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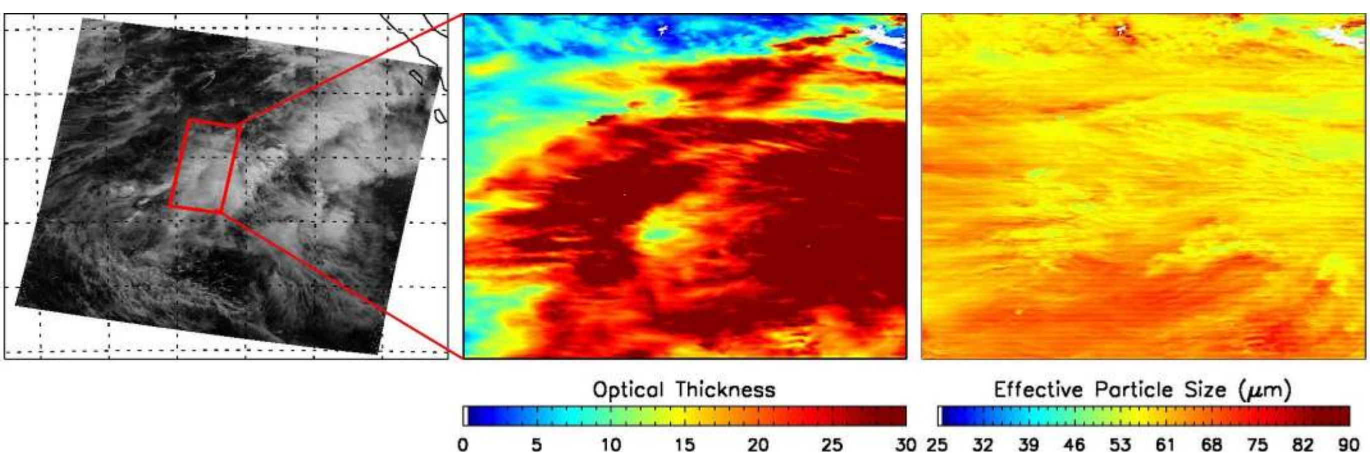

The left panel shows a MODIS granule observed over the Indian Ocean at 0435 UTC on June 22, 2006. The middle and right panels show the retrieved optical thickness and effective particle size, respectively, for the area bounded by the red box indicated in the left panel.

Uncertainties Associated With the Surface Texture of Ice Particles in Satellite-Based Retrieval of Cirrus Clouds: Part II—Effect of Particle Surface Roughness on Retrieved Cloud Optical Thickness and Effective Particle Size

Ping Yang, Gang Hong, George W. Kattawar, Patrick Minnis, and Yongxiang Hu

***Abstract*—The simplified ray-tracing technique reported in Part I of this paper is employed to compute the single-scattering properties of hexagonal columns with maximum dimensions ranging from 2 to 3500 μm with a size-bin resolution of 2 μm at wavelengths of 0.86 and 2.13 μm. For small ice crystals, the current treatment of surface roughness may not be adequate because the applicability of the principles of geometric optics breaks down for small roughness scale. However, for ice crystals smaller than 40 μm, the aspect ratios of these particles are close to one, and the effect of surface roughness is quite small. In this paper, the diffraction is accounted for in the same way as in the case of smooth particles. It is essentially unfeasible to incorporate the effect of surface roughness into the numerical computation of the diffraction contribution. The scattering properties of individual ice crystals are then averaged over 18 particle size distributions whose effective particle radii (r_e) range from 5 to 90 μm. The single-scattering properties of ice clouds are strongly sensitive to surface roughness condition. Lookup tables that are built for the correlation between the bidirectional reflectances at wavelengths of 0.86 and 2.13 μm with different roughness conditions are used to retrieve ice cloud optical thickness and effective particle size over oceans. Pronounced differences are noticed for the retrieved cirrus cloud optical thickness and effective particle sizes in conjunction with different surface roughness conditions. The values of the retrieved cirrus cloud optical thickness in the case of the rough surface are generally smaller than their counterparts associated with smooth surface conditions. The effect of surface roughness on the retrieved effective particle radii is not pronounced for slight and moderate roughness conditions. However, when the surfaces of ice crystals are substantially rough, the retrieved effective radii associated with roughened particles are larger and smaller than their smooth surface counterparts for large $(r_e > 50\ \mu\text{m})$ and small $(r_e < 35\ \mu\text{m})$ ice crystals, respectively, whereas the effect of surface roughness on the retrieved effective radii shows a nonmonotonic feature for moderate particle sizes $(35\ \mu\text{m} < r_e < 50\ \mu\text{m})$. In general, the dominant effect of surface roughness on cloud property retrievals is to decrease the retrieved optical thickness and to increase the retrieved effective particle size in comparison with their counterparts in the case of smooth ice particles.**

***Index Terms*—Effective particle size, ice crystals, optical depth, remote sensing, scattering, surface roughness.**

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I. Introduction

The scattering characteristics that are typical for pristine ice crystals with smooth surface and basic hexagonal structures either in a form of single particles or aggregates are the halo peaks in the angular distribution of scattered radiation. As articulated by Mishchenko *et al.* [1] on the basis of the observations reported in the literature, halos are not often seen in the atmosphere, and the phase functions associated with ice clouds might be featureless with no pronounced halo peaks. One of the mechanisms responsible for the featureless phase function might be the surface distortion or roughness of ice crystals [1]–[3]. Ice crystals may have rough surfaces due to evaporation/sublimation [4], [5] or riming process [6]. Rolland *et al.* [7] studied the sensitivity of retrieved optical thickness and effective particle size of ice particles to surface roughness conditions through its impact on the single-scattering properties. However, in their study, limited reflectance measurements [7, Fig. 7 and Table 5] were used, and the degree of surface roughness condition was not quantitatively stated. Thus, there is a need to further investigate the effect of the surface roughness on the retrieval of the optical and microphysical properties of ice clouds.

During the past 20 years, numerous techniques have been developed to infer the radiative and microphysical properties of ice clouds from the polarimetric or scalar radiometric measurements made by various satellite-borne sensors [8]–[15]. During the night, three infrared bands centered at 8.5, 11, and 12 μm in the thermal infrared window region are often used [16]–[18]. Note that the retrieval techniques based on the thermal infrared radiation are also applicable to the retrievals of cloud properties during daytime. The correlation of the brightness temperature difference (BTD) between 11 and 12 μm ($\mathrm{BTD}_{11-12\ \mu\mathrm{m}}$) and the BT at 11 μm ($\mathrm{BT}_{11\ \mu\mathrm{m}}$), i.e., the relationship between $\mathrm{BTD}_{11-12\ \mu\mathrm{m}}$ and $\mathrm{BT}_{11\mu\mathrm{m}}$, contains rich information for simultaneously retrieving the optical thicknesses and the effective particle sizes of ice clouds. The sensitivity of the bulk radiative properties of a cloud to the optical and microphysical properties of the cloud also exists in the correlation between the BTD between 8.5 and 12 μm (or 8.5 and 11 μm) and the BT at 8.5 μm, which can also be useful for retrieving the cloud optical thickness and the effective particle size. The technical details of this approach can be found in [16] and the references cited therein. Furthermore, the emissivity of ice clouds in the infrared channels of the thermal infrared window region can be used to infer the effective particle size [19], [20]. For the thermal infrared radiation associated with ice clouds, the spectral signatures are determined primarily by the absorption properties of the clouds, which are not sensitive to the detailed features of the scattering phase function. Additionally, the phase functions of ice crystals at infrared wavelengths may be smooth or featureless due to the absorption of these particles, which may have little sensitivity to the textures of ice crystal surfaces. For these reasons, the effect of the surface roughness of ice particles on the retrieval of cloud properties from the infrared spectral information may be insignificant. Thus, this paper focuses on the effect of the surface roughness on the retrieval of cloud properties based on visible and near-infrared radiation.

Under daytime conditions, a popular approach for a simultaneous retrieval of the optical thicknesses and the effective particle sizes is the bispectral method developed by Nakajima and King [21]. The physical basis of this method is that the reflectance under cloudy conditions at a nonabsorbing band (e.g., a band centered at 0.66 μm) is sensitive primarily to the optical thickness, whereas the reflectance of a cloud at an absorbing band (e.g., a band centered at 2.13 μm) is sensitive to the effective particle size. The comparison of a pair of measured reflectances at 0.66 and 2.13 μm with a precomputed correlation of the 2.13- and 0.66-μm reflectances provides a straightforward approach for estimating the optical thickness and the effective particle sizes. The precomputed correlation of the 2.13- and 0.66-μm reflectances, which is usually known as a lookup library used for implementing the retrieval algorithm, is critical to the correctness of the retrieval results. This bispectral method has been used in the operational cloud retrievals based on Moderate Resolution Imaging Spectroradiometer (MODIS) measurements [22], [23]. In practice, in the MODIS operational cloud retrieval algorithm, the 0.65-, 0.86-, and 1.24-μm bands are selected as the nonabsorbing bands in the bispectral algorithm for use over land, ocean, and ice/snow surfaces, respectively. The 2.13-μm band is selected as the primary absorbing band for implementing the bispectral algorithm. Furthermore, a combination of the 1.64- or 3.78-μm band and a nonabsorbing band (e.g., 0.66-, 0.86-, or 1.24-μm band) can quantify the deviations from those retrieved on the basis of a combination of the 2.13-μm band and a nonabsorbing band (e.g., the 0.66-μm band) [23]. In the development of the MODIS lookup library for the bidirectional reflectances of ice clouds [24], [25], all ice crystal habits, except aggregates, are assumed to have smooth surfaces. This paper is intended to investigate the effect of the surface roughness of ice crystals on the retrieval of the optical and microphysical properties of ice clouds by using the visible and near-infrared solar radiation reflected by ice clouds on the basis of the bispectral method developed by Nakajima and King [21] and the data acquired by the MODIS instrument aboard the Terra satellite platform.

II. Single-Scattering Properties of Roughened Ice Particles

For simplicity in the present sensitivity study, ice crystals are assumed to be randomly oriented hexagonal columns with roughened surfaces. The simplified ray-tracing technique described in Part I of this paper [26] is employed to compute the single-scattering properties of ice crystals, as it can approximately account for the effect of surface roughness on the single-scattering properties of roughened ice particles. Following Yang and Liou [3], the probability density function (pdf) for the spatial orientations of the rough surface facets of an ice crystal is specified by the first-order Gram–Charlier or the 2-D Gaussian distribution [27] as follows:

$$\xi(z_\alpha, z_\beta) = \frac{1}{\pi\sigma^2} \exp\left[-\left(z_\alpha^2 + z_\beta^2\right)/\sigma^2\right] \quad (1)$$

where the function ξ indicates the pdf. The parameters z_α and z_β indicate the slopes of a facet of the roughened surface along two orthogonal directions specified in terms of two unit vectors $\hat{\alpha}$ and $\hat{\beta}$ that are tangential to the overall averaged surface position (i.e., the case of smooth surface). Specifically, the parameters z_α and z_β can be defined as follows [3]:

$$z_\alpha = (\mu^{-2} - 1)^{1/2} \cos\varphi \quad (2a)$$

$$z_\beta = (\mu^{-2} - 1)^{1/2} \sin\varphi \quad (2b)$$

$$\mu = \cos\theta \quad (2c)$$

where θ and φ are the zenith and azimuthal angles of the normal of a roughness facet, respectively, which are specified with respect to the normal of the corresponding smooth surface. The definition of the azimuthal plane of $\varphi = 0$ is arbitrary as long as the definition is kept consistent in the ray-tracing calculation. In (1), the degree of surface roughness is specified in terms of the parameter σ. As an example, Fig. 1 shows $\xi(z_\alpha, 0)$ for three roughness conditions: $\sigma = 0.01, 0.1$, and 1.0. Note that we select $z_\beta = 0$ in Fig. 1 to avoid using a 3-D illustration. It is evident from Fig. 1 that the width of the distribution of the parameter z_α is proportional to σ. As the degree of surface roughness increases with the widths of the distributions of z_α and z_β, the parameter σ well defines how rough the ice crystal surface is. Specifically, the larger the parameter σ is, the rougher the surface is.

In the ray-tracing calculation, the normal direction of an ice crystal surface is locally titled in a random way to represent a realization of a rough surface facet for each reflection and refraction event [2], [3], as described in Part I

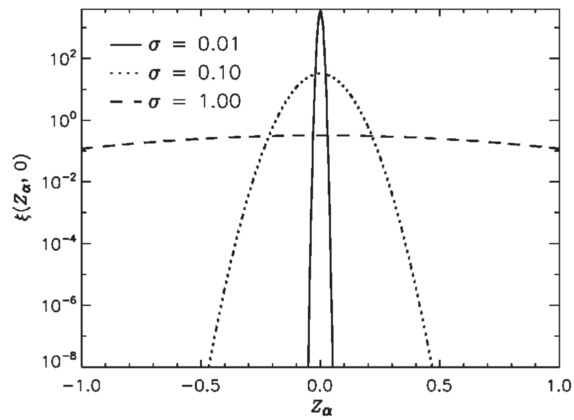

Fig. 1. PDF $\xi(z_\alpha, z_\beta)$ for the spatial orientations of the rough surface facets of an ice crystal. The parameters z_α and z_β indicate the slopes of a facet of the roughened surface along two orthogonal directions. To avoid using a 3-D illustration, here, $\xi(z_\alpha, z_\beta)$ is plotted versus z_α in the case of $z_\beta = 0$.

[26]. In practice, the Monte Carlo method can be used to specify the orientation of the normal direction of the facet on the basis of (1) and (2), as described in detail by Yang and Liou [3]. Most recently, Shcherbakov *et al.* [28] developed a new approach based on the Weibull distribution for the pdf of the rough surface facets, which can also be used to compute the single-scattering properties of roughened ice crystals.

Fig. 2 shows the phase functions at a wavelength of 0.66 μm for the randomly oriented compact hexagonal ice crystals ($2a/L = 100\ \mu\text{m}/100\ \mu\text{m}$), hexagonal columns ($2a/L = 100\ \mu\text{m}/300\ \mu\text{m}$), and hexagonal plates ($2a/L = 300\ \mu\text{m}/100\ \mu\text{m}$), where a and L indicate the semiwidth of the cross section and the length of an ice crystal, respectively. The refractive index of ice at this wavelength is $1.3078 + i1.66 \times 10^{-8}$. Four roughness conditions with $\sigma = 0$ (smooth surface), $\sigma = 0.01$ (slight roughness), $\sigma = 0.1$ (moderate roughness), and $\sigma = 1.0$ (deep roughness) are imposed in the computation. The left panels in Fig. 2 show the phase function values at scattering angles ranging from 0° to 180°, and the right panels in Fig. 2 zoom in on the phase functions in forward directions from 0° to 2°. The phase functions of the randomly oriented hexagonal ice crystals with smooth surfaces (i.e., $\sigma = 0.0$) have been extensively discussed in the literature [2], [3], and those discussions should not be recaptured here. For the slight roughness condition ($\sigma = 0.01$), the effect of the surface roughness is to decrease the backscattering intensity. Additionally, the 22° peak is slightly reduced, but the 46° halo peak is substantially diminished. For the moderate roughness condition ($\sigma = 0.1$), the surface roughness substantially smoothes out the 22° and 46° halo peaks and diminishes the backscattering. For the deep roughness condition ($\sigma = 1.0$), the phase functions are essentially featureless. These features of the scattering phase functions of roughened ice crystals are consistent with those reported in the literature (e.g., [2] and [3]). Furthermore, it is evident from the results shown in Fig. 2 that the asymmetry factors for roughened particles are smaller than their smooth surface counterparts. The asymmetry factors for the columns and plates with rough surfaces decrease with the increase of the degree of the surface roughness. On the contrary, the asymmetry factor for the compact particles with unit aspect ratio ($2a/L = 100\ \mu\text{m}/100\ \mu\text{m}$) slightly increases with the increase of the degree of surface roughness in the case of $\sigma = 0.01$, 0.1, and 1, although the asymmetry factors for the roughened particles are still smaller than their corresponding smooth surface counterparts.

It is evident from Fig. 2 that the effect of the surface roughness on the single-scattering properties of the particle also depends on the aspect ratios of the ice crystals. To further illustrate this feature of the surface roughness effect, Fig. 3 shows the comparison of the asymmetry factors as functions of the aspect ratio for $\sigma = 0.00$, 0.01, 0.10, and 1.00 (upper panel in Fig. 3) and for $\sigma = 0.00$, 0.0015, 0.0025, and 1.00 (lower panel in Fig. 3). To specify the sizes of ice crystals in the calculation, we let the surface areas of ice crystals with various aspect ratios be the same as that of an ice crystal whose size is $a/L = 60\ \mu\text{m}/300\ \mu\text{m}$. As shown in Fig. 3, the values of the asymmetry factor are the lowest when the aspect ratio is approximately one regardless of the roughness conditions. This feature of the variation of the asymmetry factor versus the aspect ratio has been reported by Macke and Mishchenko [29], Grenfell *et al.* [30], and Fu [31] in the case of smooth ice crystals. It is also evident from Fig. 3 that the effect of surface roughness on the asymmetry increases with the deviation of aspect ratio from one in both cases of columns (i.e., $2a/L < 1$) and plates (i.e., $2a/L > 1$). This feature is particularly pronounced in the comparison of the results associated with $\sigma = 0.0$ and 1.0.

When $2a/L < 0.7$ or $2a/L > 2$, the asymmetry factor monotonically decreases with the increase of σ (i.e., the degree of surface roughness) for a given aspect ratio. When $2a/L \approx 1$, the effect of surface roughness on the asymmetry factor is minimum, and the variation of the asymmetry factor versus σ is not monotonic, as is evident from the zoomed-in curves in the upper and lower panels of Fig. 3. The physical mechanism associated with the nonmonotonic variation of the asymmetry factor versus σ in the case of $2a/L \approx 1$ is not clear at this point. However, in this case, the maximum differences of the asymmetry factors for six roughness conditions ($\sigma = 0.00$, 0.0015, 0.0025, 0.01, 0.10, and 1) are on the order of 0.005 in the aspect-ratio region near $2a/L = 1$. The features of the roughness effect shown in Fig. 3 have an important implication to practical application. Small ice crystals ($< 50\ \mu$m) in cirrus clouds tend to be compact ice crystals. Thus, the effect of surface roughness on the optical properties of these particles is much smaller in comparison with the case for large particles shaped in either plates or columns.

Fig. 4 shows the asymmetry factors as functions of the maximum dimensions of columns with four different surface roughness conditions ($\sigma = 0.00$, 0.01, 0.10, and 1.00). The aspect ratio is $2a/L = 1/3$. The wavelength and the refractive index for Fig. 4 are the same as those for Figs. 2 and 3. For ice crystals smaller than approximately 20 μm, the asymmetry factors increase with increasing maximum dimensions. For larger ice crystals, the asymmetry factors tend to reach their asymptotic values. It is evident from Fig. 4 that the asymmetry

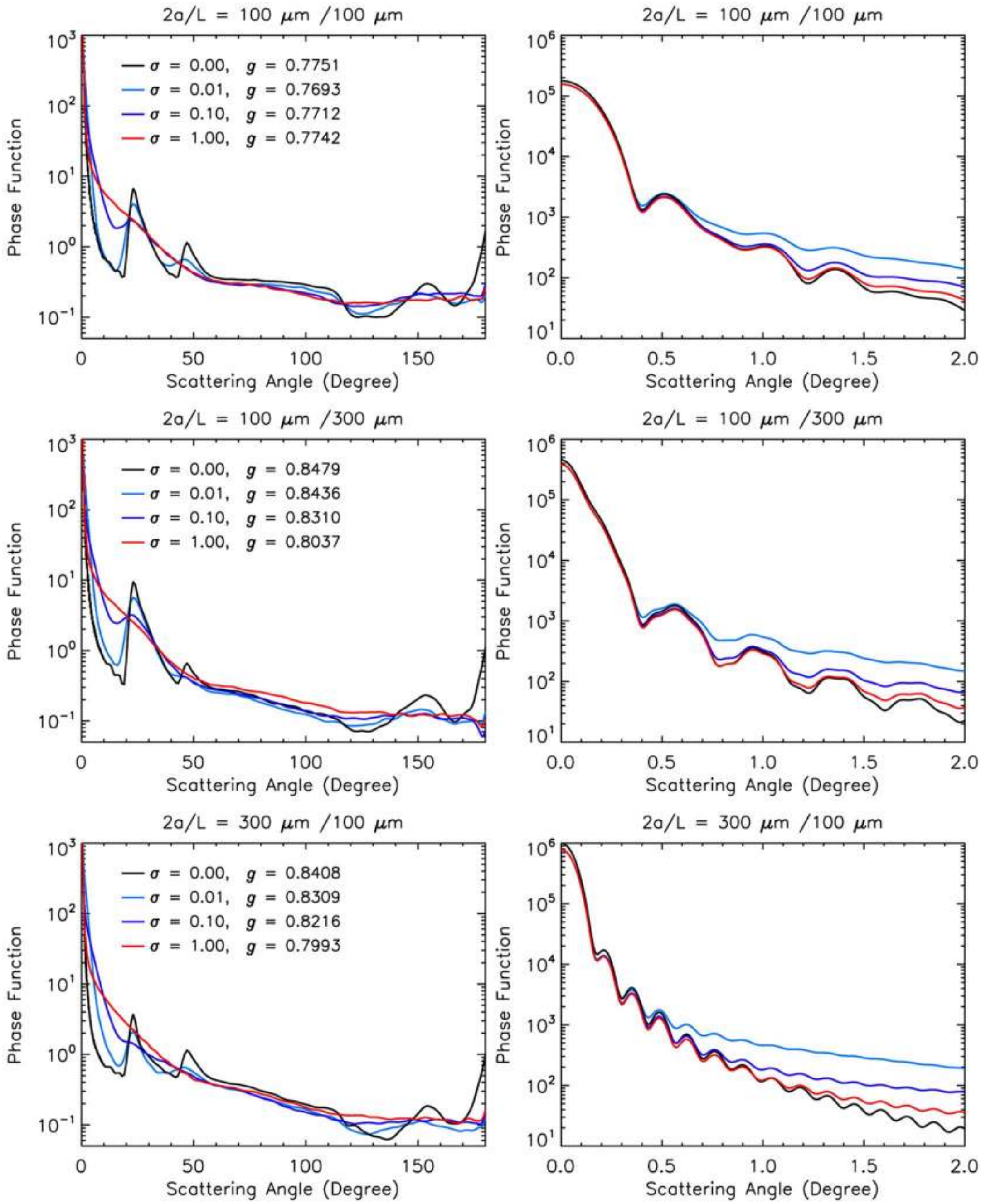

Fig. 2. Phase functions at a wavelength of 0.66 μm for the randomly oriented hexagonal ice crystals with three different surface roughness conditions. The refractive index at the wavelength of 0.66 μm is $1.3078 + i1.66 \times 10^{-8}$.

factors are strongly sensitive to surface roughness at this aspect ratio. Specifically, with increasing surface roughness, the asymmetry factors substantially decrease.

For remote sensing applications, the single-scattering properties of ice crystals must be averaged over size distributions. For a given size distribution, we assume that the aspect ratios of an ice crystal population can be specified by the formula reported by Yang *et al.* [32] as follows:

$$2a/L = \begin{cases} 1, & L \leq 40\ \mu\text{m} \\ \exp\left[-0.017835(L-40)\right], & 40 < L \leq 50\ \mu\text{m} \\ 5.916/L^{1/2}, & L > 50\ \mu\text{m}. \end{cases} \quad (3)$$

For a given size distribution, the bulk single-scattering properties of ice crystals can be obtained, e.g., for the phase function P, as follows:

$$P(\theta) = \frac{\int_{D_{\min}}^{D_{\max}} P(\theta, D) C_{\text{sca}}(D) n(D) dD}{\int_{D_{\min}}^{D_{\max}} C_{\text{sca}}(D) n(D) dD} \quad (4)$$

where D is the maximum dimension of an ice crystal, n indicates the size distribution of ice crystals, and C_{sca} is the scattering cross section of an ice crystal with a maximum dimension of D. To be consistent with the definition of the effective particle size in the MODIS operational cloud retrieval,

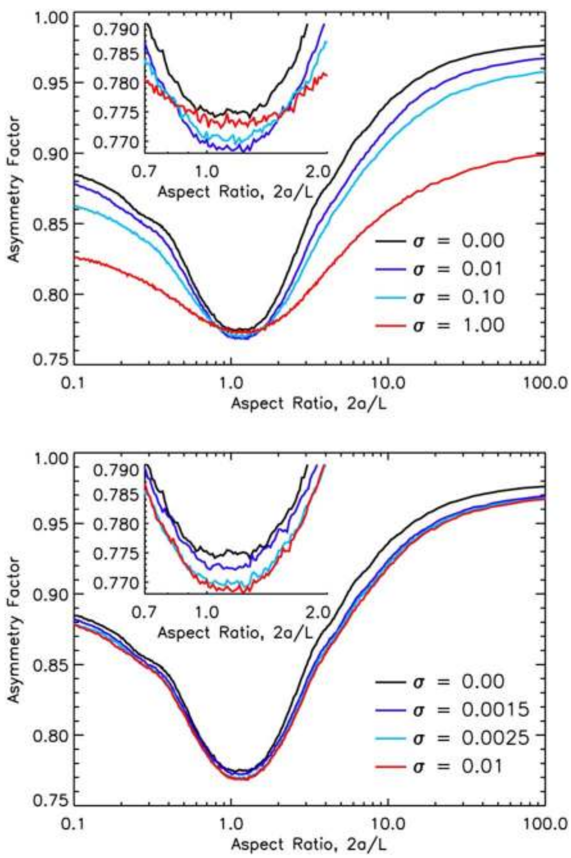

Fig. 3. Comparison of the asymmetry factors as functions of particle aspect ratio for various roughness conditions. The wavelength and the refractive used in the computation are 0.66 μm and $1.3078 + i1.66 \times 10^{-8}$, respectively. To specify ice crystal sizes, the surface areas of ice crystals are defined as the same as that of an ice crystal with $a/L = 60\ \mu\text{m}/300\ \mu\text{m}$.

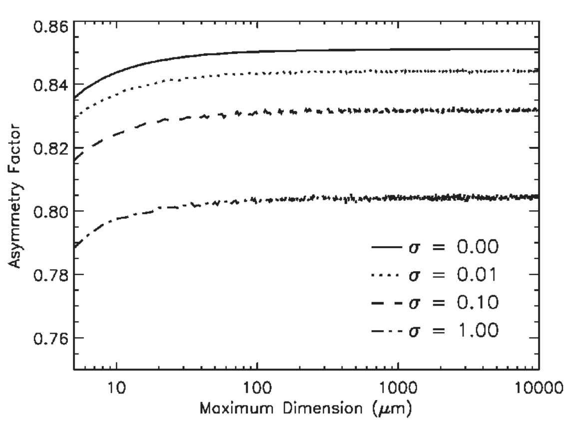

Fig. 4. Asymmetry factors as functions of maximum dimensions of column with four different surface roughness conditions: $\sigma = 0.00$, 0.01, 0.10, and 1.00. The aspect ratio is $2a/L = 1/3$. The wavelength and the refractive used in the computation are 0.66 μm and $1.3078 + i1.66 \times 10^{-8}$, respectively.

the effective particle radius is defined following King *et al.* [24] and the references cited therein as follows:

$$r_\mathrm{e} = \frac{3}{4}\frac{\int_{D_\mathrm{min}}^{D_\mathrm{max}} V(D)n(D)dD}{\int_{D_\mathrm{min}}^{D_\mathrm{max}} A(D)n(D)dD} \tag{5}$$

where V and A are the volume and the projected area of an ice crystal with a maximum dimension of D, respectively. As pointed out by King *et al.* [24], the definition in (5) is consistent with the definition given by Hansen and Travis [33] in the case of spherical water droplets.

III. Effect of Surface Roughness on Retrieving Cloud Properties

To investigate the influence of ice crystal surface roughness on cloud property retrievals, the single-scattering properties are computed from an improved geometric optics method [33] for ice crystals with maximum dimensions ranging from 2 to 3500 μm with a size-bin resolution of 2 μm. The bulk scattering properties are then derived by averaging the single-scattering properties over 18 particle size distributions with effective radii varying from $r_\mathrm{e} = 5$ to $r_\mathrm{e} = 90$ μm. The Gamma distribution (e.g., [35]) is assumed for the size distributions of ice crystals, which is given as follows:

$$n(D) = N_0 D^\mu \exp\left(-\frac{b+\mu+0.67}{D_\mathrm{m}}D\right) \tag{6}$$

where N_0 is the intercept, and μ is the dispersion usually ranging from zero to two and is assumed to be two in this paper, where D_m is the median of the distribution of D. The values of parameter b are 2.1 and 2.3 for the tropical and midlatitude ice clouds, respectively [36]. Their mean value $b = 2.2$ is used in this paper.

Fig. 5 shows the phase functions at 0.86 and 2.13 μm for four surface roughness conditions, i.e., $\sigma = 0.00$, 0.01, 0.10, and 1.00, with an effective particle radius of 30 μm. Lookup tables of the correlation between the 0.86- and 2.13-μm reflectances for the four surface roughness conditions (i.e., $\sigma = 0.00$, 0.01, 0.10, and 1.00) with a solar zenith angle of 30°, a satellite zenith angle of 0°, and a relative azimuth angle of 90° are also shown in Fig. 5. The phase functions in the case of smooth surface show distinct scattering peaks. The phase functions are smoothed as the degree of surface roughness increases. Moreover, ice crystals without surface roughness scatter more energy in backscattering directions than their roughened counterparts. The lookup tables for different roughness conditions also show pronounced differences that could result in differences in the retrieved ice cloud optical thickness and effective particle size.

Lookup tables of band reflectances as functions of solar zenith angle, satellite zenith angle, relative azimuth angle, ice cloud optical thickness, and effective particle size for four roughness conditions, i.e., $\sigma = 0.00$, 0.01, 0.10, and 1.00, are used to estimate the optical thickness and the effective particle size of ice clouds by minimizing the following cost function:

$$\chi^2 = \left[R_{0.86}^\mathrm{m}(\theta_0,\theta,\phi) - R_{0.86}^\mathrm{l}(\tau, r_\mathrm{e}; \theta_0,\theta,\phi)\right]^2 + \left[R_{2.13}^\mathrm{m}(\theta_0,\theta,\phi) - R_{2.13}^\mathrm{l}(\tau, r_\mathrm{e}; \theta_0,\theta,\phi)\right]^2 \tag{7}$$

where $R_{0.86}^\mathrm{m}$ and $R_{2.13}^\mathrm{m}$ are the satellite measured bidirectional reflectances at the 0.86- and 2.13-μm bands, respectively, and $R_{0.86}^\mathrm{l}$ and $R_{2.13}^\mathrm{l}$ are the bidirectional reflectances in the precalculated lookup table for ice clouds. The retrieved τ and

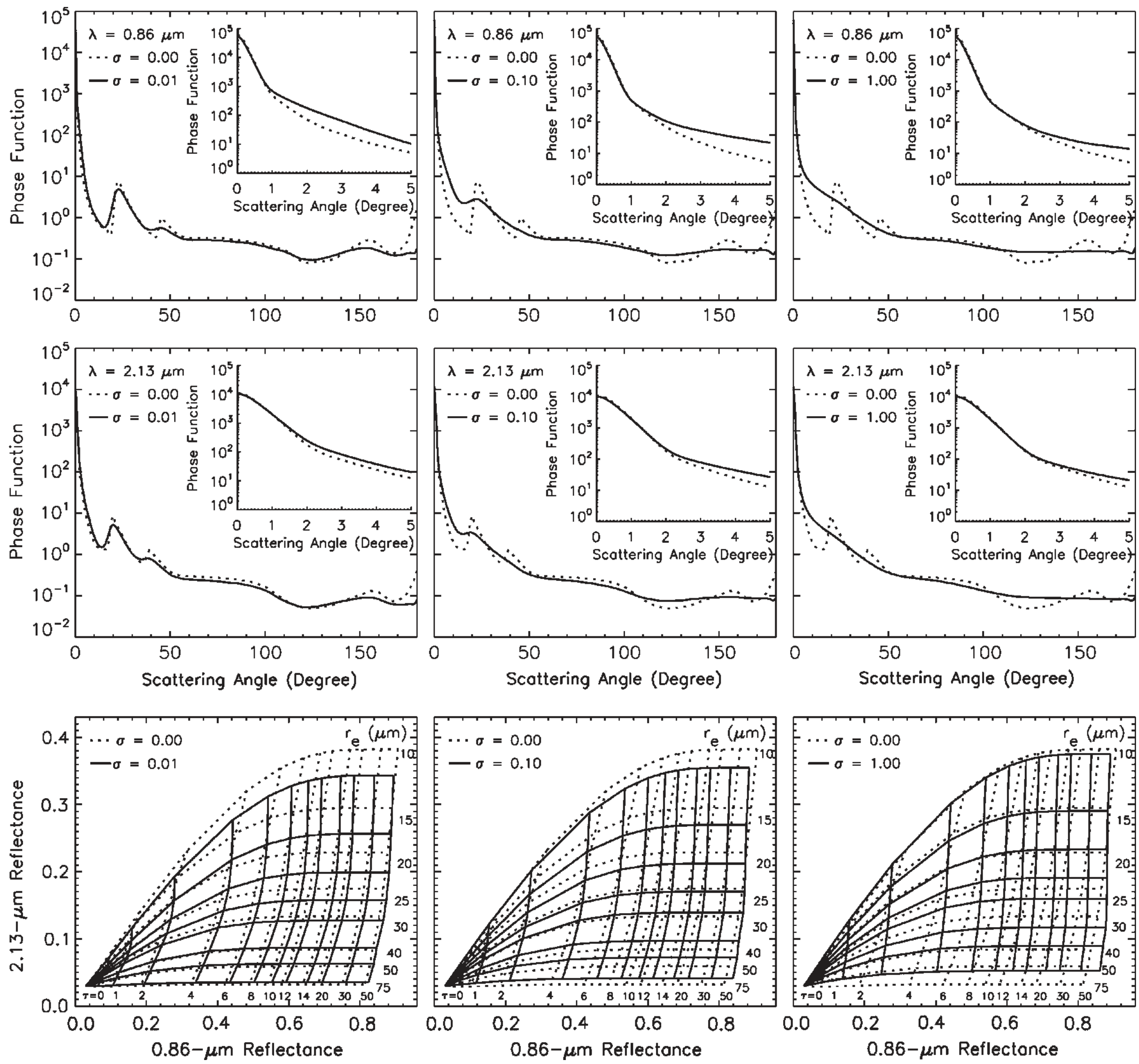

Fig. 5. Comparisons of phase functions at 0.86 and 2.13 μm for different surface roughness conditions, i.e., $\sigma = 0.00$, 0.01, 0.10, and 1.00, with an effective particle radius of 30 μm. Comparisons of built lookup tables using 0.86- and 2.13-μm reflectances for different surface roughness conditions, i.e., $\sigma = 0.00$, 0.01, 0.10, and 1.00, with a solar zenith angle of 30°, a satellite zenith angle of 0°, and a relative azimuth angle of 90°.

$D_{\rm e}$ can then be obtained from the preceding minimization procedure.

Fig. 6 shows the retrieved results based on the MODIS measurements. Specifically, a MODIS granule over the Indian Ocean at 04:35 UTC on June 22, 2006, is used in the retrieval. The red–green–blue (RGB) composite image based on MODIS band 4 (0.55 μm), 3 (0.47 μm), and 1 (0.66 μm) shows that clouds essentially cover the entire region of this granule. The properties of the ice clouds in the region included by the red box in Fig. 6 are retrieved. Moreover, the retrieval is conducted for the pixels identified as ice phase on the basis of the operational MODIS cloud product [22], [23]. Ice clouds with optical thicknesses less than 0.3 have been considered as clear sky in the current MODIS retrievals of cloud properties [37]. The same minimum threshold is also used for the retrieval in this paper. The retrieved optical thickness and effective particle size in the case of smooth surface are also shown in Fig. 6. In general, the retrieved optical thicknesses associated with roughened ice crystals are smaller than the counterparts in the case of smooth particles, particularly for the deep roughness condition ($\sigma = 1.00$). This feature becomes more pronounced for ice clouds that are optically thick.

In the cases of slight and moderate roughness conditions (i.e., $\sigma = 0.001$ and 0.10), the effect of surface roughness on the retrieved particle sizes is observed primarily for two effective radius regions of $r_{\rm e} < 40$ μm or $r_{\rm e} > 75$ μm, where the retrieved radii associated with roughened particles are slightly smaller than their smooth surface counterparts. In the case of deep roughness condition (i.e., $\sigma = 1.0$), the effect of surface roughness on the retrieved effective size ($r_{\rm e}$) is quite different for small and large particles. For small particles ($r_{\rm e} < 35$ μm), the effective sizes retrieved on the basis of the optical properties of roughened ice crystals are smaller than those based on the optical properties of smooth particles. This feature is consistent with that associated with slight or moderate roughness condition. For large particles ($r_{\rm e} > 50$ μm), the effective radii retrieved for deeply roughened ($\sigma = 1.0$) particles are much larger than their counterparts for smooth ice crystals. For ice crystals with effective radii between 35 and 50 μm, the effect of surface roughness can lead either

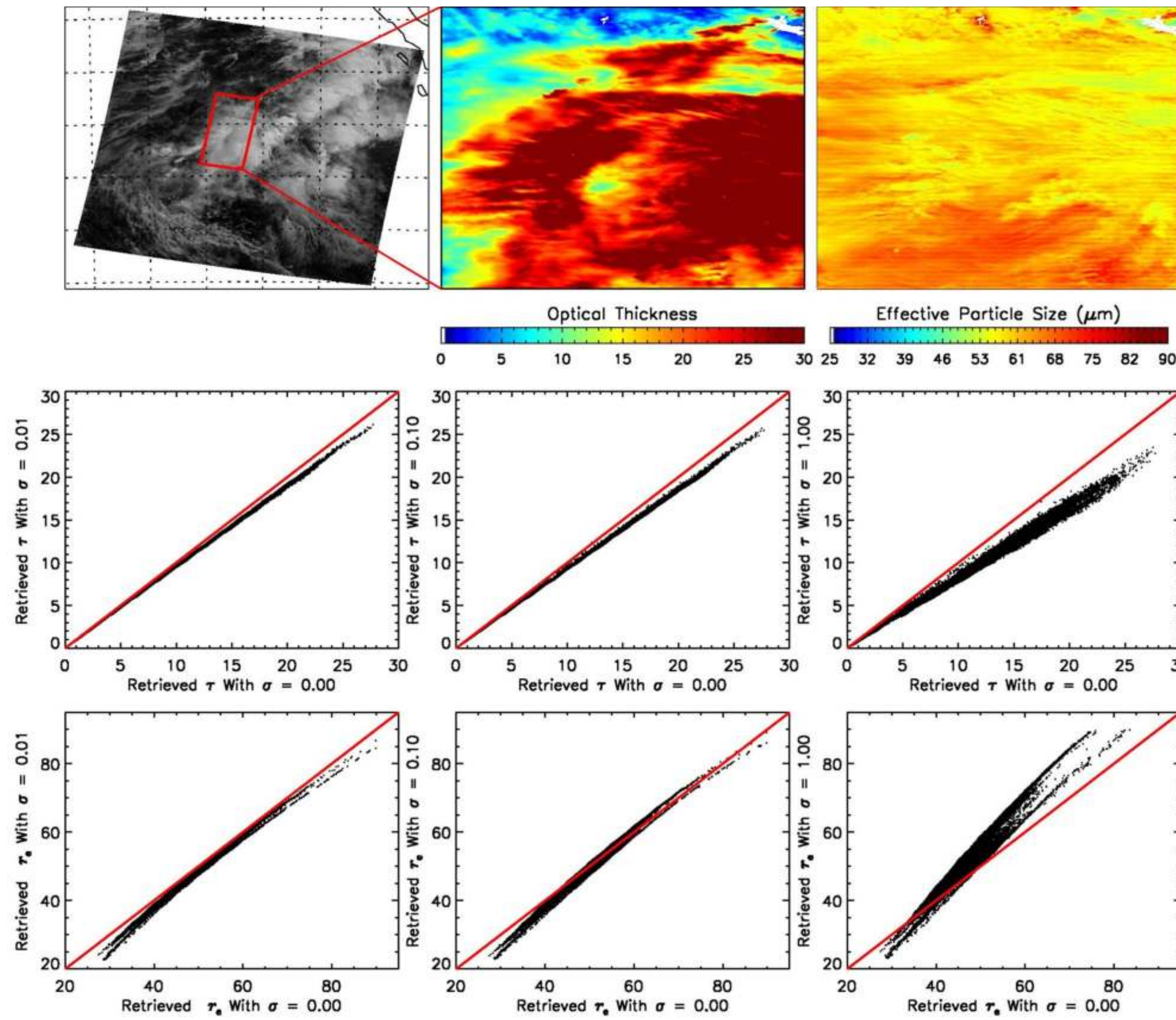

Fig. 6. (Upper panels) MODIS L1B granule image (RGB = band $4:3:1$), the retrieved ice cloud optical thicknesses, and the effective particle sizes [specifically, the effective radii defined on the basis of (5)] with roughness $\sigma = 0.00$. (Middle panels) The comparisons of retrieved ice cloud optical thicknesses from different roughness conditions: $\sigma = 0.00$, 0.01, 0.10, and 1.00. (Bottom panels) The comparisons of retrieved ice cloud effective particle sizes from different roughness conditions: $\sigma = 0.00$, 0.01, 0.10, and 1.00.

an overestimation or an underestimation in the retrieval of the effective particle size when the surfaces of ice crystals are deeply rough. For the retrieved effective particle sizes shown in Fig. 6, the variations of the retrievals for smooth particles versus their counterparts for roughened particles as functions of the degree of surface roughness seem nonintuitive. Specifically, the two retrievals are in closest agreement for an intermediate degree of surface roughness. The complicated features of the impact of surface roughness on retrieving the effective particle size of ice crystals are not clear at this point and deserve further investigation.

Fig. 7 shows the histogram distributions of the retrieved ice cloud optical thicknesses and effective particle sizes associated with smooth and roughness conditions, which correspond to the results shown in Fig. 6. In the case of the retrieved optical thicknesses, the relative distributions for $\sigma = 0$, 0.01, and 0.1 are quite similar, which however are substantially different from that for $\sigma = 1.0$. Specifically, the maximum of the distribution for $\sigma = 1.0$ is observed at a smaller optical thickness in comparison with those in other three cases (i.e., $\sigma = 0.0$, 0.01, and 0.1). It is evident from the overall patterns of the histogram distributions of the retrieved optical thicknesses that a deep surface roughness condition (e.g., $\sigma = 1.0$) systematically leads to smaller values of the retrieved cloud optical thickness, particularly for thick clouds $(\tau > 5)$.

The histogram distributions of the retrieved effective particle radii are quite similar for three roughness conditions: $\sigma = 0.0$, 0.01, and 0.1. However, the histogram distribution of the retrieved effective particle radii in the case of $\sigma = 1.0$ is systematically shifted toward larger particle sizes in comparison with the results for the other three cases. The results in Fig. 7 illustrate that the dominant effect of surface roughness associated with deeply roughened particles on the retrievals of ice cloud properties is to decrease the optical thickness and to increase the effective particle size. These results are consistent with the finding reported by Rolland *et al.* [7].

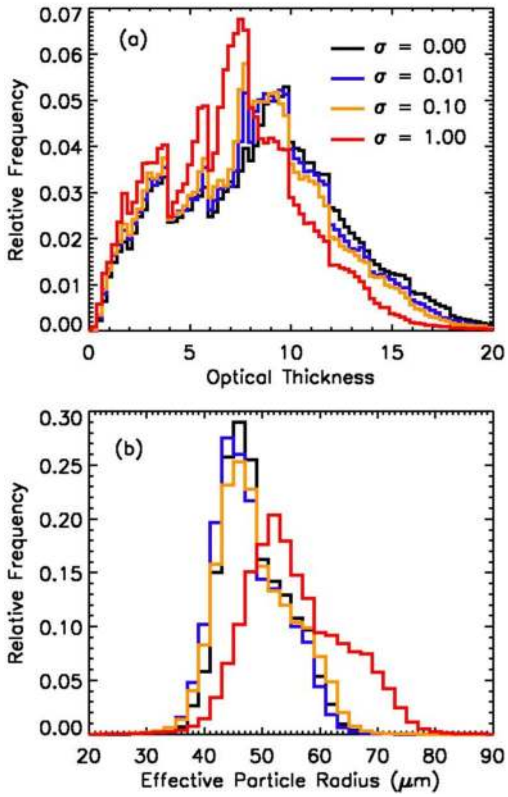

Fig. 7. Histogram distributions of the retrieved ice cloud optical thicknesses and effective particle radii for four roughness conditions ($\sigma = 0.00, 0.01, 0.10$, and 1.00), which correspond to the results shown in Fig. 6.

IV. Summary and Conclusion

Ice crystals in the atmosphere may have rough surfaces. The various surface roughness conditions could alter the single-scattering properties, thereby influencing the bulk scattering properties used for satellite-based retrieval of ice cloud properties. This paper investigated the influence of ice crystal roughness on the retrievals of ice cloud optical thickness and effective particle size. For small ice crystals, the present method for accounting for surface roughness in light scattering calculation based on the ray-tracing technique may not be adequate because the applicability of the principles of geometric optics breaks down for small roughness scale. However, ice crystals smaller than 40 μm are compact ice crystals (i.e., the aspect ratios of these particles are one), as evident from (3). In this case, the minimum impact of surface roughness on the single-scattering properties of ice crystals is observed. In this paper, the diffraction is accounted for in the same way as in the case of smooth particles. Technically, it is too complicated (or practically impossible) to incorporate the effect of surface roughness into the diffraction calculation.

A parameter describing the degree of ice crystal surface roughness is specified in computing the single-scattering properties of ice crystals. The single-scattering properties of hexagonal columns with different ice crystal surface roughness conditions have been averaged over particle size distributions to obtain the bulk scattering properties of ice clouds. The scattering properties show different features for different roughness conditions. With increasing roughness, the differences between the scattering properties of smooth and roughened ice crystals increase. The lookup tables based on the bidirectional reflectance at wavelengths of 0.86 and 2.13 μm have been used to retrieve the ice cloud optical thickness and the effective particle size for cirrus clouds over oceans. In the case of slight or moderate roughness condition, the retrieved optical thicknesses and effective radii for roughened ice particles are not substantially different from their counterparts for the smooth ice crystals. However, in the case of deep roughness condition, the dominant effect of surface roughness is to decrease the values of the retrieved cloud optical thickness and to increase the values of the retrieved effective particle size in comparison with the counterparts for the smooth ice crystals.

These results have important implications for the satellite remote sensing of cirrus clouds using visible/near-infrared channel data. Comparisons of cirrus cloud optical depths derived from surface- or aircraft-based radar, lidar, and radiometer data show that the retrievals based on smooth crystal models tend to overestimate the cloud optical depth [38]–[40], but not necessarily the ice water path [39], which is proportional to the product of the optical depth and the effective particle size. These overestimates of optical depth can also cause underestimates of thin cirrus cloud-top heights because the 11-μm BT, which is used to obtain the true cloud temperature, height, and emissivity, depends on the cloud visible optical depth [41]. The smooth ice crystal models used by the MODIS operational (Collection 5) algorithm have asymmetry values at 0.66 μm ranging from 0.78 to 0.88 [42], whereas those used by the Clouds and the Earth's Radiant Energy System (CERES) project to analyze the MODIS data [43] vary from 0.77 to 0.85 [40]. *In situ* observations indicate average values of g close to 0.76 [44], [45]. Such small asymmetry parameters are difficult to obtain without surface roughness. Thus, by using roughened crystal models in the MODIS and CERES retrieval algorithms, it should be possible to retrieve smaller optical depths and, in many cases, larger particle sizes. The smaller optical depths should yield better estimates of the true cloud temperature, whereas the ice water paths should remain virtually unchanged because the increased particle size will tend to offset the decreased optical depth. These new ice crystal scattering models have the potential for significantly reducing errors in many cirrus cloud retrievals. Further testing of the roughened ice crystal models in the operational retrieval codes is needed to verify whether the expected improvements can actually be realized.

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