale models. *Ebert and Curry* [1992] showed that the change of cloud optical thickness caused by a change in effective particle radius (r_e) can be more effective than that caused by a change in IWP in strengthening cloud albedo feedback. *Zhang et al.* [1999] found that effective radius of ice crystal sizes significantly affects the modeled radiative fluxes. Therefore, particle size of ice clouds has been included in cloud product from most major satellite project for climate studies.

[3] Currently, it is a common practice to deliberately select measured size distributions from aircraft measurements in remote sensing algorithms. For example, seven measured size distributions obtained from aircraft measurements were used by *Baum et al.* [2000] in the algorithm for the MODerate resolution Imaging Spectrometer (MODIS). *Han et al.* [1997, also A near-global survey of cirrus particle size using ISCCP, preprints of Eighth Conference on Satellite Meteorology and Oceanography, American Meteorological Society, Atlanta, Georgia, 28 Jan. to 2 Feb. 1996] made use of five measured size distributions in an early version of retrieval algorithm for the International Satellite Cloud Climatology Project (ISCCP). *Minnis et al.* [1998] chose eleven measured size distributions in the CERES algorithm. *Ou et al.* [2003] selected six measured size distributions in the retrieval schemes of the Visible/Infrared Imager/Radiometer Suite (VIIRS).

[4] The problem with randomly selected measured size distributions is that they are characterized by only one parameter, effective diameter (or radius). However, model studies have suggested that the impact of the width of size distributions cannot be neglected in radiative transfer calculations. For example, *Hansen and Travis* [1974] showed that for spherical particles two parameters (effective radius, r_e, and effective variance, v_e) are needed in characterizing size distributions for an adequate representation of scattering properties. For large nonspherical ice crystals, several studies [e.g., *Francis et al.*, 1994; *Fu*, 1996; *Fu et al.*, 1998; *Wyser and Yang*, 1998] based on less extensive calculations concluded that v_e might be not important in determining single scattering properties. Nevertheless, other studies [e.g., *Kinne and Liou*, 1989; *Mitchell and Arnott*, 1994] argued that shapes of size distributions are important in determining radiative properties of ice clouds.

[5] In recent years, careful model studies show that the one-parameter approach may lead to large uncertainties in the calculated scattering properties of nonspherical particles. For example, *Mitchell* [2002] reveals that neglecting shapes of crystal size distributions leads to large uncertainties in single scattering albedo (48%) and extinction efficiencies (100%). *Baum et al.* [2005] presented significant scatters in the relation of effective diameter and single scattering properties based on hundreds of size distributions from aircraft measurements for MODIS channels. The results of these studies cast a question about the adequacy of the *ad hoc* choice of various measured size distributions characterized only by effective diameter in different satellite retrieval algorithms. The random selection of measured size distributions could be a source of inconsistency among results of remote sensing groups and a cause of incompatibility between remote sensing and modeling studies.

[6] This study shows that retrieved ice cloud particle sizes are inconsistent using measured size distributions characterized by effective particle size alone, which is a major source of uncertainties in the retrieved cloud microphysical properties. By calculations for hexagon columns, we also show that cloud scattering properties can be

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Table 1. Single Scattering Properties for Different Measured Size Distributions

		CERES (λ = 3.73 μm)			MODIS (λ = 3.82 μm)		
Cloud Model	v_e	D_e (μm)	ϖ_0	g	r_e (μm)	ϖ_0	g
Cold Cirrus	0.85	23.86	0.7849	0.8057	8.9	0.7924	0.7840
Cirrostratus	0.52	41.20	0.7047	0.8571	19.3	0.7924	0.7840
Warm Cirrus	0.96	45.30	0.7176	0.8469	26.3	0.7927	0.7777
−40° Cirrus	0.95	67.60	0.6775	0.8731	37.3	0.7376	0.8257
Nov. 1 Cirrus	0.18	75.20	0.6281	0.9121	N/A	N/A	N/A
Cirrus Uncinus	0.15	123.1	0.5875	0.9344	78.5	0.6347	0.9242

adequately represented by two parameters, effective size and effective variance, for different size distributions observed in real ice clouds.

2. Method

[7] The impact of effective variance on single scattering properties and retrieved effective size of ice crystals is estimated by a radiative transfer model using the adding-doubling technique [*Han et al.*, 1994, 1999]. The range of effective variance, v_e, is estimated based on several measured size distributions selected in satellite retrieval algorithms, which is then used as input for calculations of single scattering properties for different size distributions and effective particle sizes. The ice crystal shape is assumed as regular hexagonal columns with different aspect ratios, which is based on the parameterization of *Mitchell and Arnott* [1994]: A = 0.35 L (L < 100 μm), = $3.48L^{0.5}$ (L > 100 μm), where the semi-width (A) and maximum length (L) of ice crystals are in microns. Twenty two size bins characterized by maximum length are used, i.e., L = 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1000, and 1500 μm. The single scattering properties of ice crystals were computed using the standard ray-tracing technique, as described by *Macke et al.* [1996]. Definitions of effective radius, effective variance and types of size distributions are described in the following.

2.1. Effective Radius and Effective Variance

[8] For non-spherical particles, the effective radius is defined as $r_e = \frac{3}{4}(\sum_{i=1}^{n} V_i n_i / \sum_{i=1}^{n} P_i n_i)$ where V_i is the volume of the *i*th particle size bin, n_i is the number density of the *i*th particle size bin, and P_i is the projected cross-section of the *i*th particle size bin, which is essentially the same as proposed by *Foot* [1988].

[9] The effective variance is defined by

$$v_e = \frac{1}{\overline{P}(L) r_e^2} \int_{L_1}^{L_2} \left(\frac{3}{4} \frac{V(L)}{P(L)} - r_e \right)^2 P(L) n(L) dL \qquad (1)$$

where $\overline{P} = \int_{L_1}^{L_2} P(L) n(L) dL$ is the averaged projection and L is the maximum dimension of ice crystals. The definitions of r_e and v_e can be applied to all particle shapes.

[10] To evaluate the typical range of v_e in ice clouds, Equation (1) is applied to six measured size distributions used by the CERES science team [*Minnis et al.*, 1998], five of which were used by the MODIS science team [*Baum et al.*, 2000], and four of which were used by the VIIRS algorithm [*Ou et al.*, 2003]. As shown in Table 1, the v_e values range from 0.96 to 0.15, which are much greater than that of water clouds, ranging from 0.11 for fair weather cumulus to 0.20 for stratus clouds [*Hansen*, 1971].

2.2. Size Distributions

[11] Similar to *Hansen and Travis* [1974], four theoretical size distributions: modified gamma, bimodal, log-normal, and power law are considered. To relax the limitation of v_e < 0.5 by the standard gamma distribution, the modified gamma distribution, $n(L) = \alpha L^{\mu} \exp(-\beta L^{\kappa})$, is used in this study. For the modified gamma distribution, $r_e = \Gamma[(4+\mu)/\kappa] / \{\beta^{1/\kappa}\, \Gamma[(3+\mu)/\kappa]\}$ and $v_e = \{\Gamma[(5+\mu)/\kappa] \cdot \Gamma[(3+\mu)/\kappa] / \Gamma^2[(4+\mu)/\kappa]\} - 1$. The bimodal distribution is in the form of $n(L) = \alpha_1 L^{\mu} \exp(-\beta_1 L^{0.5}) + \alpha_2 L^{\mu} \exp(-\beta_2 L^{0.5})$ where $\beta_i = \sqrt{x(x+1)/r_{ei}}$, i = 1, 2. The log-normal distribution is defined by $n(L) = (\sqrt{2\pi}\sigma_g L)^{-1} \exp(-(\ln L - \ln L_g)^2 / 2\sigma_g^2)$ where $L_g = r_e/(1+v_e)^{5/2}$, $\sigma_g^2 = \ln(1+v_e)$. The power law distribution is in the form of $n(L) = 2L_1^2 L_2^2 (L_2^2 - L_1^2)^{-1} L^{-3}$ for $L_1 < L < L_2$ and $n(L) = 0$ for $L_1 > L$ or $L_2 < L$. The disadvantage of the power law distribution is that there is a rigid relationship between L_1, L_2 and r_e, v_e, which makes this type of size distribution less flexible when comparing with observations.

3. Results

[12] Neglecting the impact of v_e in measured size distributions may lead to large uncertainties in single scattering albedo and phase functions as shown in Figures 1 and 2, respectively. Figure 1 plots single scattering albedo (ϖ_0) values from all size distributions. It can be seen that at a typical effective radius of 30 μm the variation of v_e from 0.15 to 1.0 leads to a range of single scattering albedo, ϖ_0, from ∼0.66 to ∼0.70; generally ϖ_0 increases as v_e increases. Similarly, Figure 2 demonstrates that the effect of v_e variation upon scattering phase function is also significant. Similar calculations have been done for other spectral bands. Generally, the effect of v_e on single scattering properties is more significant when particle absorption is stronger.

[13] Analogous to the findings of *Hansen and Travis* [1974] regarding water droplet size distributions we find that effective radius and effective variance are also suitable in charactering single scattering properties of ensembles of ice particles with the shapes of hexagonal columns. Figures 3 and 4 demonstrate the above assertion. Figure 3

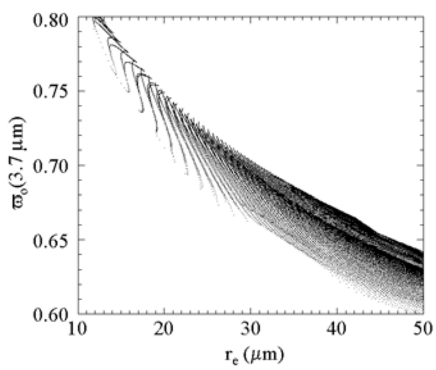

Figure 1. Single scattering albedo at λ = 3.7 μm as function of effective radius for four size distributions (modified gamma, bimodal, log normal and power law) with effective variance changing from 0.15 to 1.0

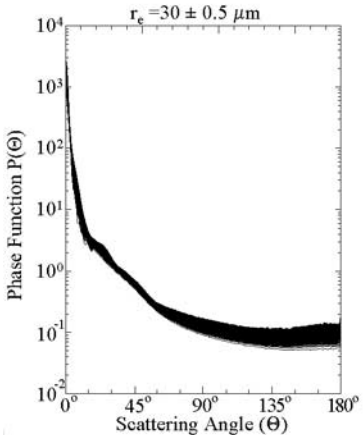

Figure 2. Phase function for $r_e = 30 \pm 0.5$ μm hexagonal columns at λ = 3.7 μm for four size distributions (modified gamma, bimodal, log normal and power law) with effective variance changing from 0.15 to 1.0.

plots ϖ_0 as a function of effective radius at three fixed effective variance values of 0.1, 0.3, and 0.5. Different symbols in Figure 3 correspond to different theoretical distributions where only three data points from the power law distribution fit the r_e, v_e range due to the reason stated above, which are masked by points from other distributions. It is apparent that the symbols representing different size distributions almost overlap one another for the same r_e and v_e. Figure 4 shows the scattering phase functions obtained for $r_e = 30 \pm 0.5$ μm and $v_e = 0.25 \pm 0.005$. The differences among different theoretical size distributions are negligible. It further confirms the notion that once r_e and v_e are fixed the single scattering properties for a distribution of hexagon-column ice particles are practically determined.

[14] We now turn to the examination of the measured ice particle distributions often used in various retrieval algorithms listed in Table 1 in ascending order of r_e or D_e, where D_e is defined by $D_e = \int_{L_1}^{L_2} LD^2\, n(L)dL / \int_{L_1}^{L_2} LDn(L)dL$ where L is the length and D is the basal plane diameter of a hexagon column. Note that in general $D_e \neq 2r_e$ although these two size parameters are positively correlated.

[15] A general trend visible in Table 1 is that as effective particle size increases single scattering albedo, ϖ_0, decreases and asymmetry factor, g, increases. However, the trend is interrupted by "cirrostratus" which has a smaller r_e but smaller ϖ_0 as well as larger g than the "warm

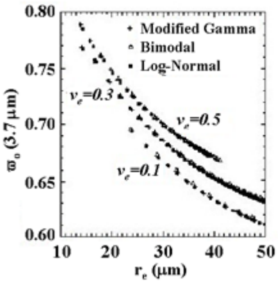

Figure 3. Single scattering albedo (λ = 3.7 μm) as function of effective radius and effective variances for four size distributions (modified gamma, bimodal, log normal and power law).

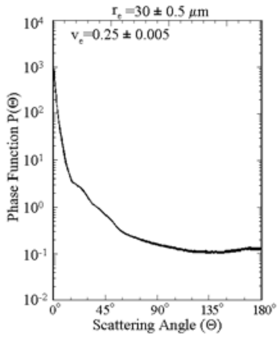

Figure 4. Phase function of hexagonal columns at λ = 3.7 μm for $r_e = 30 \pm 0.5$ μm, $v_e = 0.25 \pm 0.005$ for four size distributions (modified gamma, bimodal, log normal and power law).

cirrus" distribution. Such a reversal is caused by the much smaller v_e value of 0.52 for "cirrostratus" as opposed to 0.85–0.96 for its neighboring distributions (see Figure 1). To evaluate its impact on remote sensing of cloud microphysics, single scattering properties of these measured distributions are fed into an adding-doubling radiative transfer model [*Han et al.*, 1994, 1999] to calculate the bispectral reflection function at 0.64 μm and 3.7 μm.

[16] Figure 5 illustrates the calculated result of the bispectral calculations for a solar zenith angle of 60° and a nadir viewing geometry over ocean surface. As with water clouds, the 0.64 μm reflectance is generally a monotonic function of optical thickness, τ, for a given D_e while the 3.7-μm reflectance is mostly determined by the effective particle size. As expected, the only exception of this relation between the 3.7-μm reflectance and effective particle size occurs exactly where the aforementioned reversal occurs, i.e. at the "cirrostratus" distribution. One can certainly avoid this multiple-solution problem by excluding either the measured "cirrostratus" or the "warm cirrus" size distribution from consideration. However, this means that in retrieval practices one may mistake a distribution with larger r_e and smaller v_e for a distribution with smaller r_e but larger v_e.

4. Discussion

[17] This study has shown that the impact of the width of ice crystal size distributions, commonly characterized by the

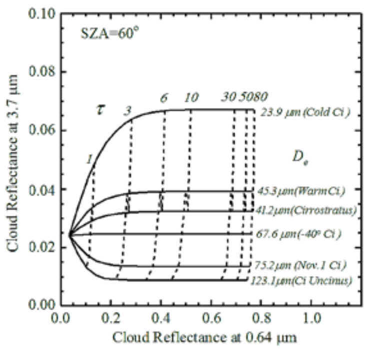

Figure 5. Bispectral reflection functions at λ = 0.64 μm and λ = 3.7 μm for six measured size distributions at solar zenith angle 60° and nadir viewing angle.

effective variance, v_e, on the radiative properties of ice clouds cannot be neglected and that for a fixed r_e and v_e, the single scattering properties of ice clouds can be determined for remote sensing purpose. The *ad hoc* selection of different measured size distributions adopted in remote sensing and model groups neglects the effect of effective variance and thus may cause inconsistency and multiple solution problems in the retrieved results. Furthermore, it is difficult to define a "standard set" of measured size distributions for remote sensing and modeling studies. Therefore, in remote sensing of ice cloud properties, theoretical size distributions with explicitly assumed v_e should be used, similar to the practice adopted for water clouds. The practice of assuming a fixed value of v_e could be further improved when r_e and v_e can be simultaneously retrieved using multi-angle polarized reflectances from upcoming missions like NASA/Glory and NPOESS/APS.

[18] Another problem of using randomly selected measured size distribution is the incompatibility between results of remote sensing and model studies because parameterizations of radiative properties in models are using measured size distributions at the choice of each developer group. For example, in the work by *Fu et al.* [1998], parameterization schemes for single scattering properties were based on 28 measured size distribution models, *Ou et al.* [2003] developed parameterization for single scattering albedo based on six measured size distributions and a similar scheme from *Takano and Liou* [1989] was based on four measured size distributions. The coefficients in these parameterization schemes are significantly different, which leads to discrepancies in the resultant radiative properties (e.g., cloud albedo) between model study and remote sensing results even though the cloud microphysical properties are the same.

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References

Baum, B. A., D. P. Kratz, P. Yang, S. C. Ou, Y. Hu, P. F. Soulen, and S.-C. Tsay (2000), Remote sensing of cloud properties using MODIS airborne simulator imagery during SUCCESS: 1. Data and models, *J. Geophys. Res.*, *105*, 11,767–11,780.

Baum, B. A., A. J. Heymsfield, P. Yang, and S. T. Bedka (2005), Bulk scattering models for the remote sensing of ice clouds: 1. Microphysical data and models, *J. Appl. Meteorol.*, in press.

Ebert, E. E., and J. A. Curry (1992), A parameterization of ice cloud optical properties for climate models, *J. Geophys. Res.*, *97*, 3831–3836.

Foot, J. S. (1988), Some observations of the optical properties of clouds. II: Cirrus, *Q. J. R. Meteorol. Soc.*, *114*, 145–164.

Francis, P. N., A. Jones, R. W. Saunders, K. P. Shine, A. Slingo, and Z. Sun (1994), An observational and theoretical study of the radiative properties of cirrus: Some results from ICE'89, *Q. J. R. Meteorol. Soc.*, *120*, 809–848.

Fu, Q. (1996), An accurate parameterization of the solar radiative properties of cirrus of clouds for climate models, *J. Clim.*, *9*, 2058–2082.

Fu, Q., P. Yang, and W. B. Sun (1998), An accurate parameterization of the infrared radiative properties of cirrus clouds for climate models, *J. Clim.*, *11*, 2223–2237.

Han, Q., W. B. Rossow, and A. A. Lacis (1994), Near-global survey of effective droplet radii in liquid water clouds using ISCCP data, *J. Clim.*, *7*, 465–497.

Han, Q. Y., J. Chou, and R. M. Welch (1997), Ice cloud microphysics and its temperature dependence retrieved from satellite data, *Proc. SPIE Int. Soc. Opt. Eng.*, *3220*, 39–47.

Han, Q. Y., W. B. Rossow, J. Chou, K. Kuo, and R. M. Welch (1999), The effects of aspect ratio and surface roughness on satellite retrievals of ice-cloud properties, *J. Quant. Spectrosc. Radiat. Transfer*, *63*, 559–584.

Hansen, J. E. (1971), Multiple scattering of polarized light in planetary atmospheres. Part II: Sunlight reflected by terrestrial water clouds, *J. Atmos. Sci.*, *28*, 1400–1426.

Hansen, J. E., and L. D. Travis (1974), Light scattering in planetary atmospheres, *Space Sci. Rev.*, *16*, 527–610.

Kinne, S., and K. N. Liou (1989), The effects on nonsphericity and size distribution of ice crystals on the radiative properties of cirrus cloud, *Atmos. Res.*, *24*, 273–284.

Macke, A., J. Mueller, and E. Raschke (1996), Single scattering properties of atmospheric ice crystals, *J. Atmos. Sci.*, *53*, 2813–2825.

Minnis, P., D. P. Garber, D. F. Young, R. F. Arduini, and Y. Takano (1998), Parameterizations of reflectance and effective emittance for satellite remote sensing of cloud properties, *J. Atmos. Sci.*, *55*, 3313–3339.

Mitchell, D. L. (2002), Effective diameter in radiation transfer: General definition, applications, and limitations, *J. Atmos. Sci.*, *59*, 2330–2346.

Mitchell, D. L., and W. P. Arnott (1994), A model predicting the evolution of ice particle size spectra and radiative properties of cirrus clouds. Part II: Dependence of absorption and extinction on ice crystal morphology, *J. Atmos. Sci.*, *51*, 817–832.

Ou, S. C., Y. Takano, K. N. Liou, G. J. Higgins, A. George, and R. Slonaker (2003), Remote sensing of cirrus cloud optical thickness and effective particle size for the national polar-orbiting operational environmental satellite system visible infrared imager radiometer suite: Sensitivity to instrument noise and uncertainties in environmental parameters, *Appl. Opt.*, *42*(36), 7202–7214.

Takano, Y., and K. N. Liou (1989), Solar radiative transfer in cirrus clouds. Part I: Single-scattering and optical properties of hexagonal ice crystals, *J. Atmos. Sci.*, *46*, 3–19.

Wyser, K., and P. Yang (1998), Average ice crystal size and bulk short-wave single-scattering properties of cirrus clouds, *Atmos. Res.*, *49*, 315–335.

Zhang, Y., A. Macke, and F. Albers (1999), Effect of crystal size spectrum and crystal shape on stratiform cirrus radiative forcing, *Atmos. Res.*, *52*, 59–75.

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