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The effects of aspect ratio and surface roughness on satellite retrievals of ice-cloud properties

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Abstract

This study investigates the effects of non-sphericity on satellite retrievals of ice-cloud properties including optical thickness and particle sizes. Ray-tracing technique is used to calculate single scattering phase function and single scattering albedo for both smooth and rough surfaces of hexagonal columns and plates at visible and near-infrared wavelengths. Two parameters, aspect ratio and distortion parameter, are used to simulate different, randomly oriented, ice crystal shapes and surface roughnesses in the ray-tracing process. A wide range of aspect ratio and distortion parameter is explored in the calculations. The resultant phase functions and single scattering albedos are used to compute bidirectional reflection functions by a radiative transfer model with adding–doubling technique. The results show that in a direct backscattering regima ($\Theta > 150°$), if no information of particle shape is available, the uncertainties in the retrieved optical thickness (a factor of more than ten) would make the retrieval meaningless. For images with viewing geometry outside of this region, the typical range of uncertainty of retrieved optical thickness is less than a factor of about two. Using averaged phase function will cut this uncertainty in half. That is, the uncertainty in the retrieved optical thickness is about 40%. Sensitivity tests show that aspect ratios are critical in reducing the uncertainties of the retrieved optical thickness using satellite data. The uncertainties in the retrieved ice particle sizes are also estimated in a similar way. It is found that using an averaged aspect ratio and roughness, the uncertainty of retrieved particle size is about 30% for small particles and 10% for large particles at $\lambda = 3.7$ μm. The corresponding uncertainties are about 70% for small particles and 35% for large particles if data at $\lambda = 1.6$ or 2.2 μm are used in the retrieval. However, at $\lambda = 1.6$ and 2.2 μm, retrieval of particle size may encounter even larger uncertainties for thin ice-clouds ($\tau < 3$).

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1. Introduction

Ice-clouds have very important climate influence which is strongly dependent on the radiative properties and microphysics [1]. Model calculations show that cloud radiative forcing is a strong function of optical thickness and ice particle size (e.g. [2]). Their results suggest that even the sign of cloud radiative forcing may be changed for different combination of optical thickness and ice crystal sizes. Because satellite data are widely used for monitoring cloud properties, the accuracy of the retrieved optical thickness and particle size from satellite is critical to climate change studies. One of the difficulties encountered in the satellite retrieval of ice-cloud properties is the effect of non-spherical particle shapes on the scattering phase function, single scattering albedo and uncertainty about the actual particle shapes present. Results from satellite remote sensing are widely used for climate change studies for its ability to provide global coverage and the fine temporal resolution. In satellite remote sensing, the spatial distribution of scattered solar radiances by clouds is the major source for retrieving cloud properties including optical thickness and particle sizes. For water clouds, Mie theory can be used to calculate phase functions and single scattering albedo for different wavelengths due to the simple spherical shape of water droplets. The calculated phase functions and single scattering albedo were used to compute the radiance spatial distributions which are the basis of remote sensing of water cloud properties [3–5]. For ice-clouds, however, there are all kinds of different non-spherical shapes of ice crystals, such as columns, plates, dendrites, stellars, hollowed columns, bullet rosettes, etc. [6], and each of them has specific features in its phase function. However, for satellite remote sensing, there are only limited channels to use for retrieval of ice-cloud properties. For example, for AVHRR, channel 1 is used for retrieval of cloud optical thickness and channel 3 (centered at $\lambda = 3.7$ μm) can be used to retrieve particle size. Because reflection functions are dependent on optical thickness, phase function and single scattering albedo, one has to assume the phase function and single scattering albedo in the retrieval process. The problem is that we do not know which phase function and single scattering albedo should be used in the retrievals due to the wide range of ice particle shapes. A comparison of the ratio of reflection functions at visible band between two sample crystals (a fractal crystal and a regular hexagon column) shows that it may cause significant error (possibly a factor of four) in the calculation of reflection functions if the wrong phase function is used [7]. Their results raised serious concern about the ability of retrieving ice-cloud properties from space because differences of ice crystal shapes in real ice-clouds can be more than that between the fractal and the regular hexagon column discussed in that study. To investigate the possible effect of different ice crystals on scattering radiance, we calculated phase functions for a variety of randomly oriented particles with different aspect ratios and surface roughnesses by ray-tracing technique [8,9]. These phase functions are then used to compute reflection functions through a radiative transfer model. The features of these reflection functions are examined to estimate the possible range of uncertainties in the retrieved properties of ice-clouds.

In ray-tracing process, different non-spherical particle shapes can be approximately represented by two parameters: aspect ratio and surface roughness [8–10]. The aspect ratio refers to the ratio of the maximum and the minimum dimensions of a particle, which has been measured by aircraft observations since 1940s' (see [11] and references therein), and determines the first-order deviation of the particle shape from spherical. The surface roughness is a measure of the smaller-scale surface irregularity of a particle, such as results from riming and aggregation, and can be expressed in terms of deviations from any regular geometric shape. For regular particles, such as spheroids and hexagons, the differences in aspect ratio are easily recognized since the surfaces are smooth (small surface roughness). However, for highly irregular particles, the surface roughness is so prominent that the role of aspect ratio may be not apparent. For example, the difference in surface roughness between the two particle shapes used in [7], i.e., fractal and hexagon column, is easily seen. However, one has to realize that the aspect ratios of these two crystals are also different: $L/D \approx 1$ for the fractal shape and $L/D = 2$ for the hexagonal column. In this study, phase functions and single scattering albedo are calculated for seven aspect ratios, ($L/D = 6, 4, 2, 1, 1/2, 1/4$, and $\frac{1}{6}$), five distortion parameters ($s = 0$, 15, 30, 60, and 80°) and five different sizes ($r_e = 11.07, 14.76, 22.15, 44.29$ and 88.58 μm) for $\lambda = 0.67, 1.60, 2.25$, and 3.7 μm. These phase functions and single scattering albedo values are used to compute the bidirectional reflection functions through a radiative transfer model. The variation range of reflection functions for a given optical thickness represents the possible uncertainty of cloud properties retrieved for satellite remote sensing. Based on these results, we estimate the effects of aspect ratio and surface roughness on the retrieval of ice-cloud properties.

2. Methodology

Ray-tracing program developed by Masuda and Takashima [8,9] is used to generate single scattering albedos and phase functions for both smooth and rough hexagonal columns at visible and near-infrared wavelengths. This code can calculate the 4×4 scattering matrix of both convex and concave cirrus particles using the geometrical optics approximation method and the Fraunhofer diffraction theory. The computational results agree well with the results by Takano and Liou [12] and Macke [13]. The surface roughness is represented by distortion parameters in the ray-tracing program [9,10]. There are two kinds of distortion distribution functions: uniform distribution from 0 to $t°$ [10] and a standard Gaussian distribution described by a mean of 0° and standard deviation of $s°$ [9]. We use the Gaussian distribution with $s = 0°$ for a smooth surface and $s = 80°$ for a very rough surface. Hexagonal columns and plates are used as the regular shape, starting from a basic shape with maximum length, $L = 200$ μm, and basal plane diameter, $D = 80$ μm. The effective radius of this particle (see definition below) is $r_e = 44.3$ μm. Four other particle sizes are considered: $2r_e$ (88.6 μm), $r_e/2$ (22.2 μm), $r_e/3$ (14.8 μm), and $r_e/4$ (11.1 μm). For each r_e, seven different aspect ratios are used: $L/D = 6, 4, 2, 1\,\frac{1}{2}, \frac{1}{4}$, and $\frac{1}{6}$. For example, for the case of $r_e = 44.3$ μm, the seven aspect ratios are: L(μm)/D(μm) = 97.72/97.72; 63.62/127.24; 46.57/186.29; 40.89/245.35; 165.91/82.95; 302.28/75.57; and 438.66/73.11. These sizes and aspect ratios are within the range observed in ice-clouds (e.g., [11]).

The definition of effective particle radius used in this study is

$$r_e = \frac{3}{2}\frac{\sum_{i=1}^{n} V_i n_i}{\sum_{i=1}^{n} \sigma_i n_i},$$

where V_i is the volume of the ith particle shape/size, n_i is the number density of the ith particle shape/size, σ_i is the extinction cross-section, which is twice the value of its geometrical cross-section in the limit of geometrical optics. This form is essentially the same as proposed by Foot (1988). We use this definition because it has the advantages of being applicable for remote sensing, in situ measurement and model studies, being consistent with the size definition of water droplets (spheres), and linking ice water content by optical thickness and effective radius [14].

We use phase functions of hexagonal crystals with different aspect ratios in doubling–adding calculations [4] to explore the *relative* effects on the BDRF of changing particle aspect ratio and roughness through their effect on the values of $\tilde{\omega}_o$ and phase functions, which, together with τ, determine the BDRF.

3. Results

Fig. 1 shows phase functions for different aspect ratio and roughness. Although it is hard to recognize each phase function with specific aspect ratio and surface roughness, the major purpose of this figure is to show the typical range of possible phase function differences when the specific particle shape within a certain ice-cloud is unknown a priori in satellite remote sensing. The phase functions of fractal and hexagon used in Mishchenko et al. [7] are within this range. The roughness parameter of the fractal shape used in that paper is estimated as $s \sim 15^\circ$ by comparing the shapes of phase functions. Therefore, the two phase functions used in [7] are approximately represented by distortion $s = 0^\circ$, $D = L/2$ for the hexagon column and $s = 15^\circ$, $D = L$ for the fractal. As pointed out by other authors [13], the major departure of phase functions of rough surface crystals from that of hexagons with smooth surfaces is the general smoothness of the phase functions and the disappearing of the resonance features around 22 and 46°. The other difference is that, for all aspect ratios, hexagons with smooth surfaces have much stronger scattering (about 1 order more) than rough surface crystals at the back scattering angle, i.e., $\Theta = 180^\circ$. Such a wide range of phase functions may cause significant uncertainties in calculated spatial distribution of scattered radiances by ice-clouds.

The effects of aspect ratio on phase functions for different surface roughnesses are shown in Fig. 2. It is readily seen that the largest effect of the aspect ratio on phase functions occurs when distortion parameter equals to zero, i.e., smooth hexagon columns and plates. This effect decreases as the surface roughness of the crystal increases. The major feature of phase functions with large distortion parameters ($s \geq 30^\circ$) is the lower scattered energy at backscattering angles. Another feature in these phase functions is that for all values of the distortion parameter, the largest side scattering occurs when the aspect ratio equals to 1, i.e., $L = D$.

Fig. 3 is the calculated reflection functions of different phase functions. The five phase functions used include different combinations of aspect ratios and surface roughnesses. That is, $D = L/6$, distortion parameter $s = 0^\circ$, $D = L$, $s = 0^\circ$, $D = 6L$, $s = 0^\circ$, $D = L$, $s = 15^\circ$, and $D = 4L$, $s = 80^\circ$, which are chosen to represent the maximum variation of the range in the spatial distribution of scattered radiances. The variation range of the reflection functions can be used for estimation of possible errors caused by different crystal shapes in satellite remote sensing of ice-cloud optical thickness. It is apparent that this error is dependent on viewing geometry. The most significant feature is that there are significant differences of reflection functions among these phase functions (see cases of VZA = 0°, SZA = 0°; VZA = 30°, SZA = 30°, RAZM = 180°; and VZA = 60°, SZA = 60°, RAZM = 180°). This result is consistent with that of Mishchenko et al. [7] but the variation range is even larger due to the fact that a wide range of different particle shapes are

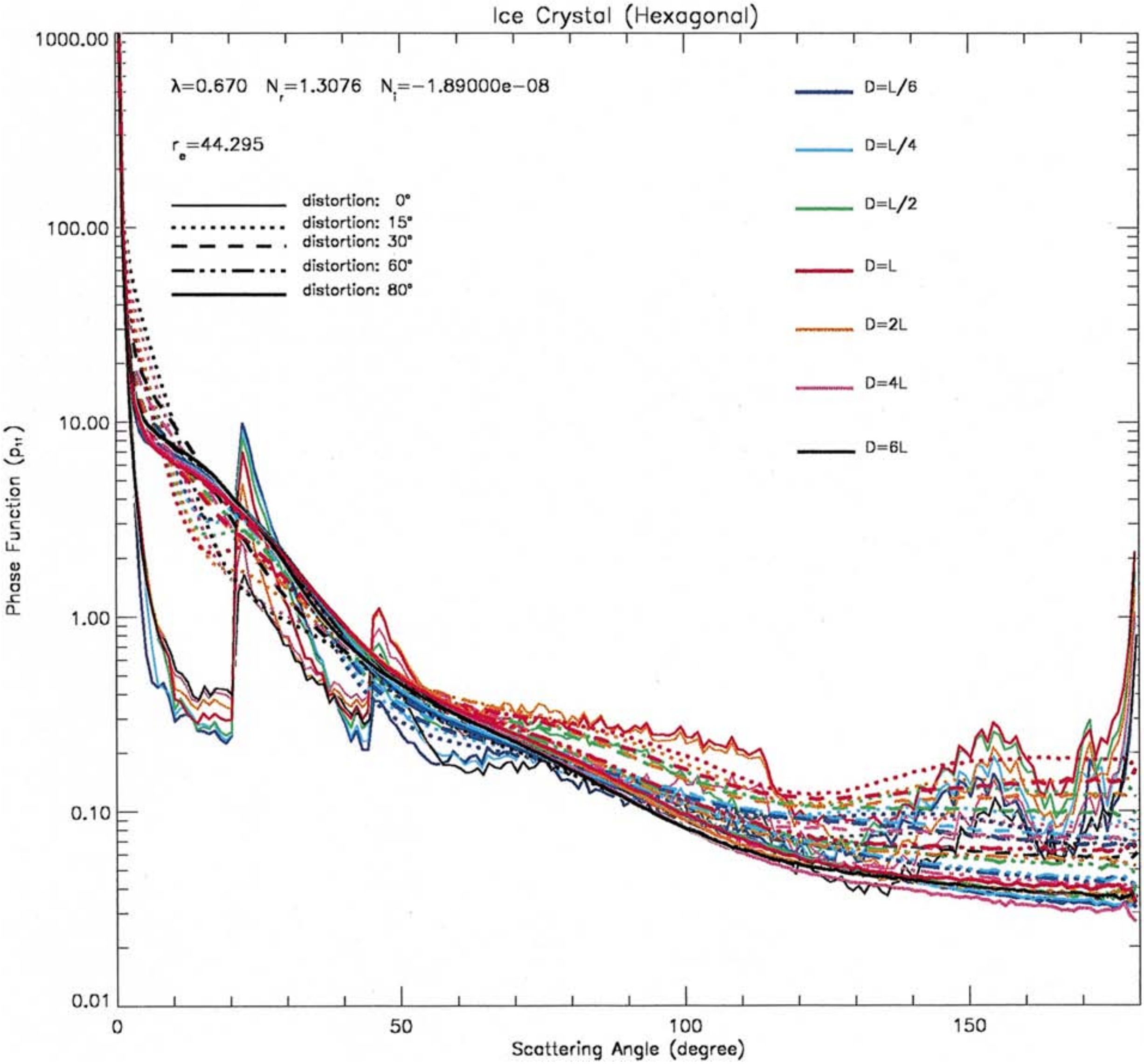


Fig. 1. Phase functions of hexagon ($s = 0°$) and fractals for seven different aspect ratios and five different surface roughness.

considered in this study. The fact that the largest differences among these reflection functions occur at this specific viewing geometry can be explained by the differences of phase functions at $\Theta = 180°$. Around this viewing geometry, the uncertainty of retrieved optical thickness is so large (easily more than a factor of ten) that the retrieval is meaningless if no particle shape information were supplied a priori. This fact suggests that images close to this viewing geometry ($\Theta > 150°$) should be avoided in satellite remote sensing of cloud properties. For most other viewing geometries, the variation range in the retrieved optical thickness is less than a factor of about two. For a given optical thickness, the highest value of reflection function is usually generated by particles with aspect ratio equal to unity, i.e., $D = L$, and the lowest value is from hexagon plates with large aspect ratio ($D = 6L$). Our calculations suggest that the uncertainty in retrieved optical thickness can be reduced by half, i.e., uncertainty in retrieved optical thickness is less than 40%, if phase functions of

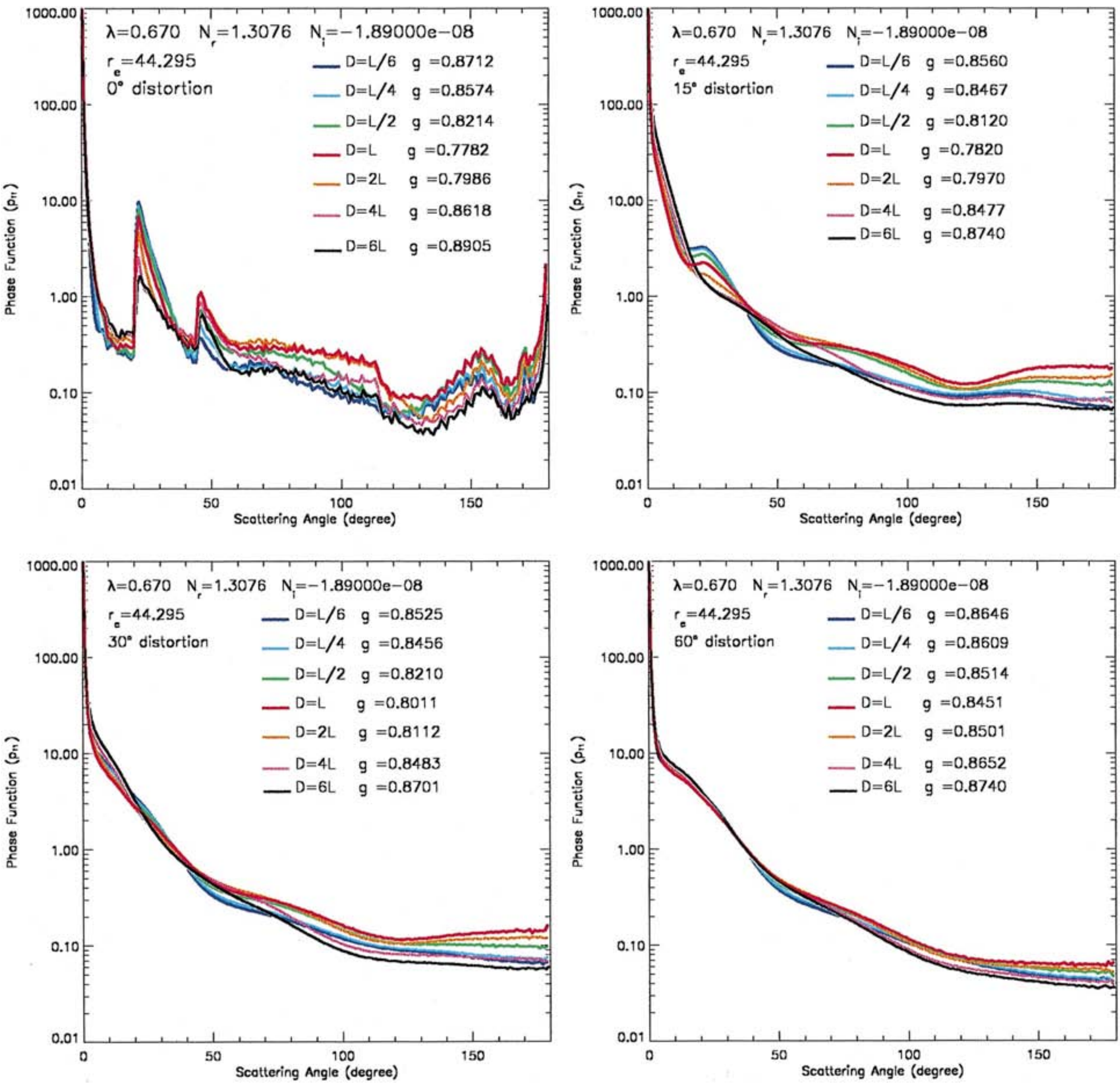


Fig. 2. *Caption opposite.*

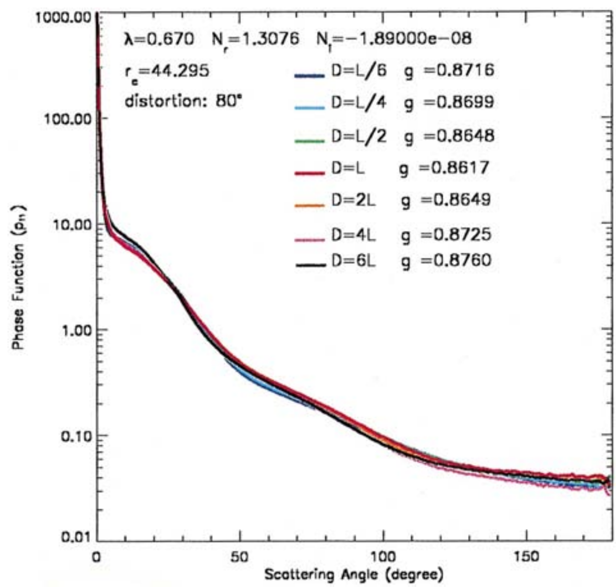
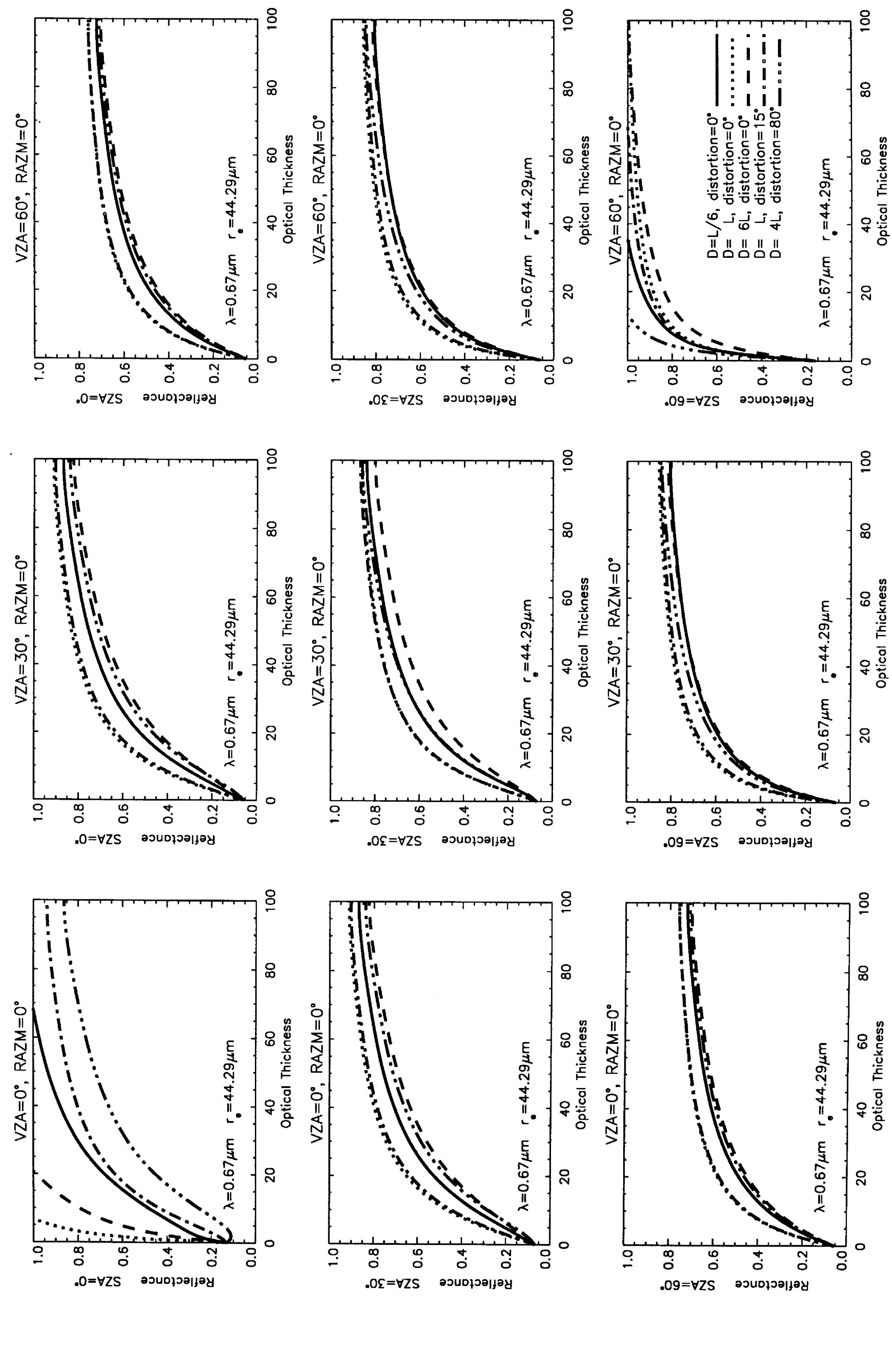


Fig. 2. Same as Fig. 1 but results of different surface roughnesses are separated.

"average shape" are used, for example, phase functions with $D = L/2$, $s = 15°$. This error can be considered as an upper limit because for satellite remote sensing, the typical image pixel size is larger than 1 km. Ice crystal shapes in such a wide region usually are mixtures of different surface roughnesses and aspect ratios. A practical way to obtain the averaged phase function to reduce the uncertainty is to use phase functions weighted by observed aspect ratios, which is dependent on the category of particle sizes (e.g. [15]).

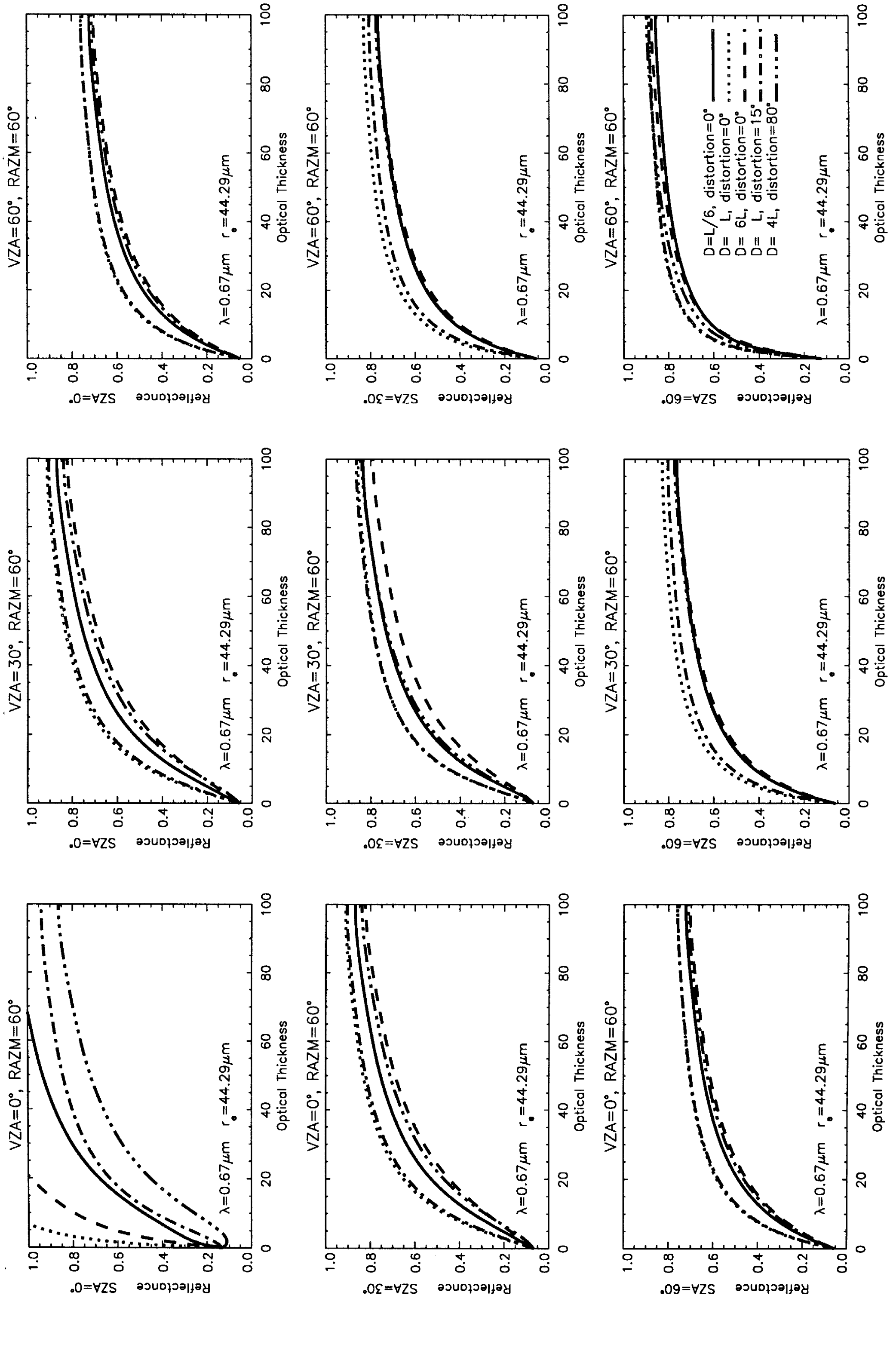
To estimate the uncertainty range when an average phase function is used, sensitivity tests of reflection functions to the aspect ratios and to the distortion parameters are conducted. Calculations are performed for all values of distortion parameters ($s = 0, 30, 60, 80°$) and all aspect ratios ($D = L/6$, $L/4$, $L/2$, L, $2L$, $4L$, and $6L$). Two examples of calculated results are shown in Fig. 4, i.e., aspect ratio $D = L/2$ for sensitivity of distortion parameter (Figs. 4a–d) and distortion parameter $s = 15°$ for sensitivity of aspect ratio (Figs. 4e–h). Figs. 4a–d show that if aspect ratio is close to the assumed value of $D = L/2$, the retrieved uncertainty in optical thickness can be further reduced except for images with viewing geometry $\Theta \geq 150°$. Therefore, in situ measurements of aspect ratio and its seasonal and regional variations, not only the maximum dimension of ice crystals, are important in the future field experiment. Figs. 4e–h show that for an averaged roughness parameter, the variation range of the aspect ratio still causes large uncertainty in determining optical thickness by reflection functions even at non-backscattering angles ($\Theta \leq 150°$). This further illustrates the importance of the information of aspect ratio of ice crystals in remote sensing of cloud properties.

The effects of aspect ratio and surface roughness on the retrieval of particle size of ice-clouds have been investigated in a similar way. The effect of roughness on the reflection function of longer wavelength ($\lambda = 1.6$, 2.2, and 3.7 μm) is smaller than that in the visible band ($\lambda = 0.67$ μm). Fig. 5



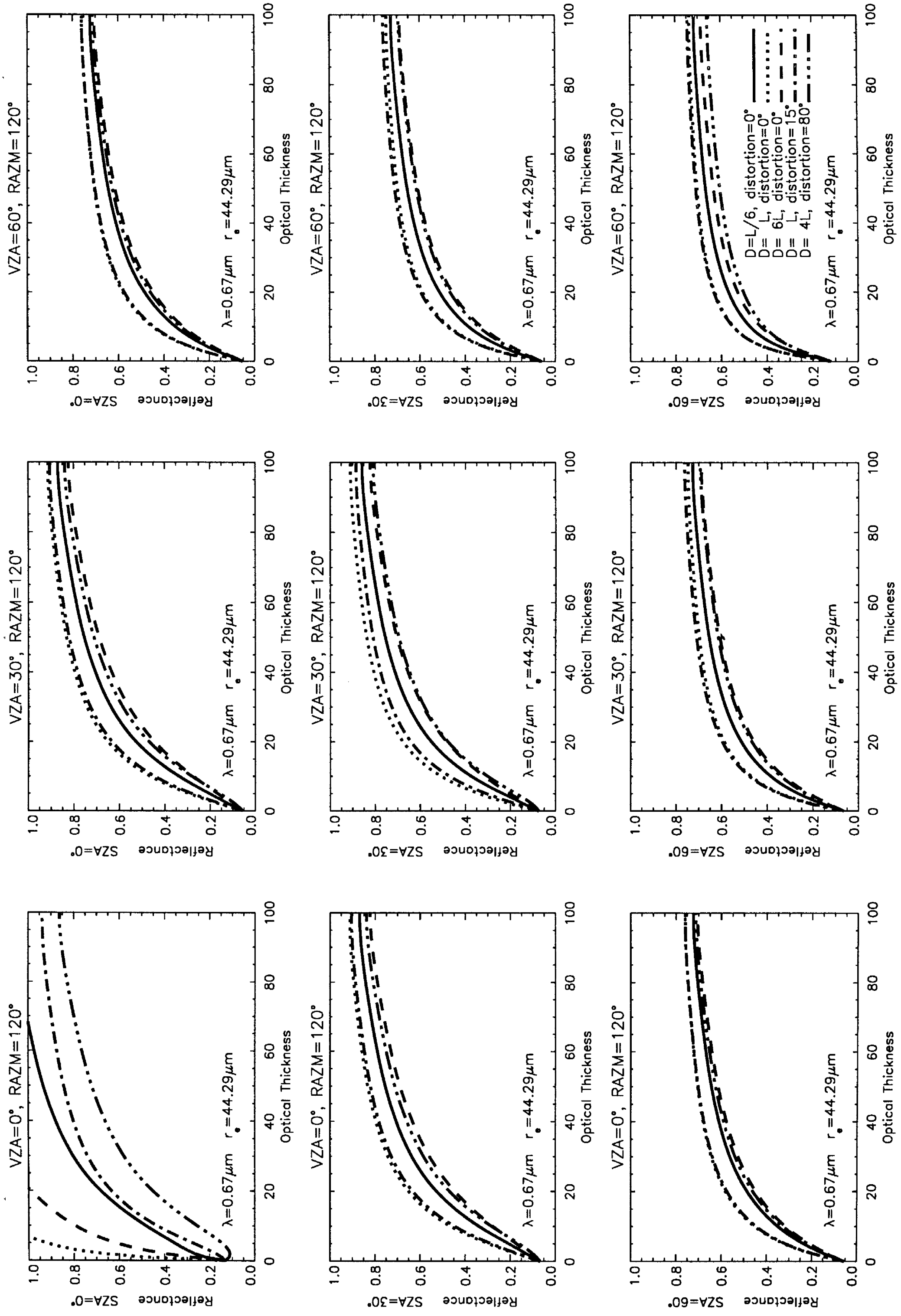
(a)

Fig. 3(a). *Caption on p. 569.*



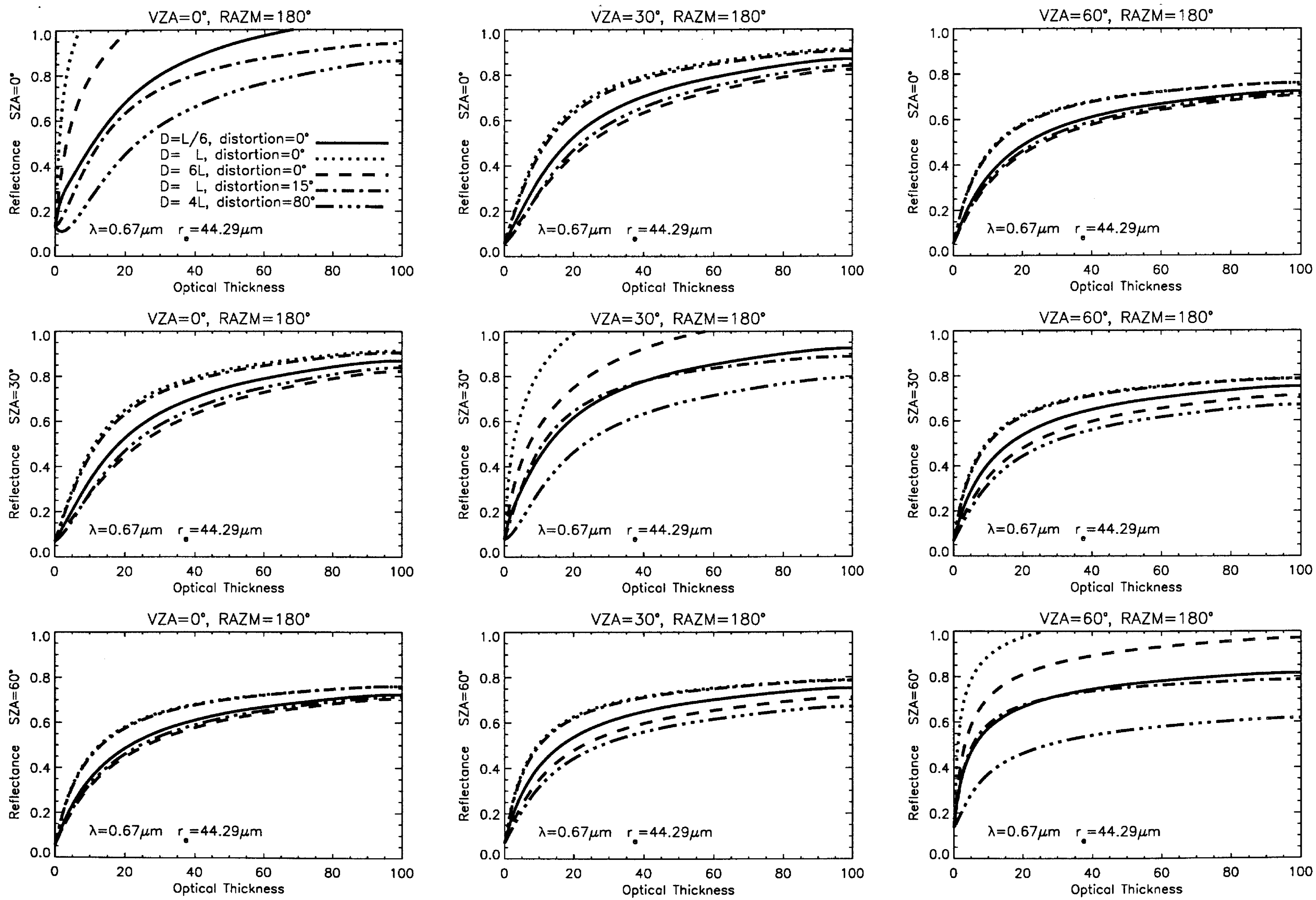
(b)

Fig. 3(b). *Caption on p. 569.*



(c)

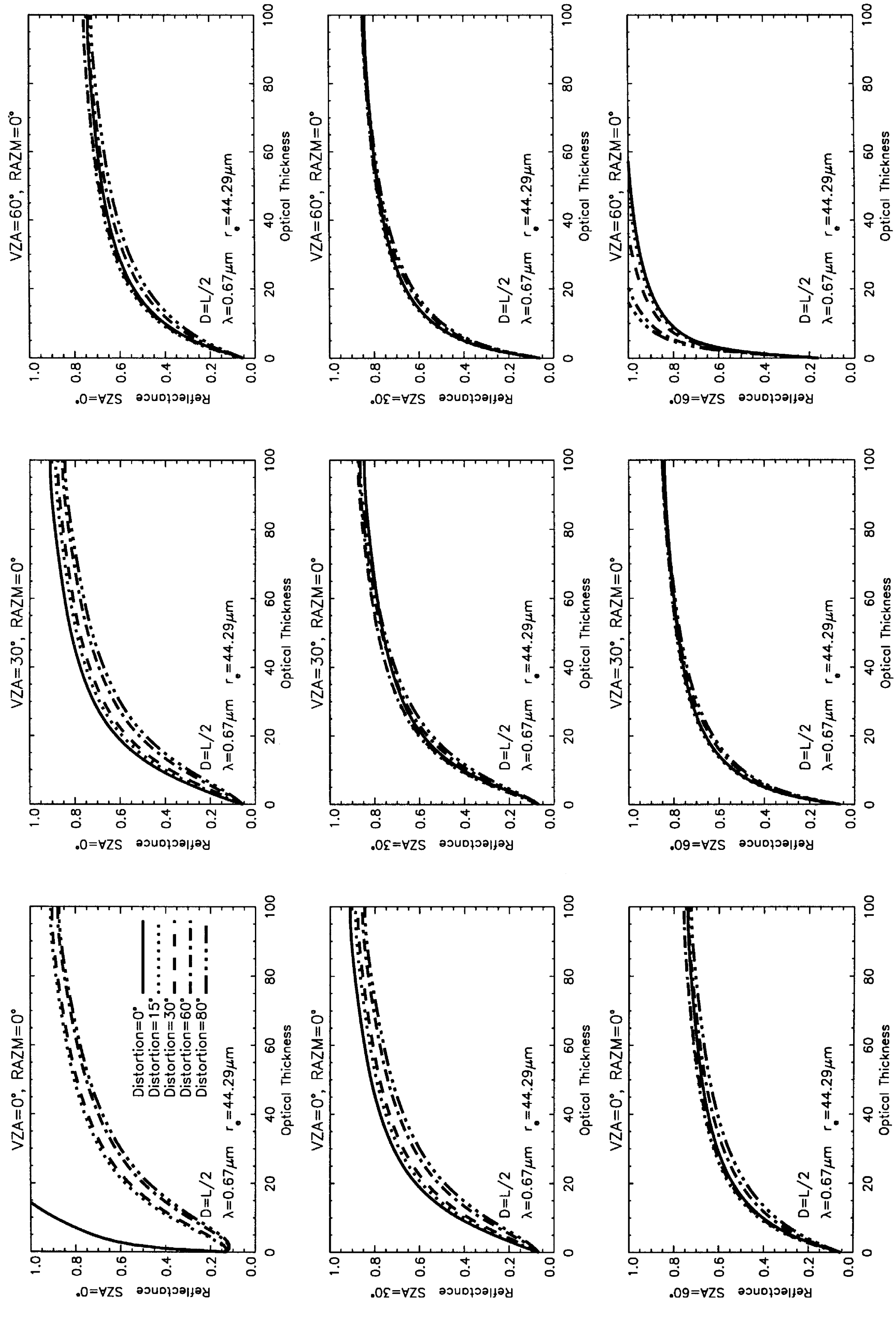
Fig. 3(c). *Caption opposite.*



(d)

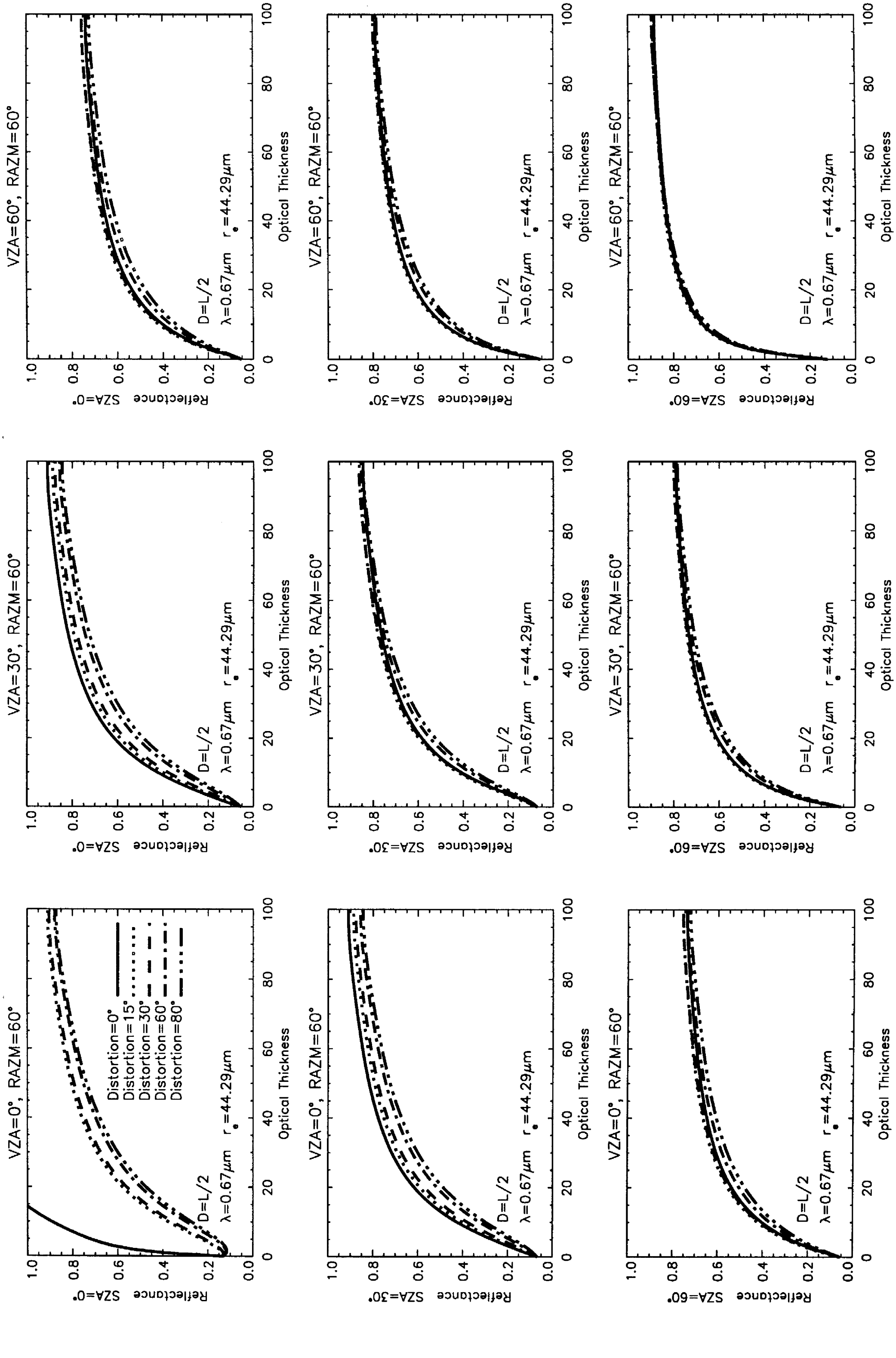
Fig. 3(d).

Fig. 3. Bidirectional reflection functions for $r_e = 443$ μm using five different phase functions that produces the maximum variation range of reflection functions for the same optical thickness. (a) for relative azimuth angle (RAZM) $= 0°$, (b) for RAZM $= 60°$; (c) for RAZM $= 120°$; (d) for RAZM $= 180°$.



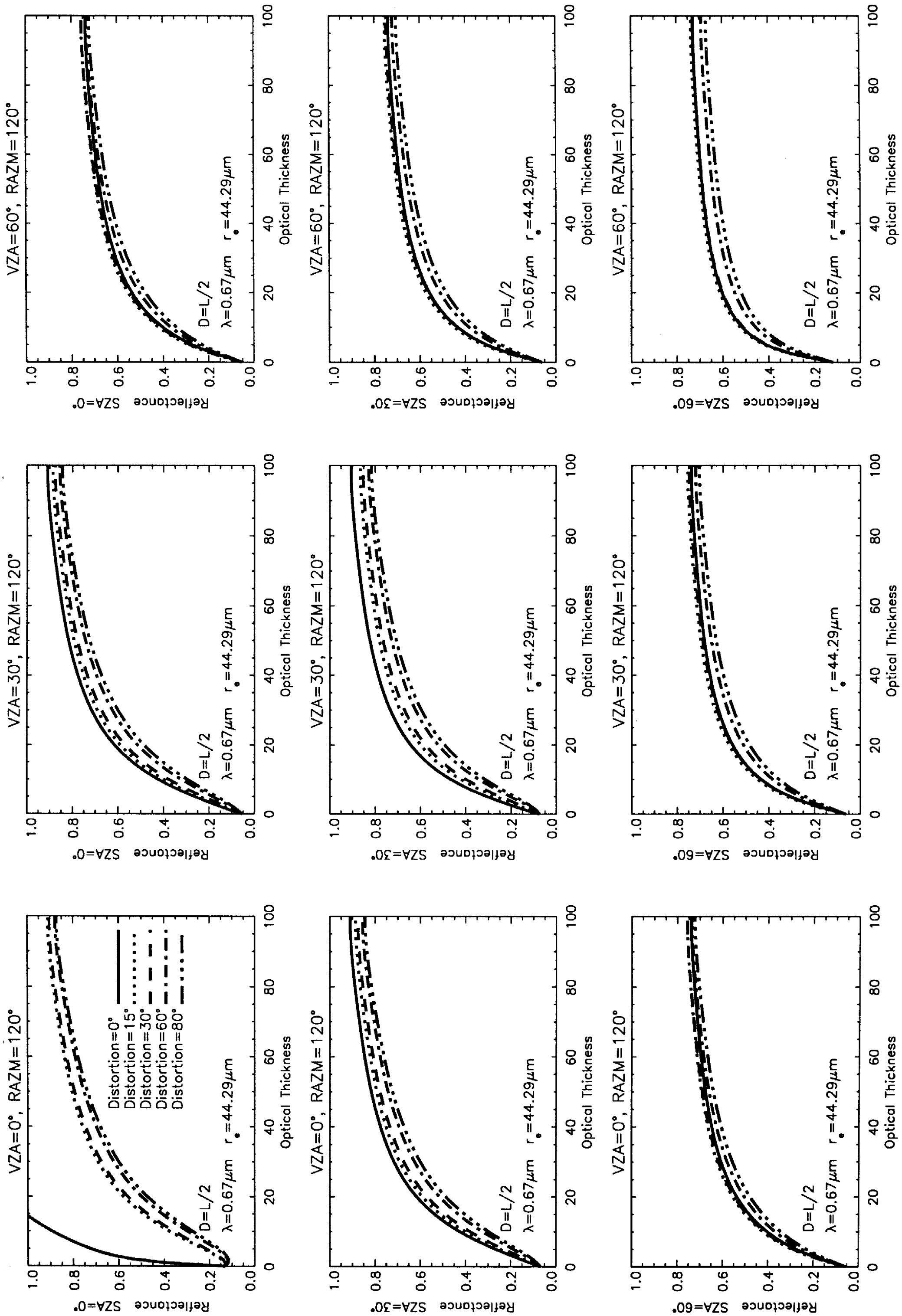
(a)

Fig. 4(a). *Caption on p. 577.*



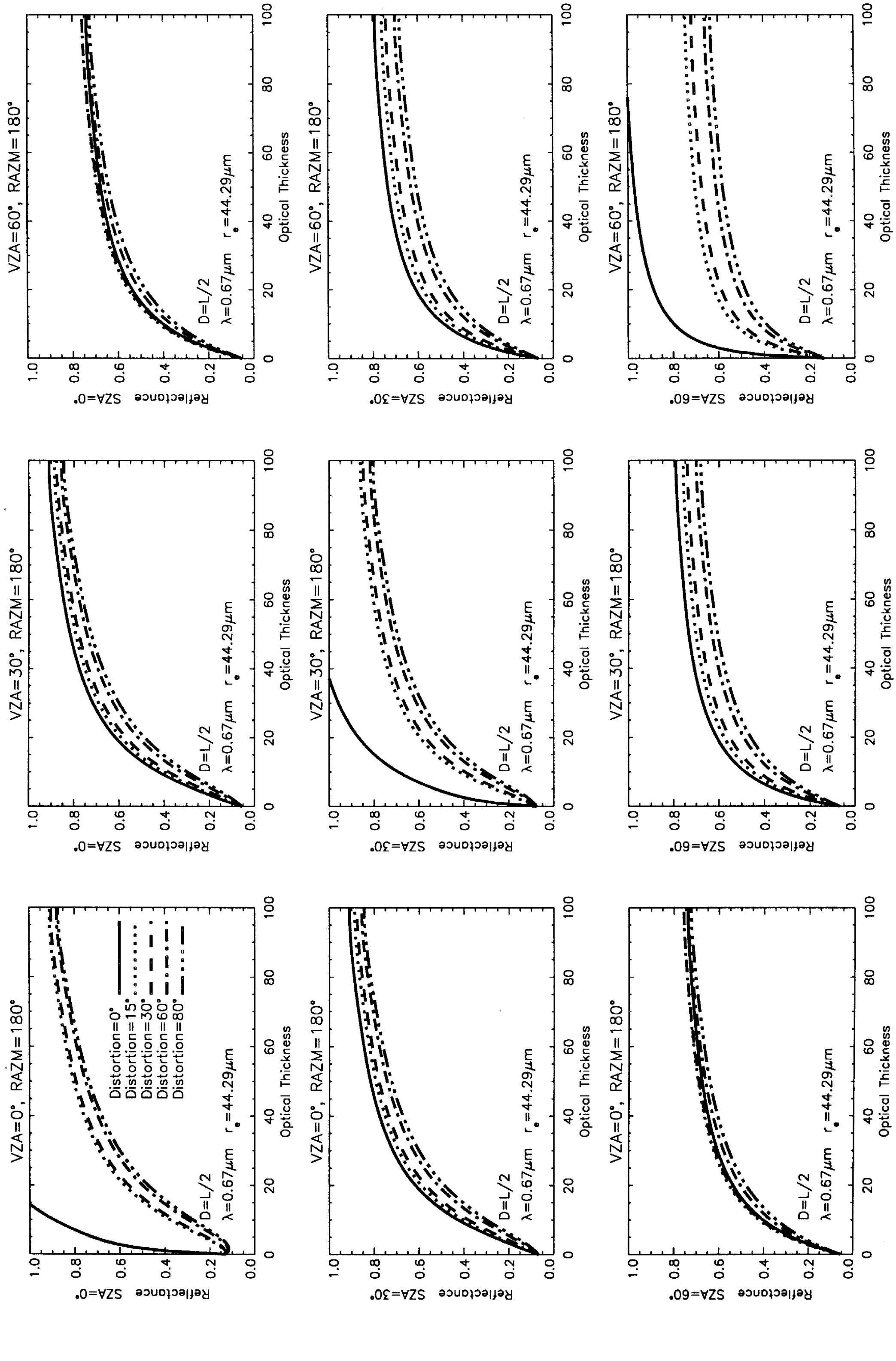
(b)

Fig. 4(b). *Caption on p. 577.*



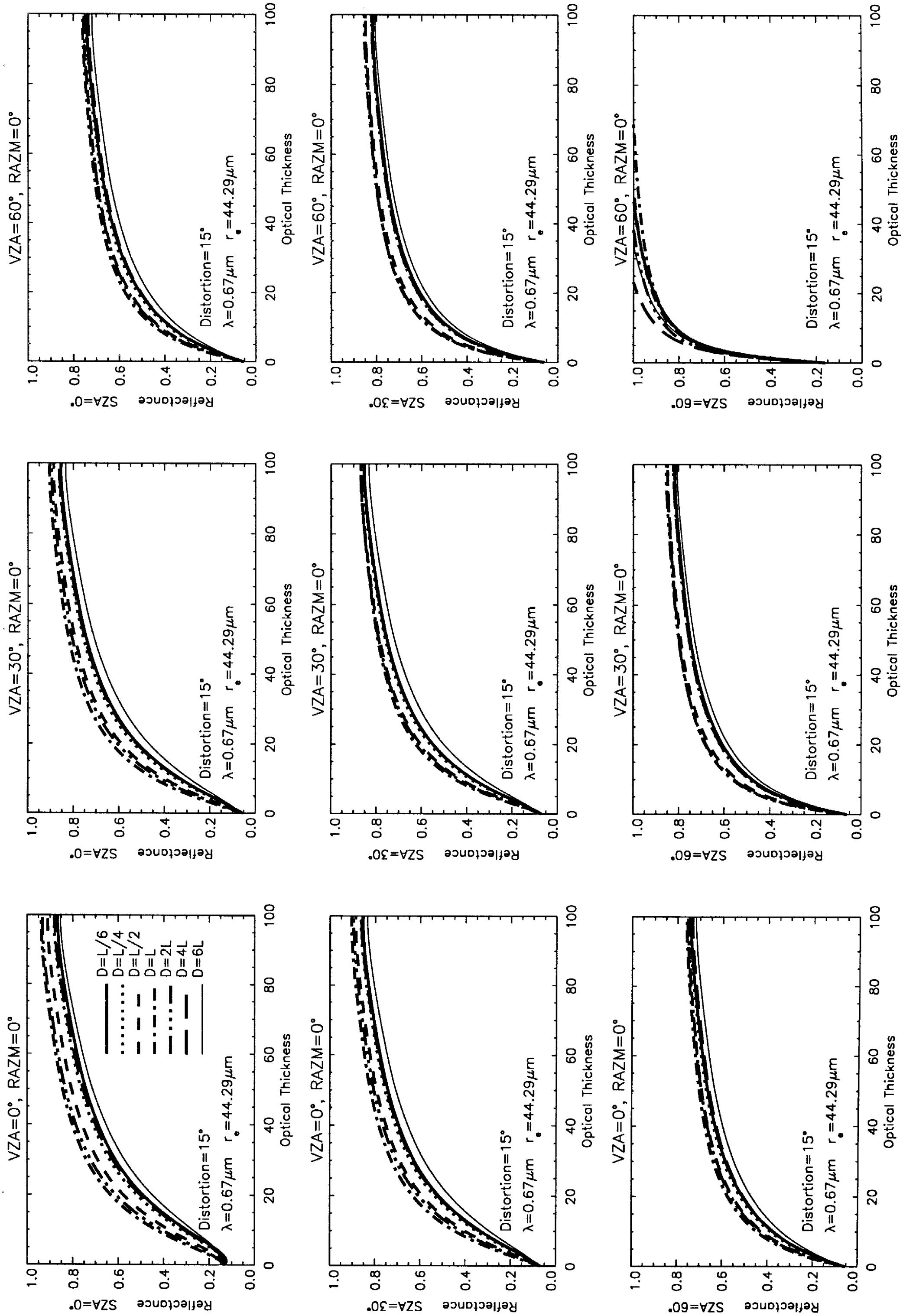
(c)

Fig. 4(c). *Caption on p. 577.*



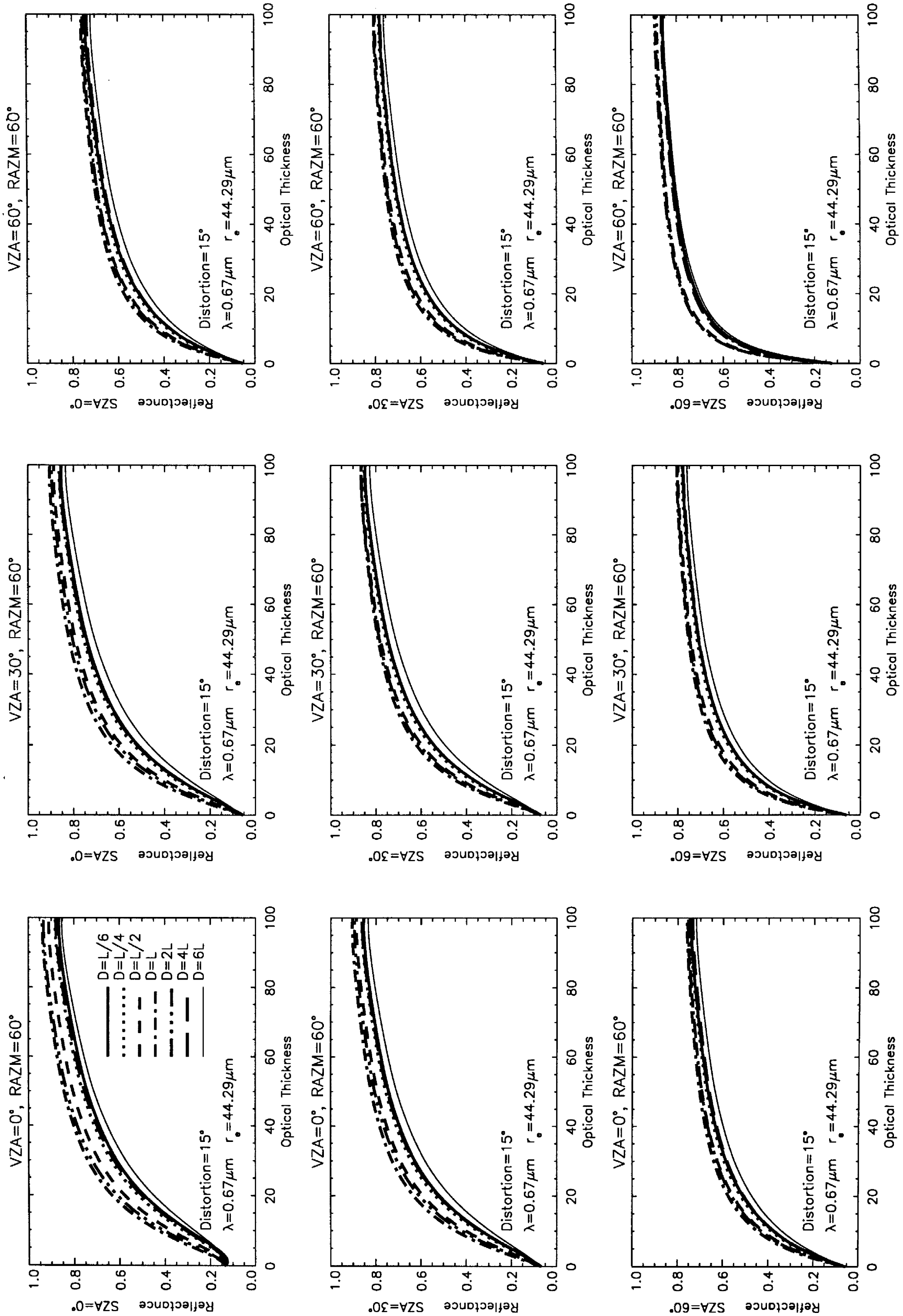
(d)

Fig. 4(d). *Caption on p. 577.*



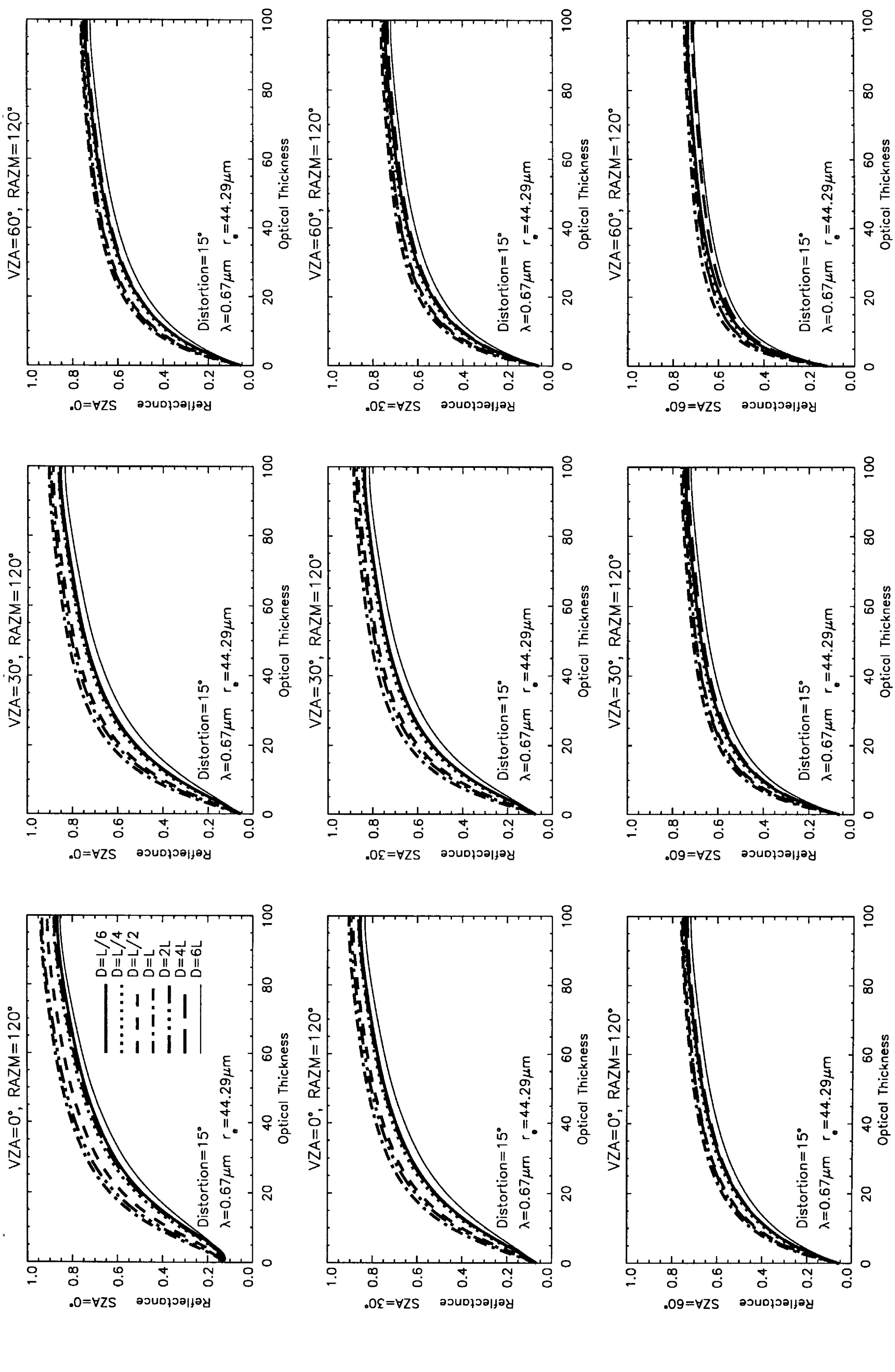
(e)

Fig. 4(e). Caption on p. 577.



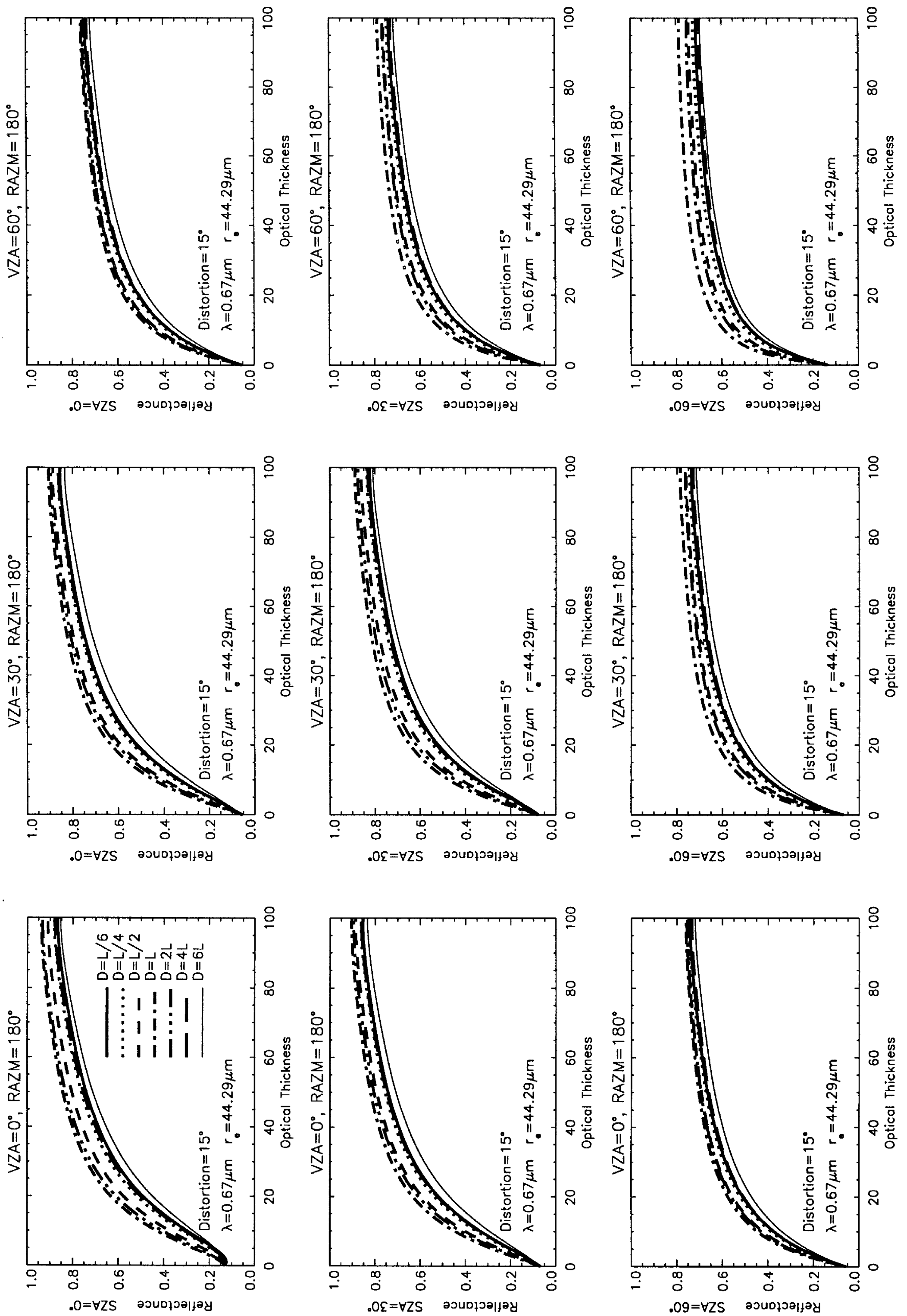
(f)

Fig. 4(f). *Caption on p. 577.*



(g)

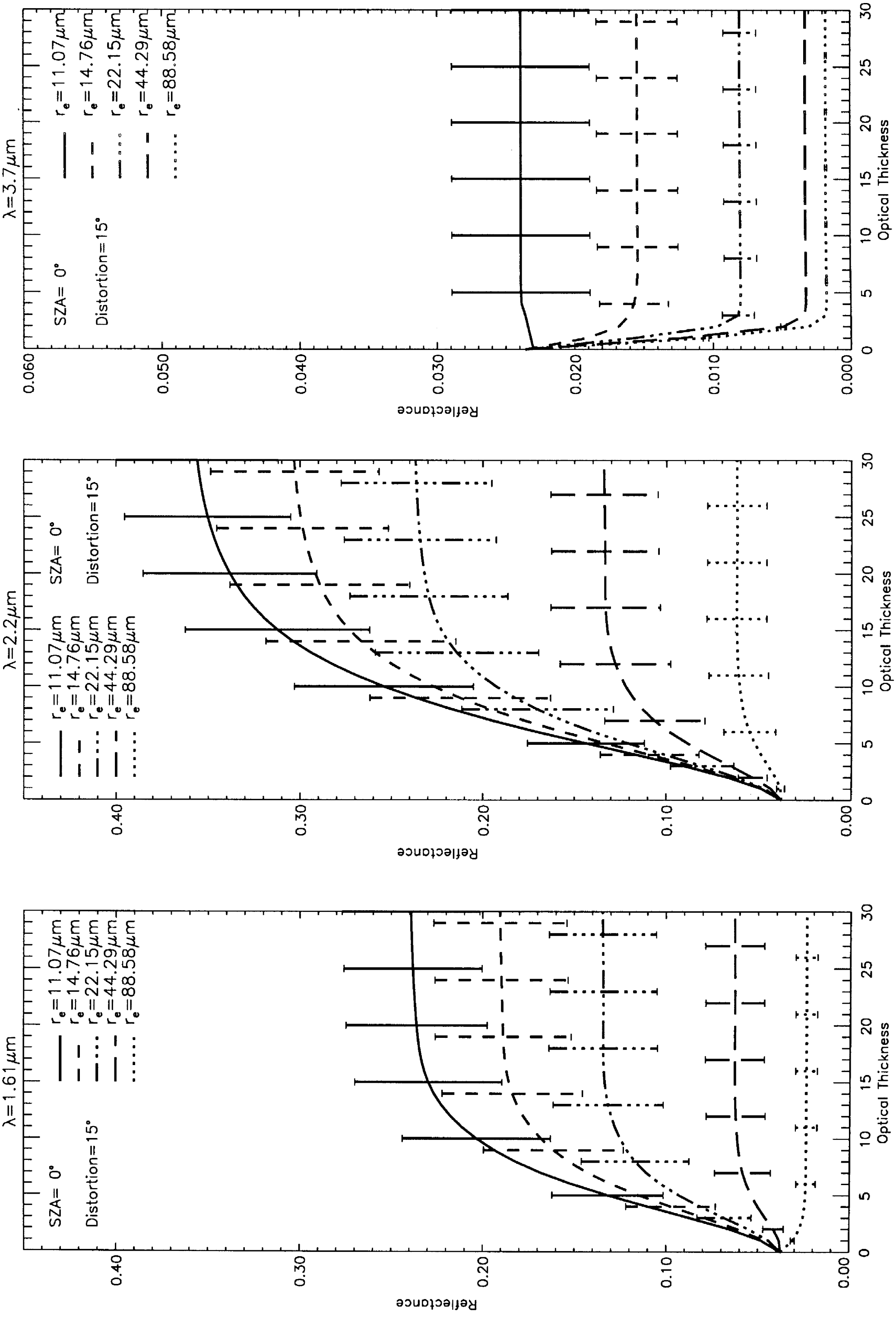
Fig. 4(g). *Caption opposite.*



(h)

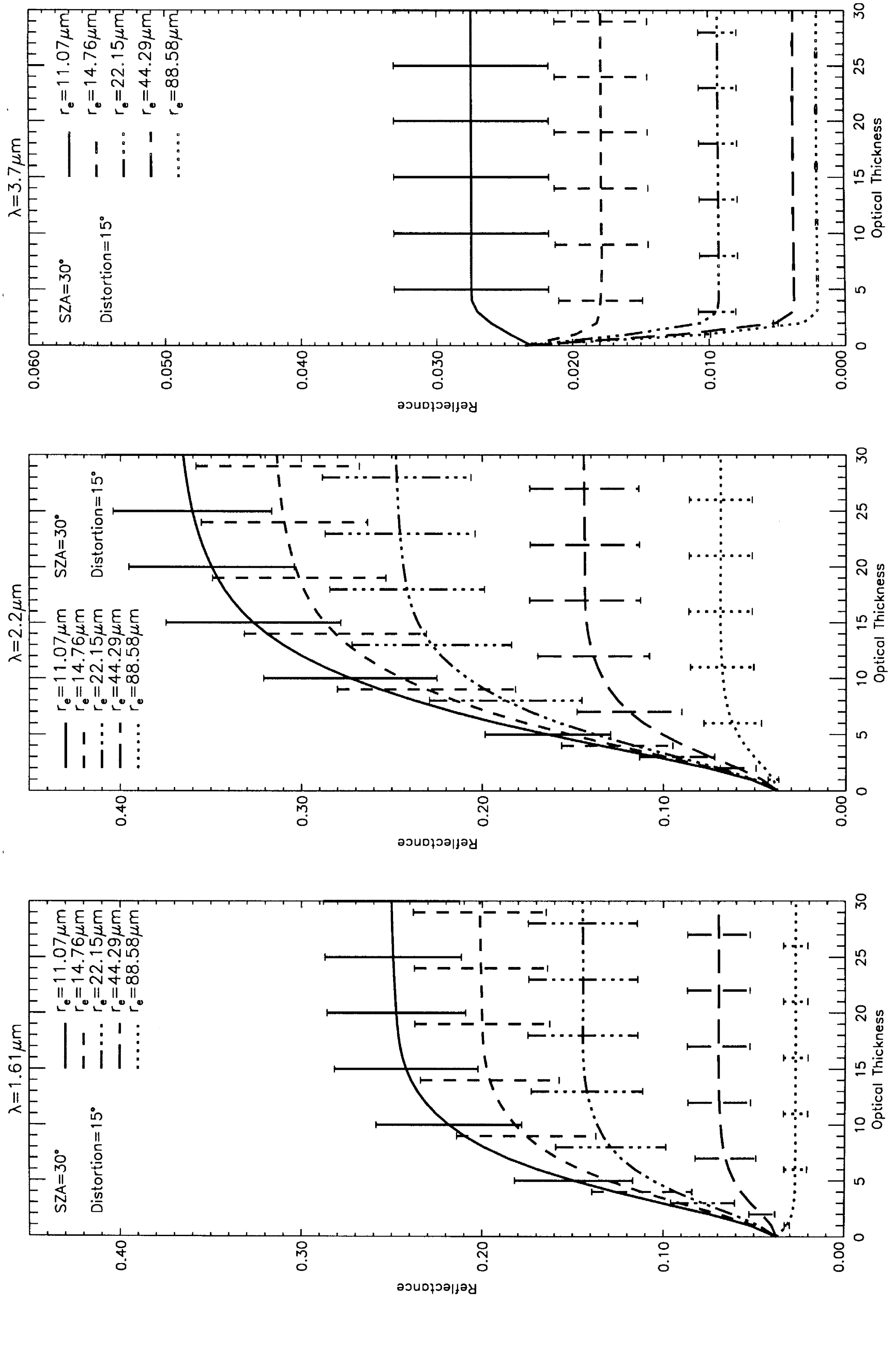
Fig. 4(h).

Fig. 4. Sensitivity tests for different surface roughness (a–d) and different aspect ratios (e–h).



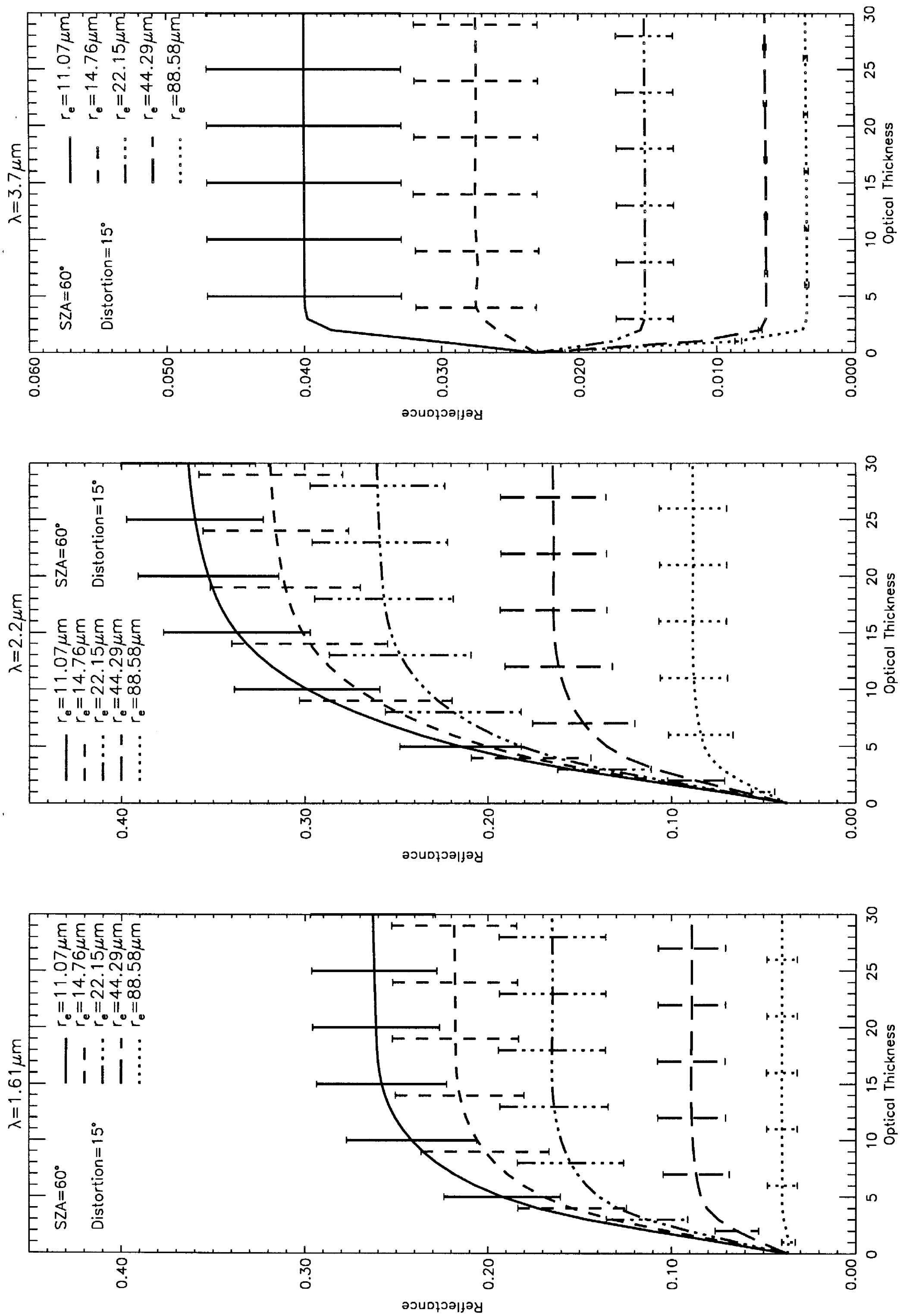
(a)

Fig. 5(a). *Caption on p. 580.*



(b)

Fig. 5(b). *Caption overleaf.*



(c)

Fig. 5(c).

Fig. 5. Uncertainties in the retrieved ice particle size for nadir viewing pixels if average phase function for distortion parameter $s = 15°$ are used (a) solar zenith angle = 0°, (b) solar zenith angle = 30°, (c) solar zenith angle = 60°.

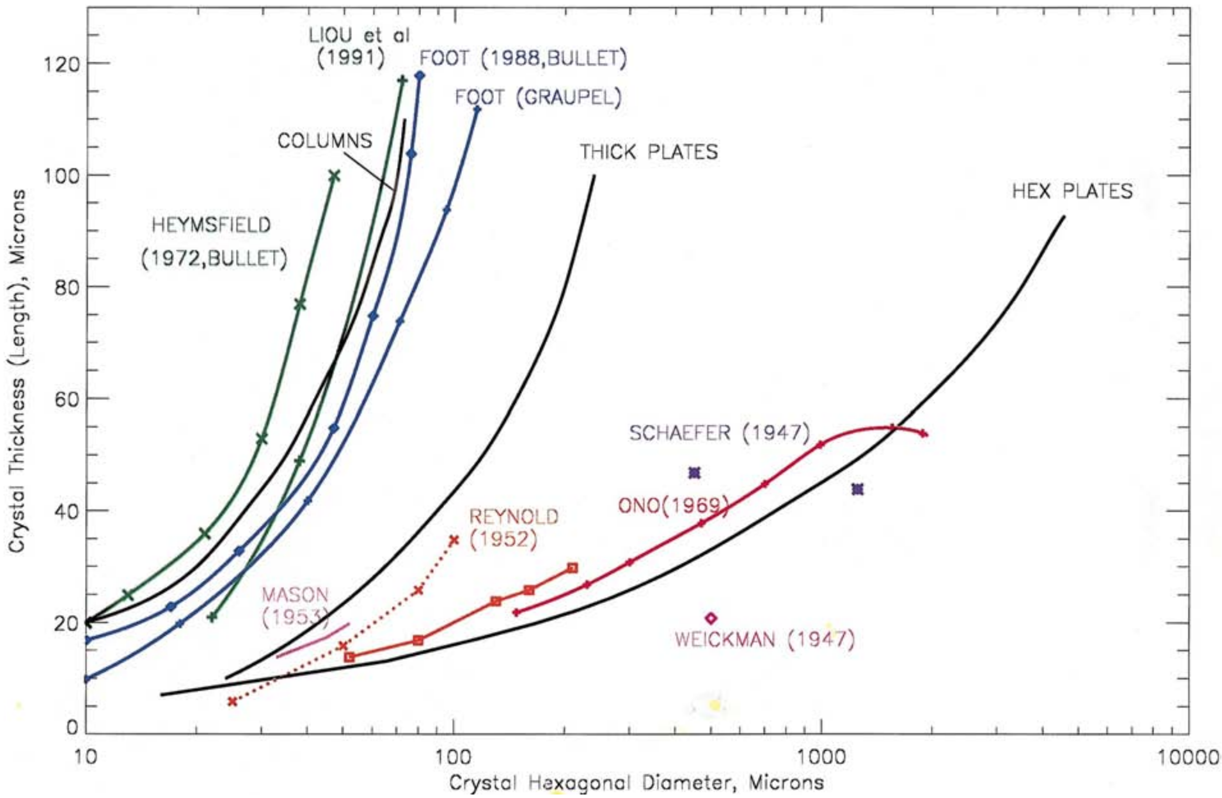


Fig. 6. Observed aspect ratios from aircraft measurement in the literature.

shows the possible errors caused by variations of ice crystal shape if an average aspect ratio and distortion parameter $s = 15°$ is used for retrieval of particle sizes for the three wavelengths available in satellite data. The average aspect ratio can be obtained from field experiments (e.g., [19]). The error bars shown in this figure represent the standard deviation. The values of reflection values are highest at $\lambda = 2.25$ μm and lowest at $\lambda = 3.7$ μm. This is due to the different values of the imaginary parts of the refractive index of ice at these three wavelengths (3.37×10^{-4} for $\lambda = 1.6$ μm, 2.03×10^{-4} for $\lambda = 2.25$ μm, and 6.85×10^{-3} for $\lambda = 3.73$ μm). This figure suggests that at 3.7 μm, for moderate and thick clouds ($\tau > 3$), by using an average phase function, the uncertainty in the retrieved particle size is about 3 μm or 30% for small particles ($r_e = 11$ μm) and about 10% for large particles ($r_e > 40$ μm). At 1.6 and 2.25 μm, the corresponding uncertainties are larger for thick ice-clouds. The estimated uncertainties are ~ 7 μm or 70% (at $\lambda = 1.6$ μm) and ~ 9 μm or 90% (at $\lambda = 2.25$ μm) for small particles ($r_e = 11$ μm); ~ 20 μm or 20% (at $\lambda = 1.6$ μm) and ~ 30 μm or 35% (at $\lambda = 2.25$ μm) for larger particles ($r_e = 88$ μm). The other potential problem with $\lambda = 1.6$ and 2.25 μm is that this uncertainty deteriorated rapidly when cloud optical thickness is smaller. For example, at about $\tau = 3$, the uncertainty can be about 30 μm for small ($r_e = 11$ μm) to moderate ($r_e = 44$ μm) particles for these two wavelengths. Similar results are obtained from other viewing geometries.

Given the importance of the information of aspect ratio on the retrieval of ice-cloud properties, a brief summary of in situ measurements of this parameter is in order. In history, the summary of measurements of aspect ratios by Auer and Veal [11] has been widely cited and used as a restrain for remote sensing purposes (e.g., [15]). In Fig. 6, measurement results of recent years are shown in comparison with those before 1970s. Although it may be not a complete summary, this figure shows the typical range of measured aspect ratio recorded in literature. Three curves named "Columns", "Thick plates" and "Hex plates" are the summarized results of Auer and Veal [11]. The data before 1970 are adopted from Auer and Veal [11]. Despite the very large range of the aspect ratios, it is very interesting to notice that during 1950s and 1960s, the major crystal habits measured are plates, that is, $D > L$, while columns ($D < L$) are the dominant habits measured in more recent years. There is no apparent explanation for this phenomenon (although it may be a result of the changes of measurement technique or environment such as cloud height, temperature ...). In applications for remote sensing, most authors (e.g., [15,20]) used a curve similar to the one labeled "Column" from Auer and Veal [11] as a typical restrain condition. A further detailed research on the temporal and spatial variations of aspect ratio in the future field campaign is critical in reducing the uncertainties of cloud properties retrieved from the satellite data.

4. Discussions and conclusions

It is well known that Mie theory cannot be used for calculations of phase functions in retrievals of ice-cloud properties. It was recognized that differences among phase functions of non-spherical particles are much smaller than that between spherical and non-spherical particles. In this sense, phase functions of hexagon columns and plates have been used for retrieval of ice-cloud properties [16–18]. More recently, a detailed study [7] pointed out the importance of ice crystal shapes in calculations of reflection functions. One of the implications of that study is that, even among non-spherical shapes, the uncertainty of reflection functions for the same optical thickness is still significant. This study estimates the possible uncertainties of retrieved optical thickness and particle sizes based on calculations of phase functions and single scattering albedo for a wide range of different particle aspect ratios and surface roughnesses. The results show that the uncertainty in the retrieved optical thickness of ice-clouds for most viewing-geometries is about 40% if an average phase function is used, which is much larger than the case of water clouds. At scattering angle close to $\Theta = 180°$, the uncertainties of the retrieved optical thickness become so large that it makes the retrieval meaningless. Therefore, satellite images with similar viewing geometry (we suggest a threshold of $\Theta > 150°$) should be avoided. For thick ice-clouds, the estimated uncertainties in retrieved particle size are 30% (at $\lambda = 3.7$ μm), 70% (at $\lambda = 1.6$ μm) and 90% (at $\lambda = 2.25$ μm) for small particles ($r_e = 11$ μm); 10% (at $\lambda = 3.7$ μm), 20% (at $\lambda = 1.6$ μm) and 35% (at $\lambda = 2.25$ μm) for larger particles ($r_e = 88$ μm). Uncertainties of retrieved particle size for thin ice-clouds ($\tau < 3$) are much larger if data from $\lambda = 1.6$ and 2.2 μm are used. The errors can be about 30μm for small ($r_e = 11$ μm) to moderate ($r_e = 44$ μm) particles for these two wavelengths.

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