

Optical properties of cloud particles and dust aerosols and the truncation of scattering phase function

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Outline

- ❑ Accomplishments
- ❑ Delivered data and codes
- ❑ Advances in science
- ❑ Plan for the next year

Accomplishments

- Derive the single/bulk scattering properties of cloud particles (ice/water) and dust aerosols.
- Interpolate the single/bulk scattering property database to 3001 wavelengths between 0.225 and 20.0 μm .
- Expand the scattering phase functions in terms of the Legendre polynomials.
- Simulate the bidirectional reflectances and study the sensitivity of bidirectional reflectance to the number of Legendre polynomials of the truncated phase function.

Delivered data and codes (1): Aerosols

- The bulk scattering properties of spheroidal dust aerosols with an aspect ratio $\varepsilon=1.7$
- An extensive bulk scattering property database of dust aerosols (3001 wavelengths between 0.225 and 20.0 μm)
- The datasets of 4, 8, 16, and 32 terms Legendre polynomial expansion coefficients

Delivered data and codes (1): Ice clouds

- The single scattering properties of ice particles of droxtals, hexagonal plates, solid columns, hollow columns, aggregates and 3D bullet rosettes
- The bulk scattering properties by averaging the single-scattering properties over an ice particle habit distribution and 18 particle size distributions.
- The interpolated bulk scattering property database (3001 wavelengths between 0.225 and 20.0 μm)
- The datasets of 4, 8, 16, and 32 terms Legendre polynomial expansion coefficients

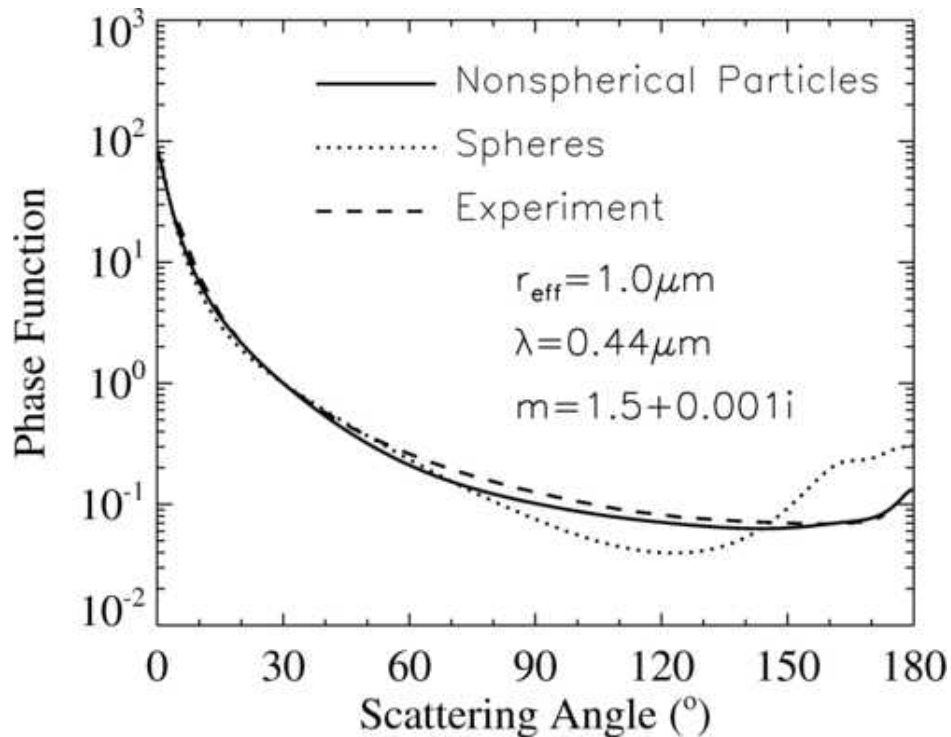
Delivered data and codes (1): Water clouds

- The bulk scattering properties of water droplets
- The Interpolated bulk scattering property database (3001 wavelengths between 0.225 and 20.0 μm)
- The datasets of 4, 8, 16, and 32 terms Legendre polynomial expansion coefficients

Advances in science

- Dust aerosols
- Ice clouds
- Water clouds

Dust aerosol



The comparison of averaged phase function between simulated and experimental results. The solid line shows the simulation based on the assumption of spheroid particle shape. The dot line shows the phase function simulated for spherical particles. (Feng et al. in preparation)

The scattering phase function describes the angular distribution of scattered radiation. The equivalent-sphere approximation leads to quite large errors in comparison with measurements at large scattering angles.

Methodology

□ Model simulation of the scattering properties of nonspherical mineral dust aerosols.

❖ Spheroid particle shape is widely recognized.

❖ Single scattering properties are based on a combination method (Dubovik et al., 2006).

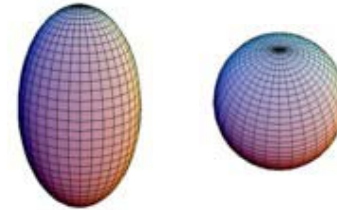
T-matrix (Mishchenko and Travis, 1994)

An approximate method (Yang et al., 2007)

phase matrix (IGOM, Yang & Liou, 1996)

$$Q_e = Q_{e,IGOM} + Q_{e,edge} \text{ (Fournier \& Evans, 1991)}$$

$$Q_a = Q_{a,IGOM} + Q_{a,above-edge} + Q_{a,below-edge} \text{ (Nussenzveig \& Wiscombe, 1980)}$$

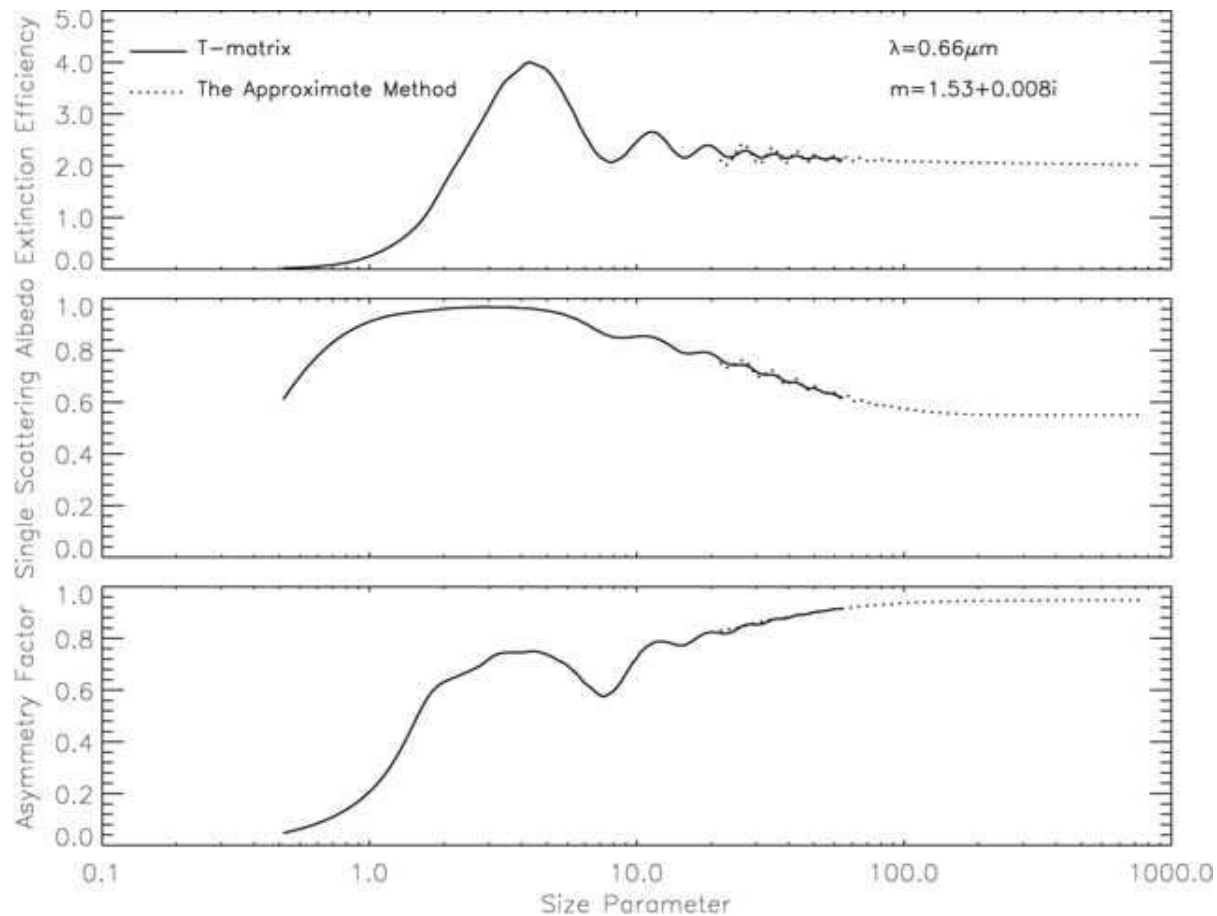


❖ Averaged scattering properties are based on the integration over particle size distribution

Lognormal distribution:
$$n(r) = \frac{1}{(2\pi)^{1/2} \sigma_g r} \exp[-(\ln r - \ln r_g)^2 / (2\sigma_g^2)]$$

Dust aerosol

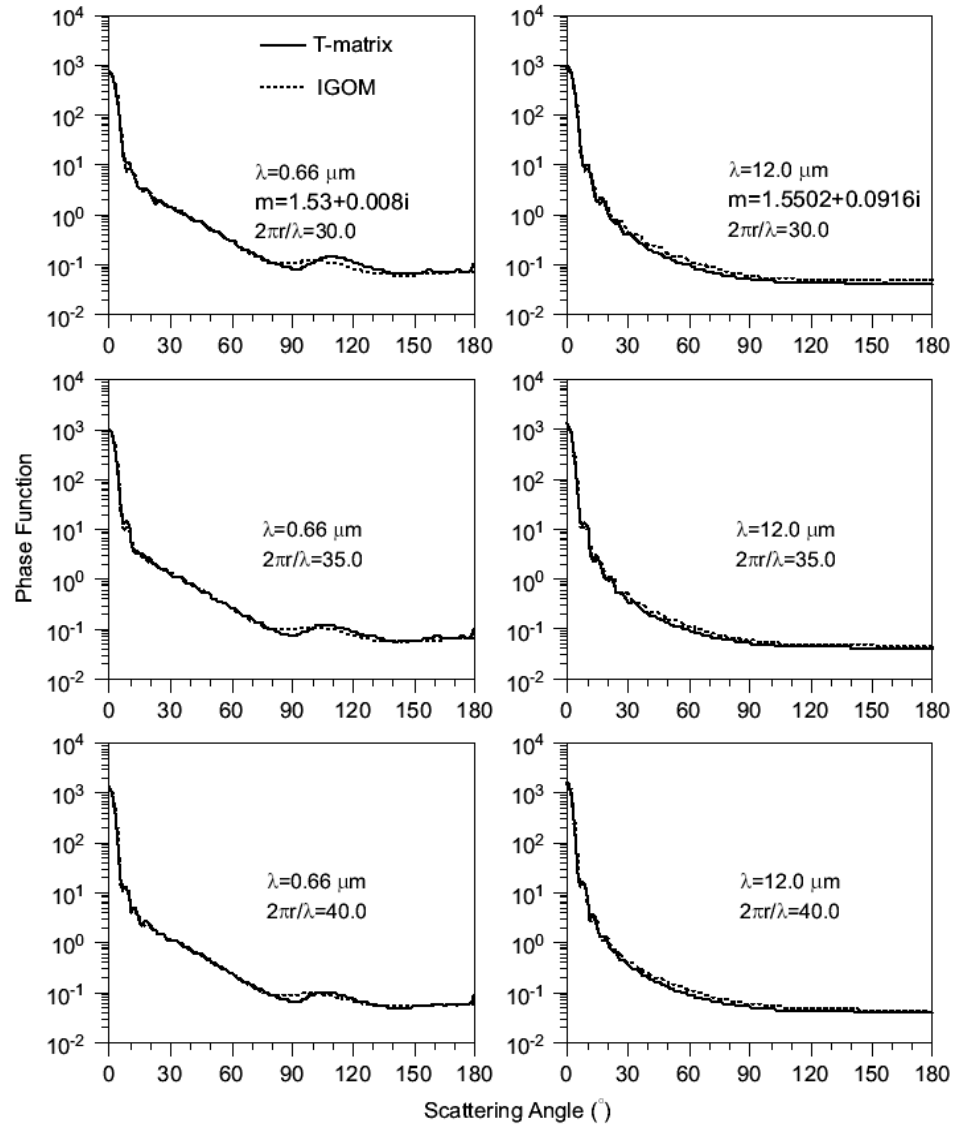
The Combination of T-Matrix and IGOM (1)



Comparison between the T-matrix solutions and their counterparts computed from the approximate method (Yang et al., 2007)

Dust aerosol

The Combination of T-Matrix and IGOM (2)



Comparison of the phase functions computed from the T-matrix and the IGOM for three size parameters at two wavelengths (Yang et al., 2007)

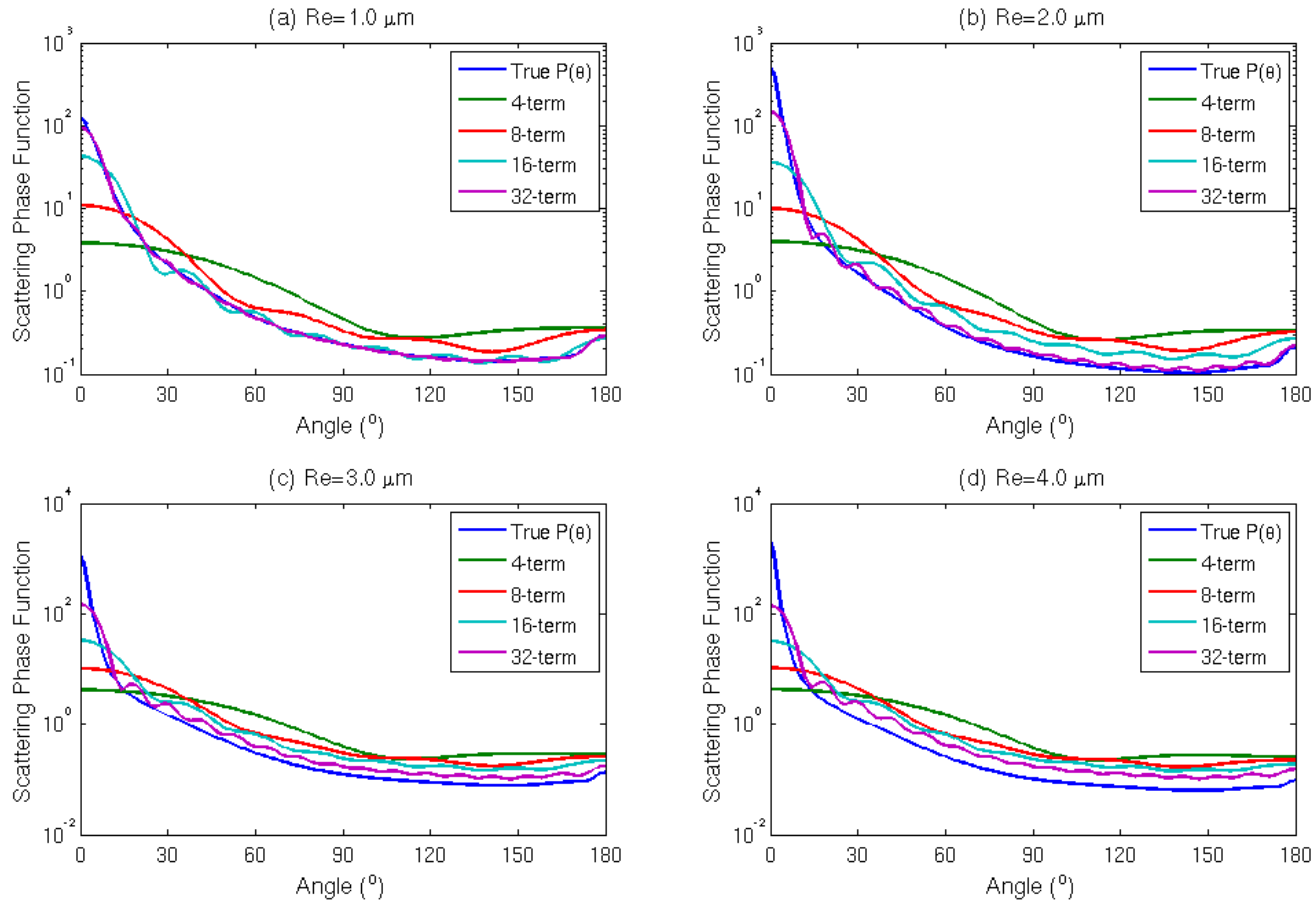
Phase Function Truncation

- ❑ Why do we need truncation?
 - ❑ Remove the strong forward scattering peak to save CPU time

- ❑ Methodology: the δ -fit method (Hu et al., 2000)

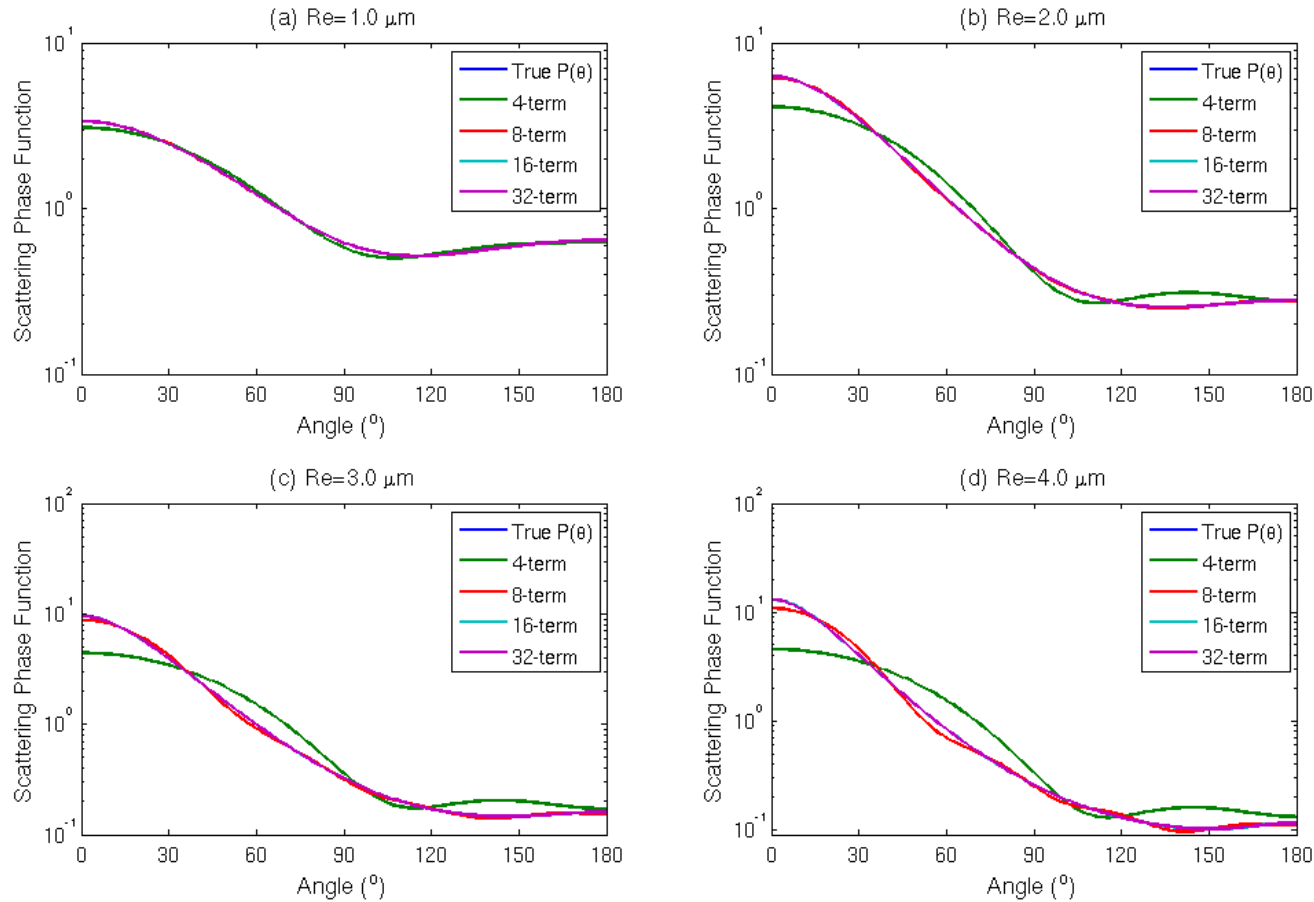
- ❑ Advantages of the δ -fit truncation:
 - ❑ Better estimation of phase function
 - ❑ Easy removal of the forward peak

The Truncated Phase Function (1)



Comparison of dust aerosol scattering phase functions: original phase function, 4-term, 8-term, 16-term, and 32-term Legendre polynomial fits at the wavelength of $0.55 \mu\text{m}$ for effective radius (a) $\text{Re}=1.0$, (b) $\text{Re}=2.0$, (c) $\text{Re}=3.0$, and (d) $\text{Re}=4.0 \mu\text{m}$.

The Truncated Phase Function (2)



Comparison of dust aerosol scattering phase functions: original phase function, 4-term, 8-term, 16-term, and 32-term Legendre polynomial fits at the wavelength of $11.0 \mu\text{m}$ for effective radius (a) $Re=1.0$, (b) $Re=2.0$, (c) $Re=3.0$, and (d) $Re=4.0 \mu\text{m}$.

The adjustment of optical properties

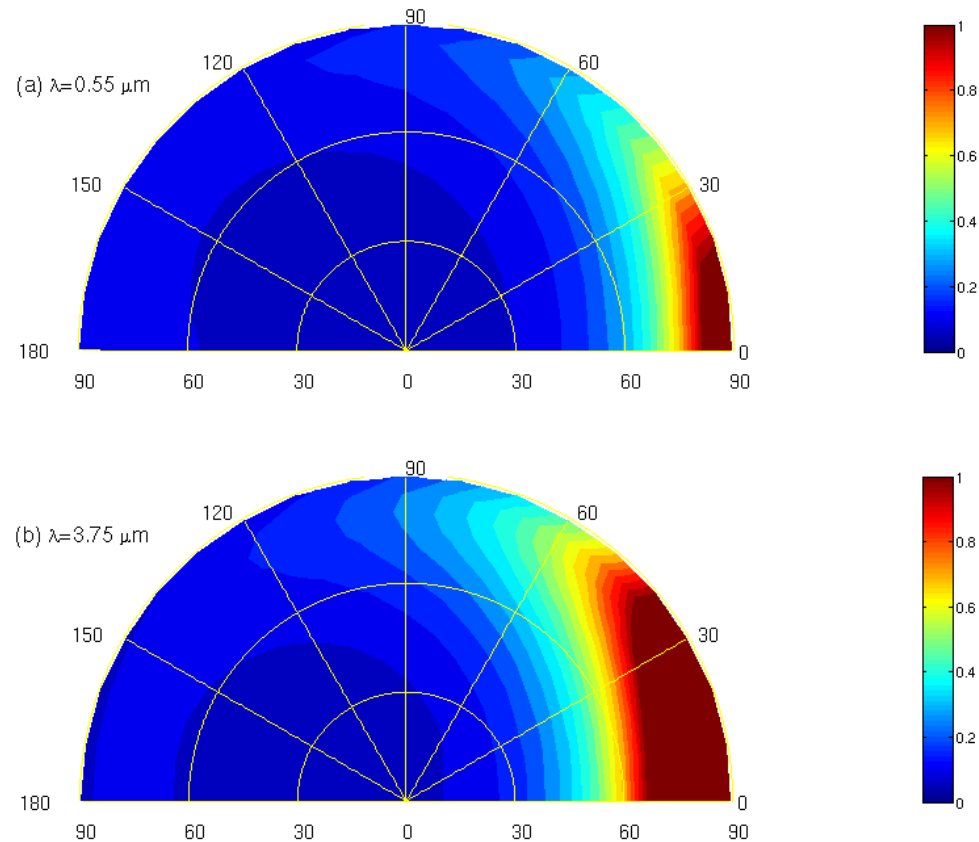
To achieve the same accuracy in multiple scattering calculations with the truncated phase functions as those with non-truncated phase functions, an adjustment must be made to the optical depths and single-scattering albedos.

The adjusted single-scattering albedo and optical depths are given by:

$$\omega' = \frac{(1 - f_\delta)\omega}{1 - f_\delta\omega}$$
$$\tau'_{sca} = (1 - f_\delta)\tau_{sca}$$

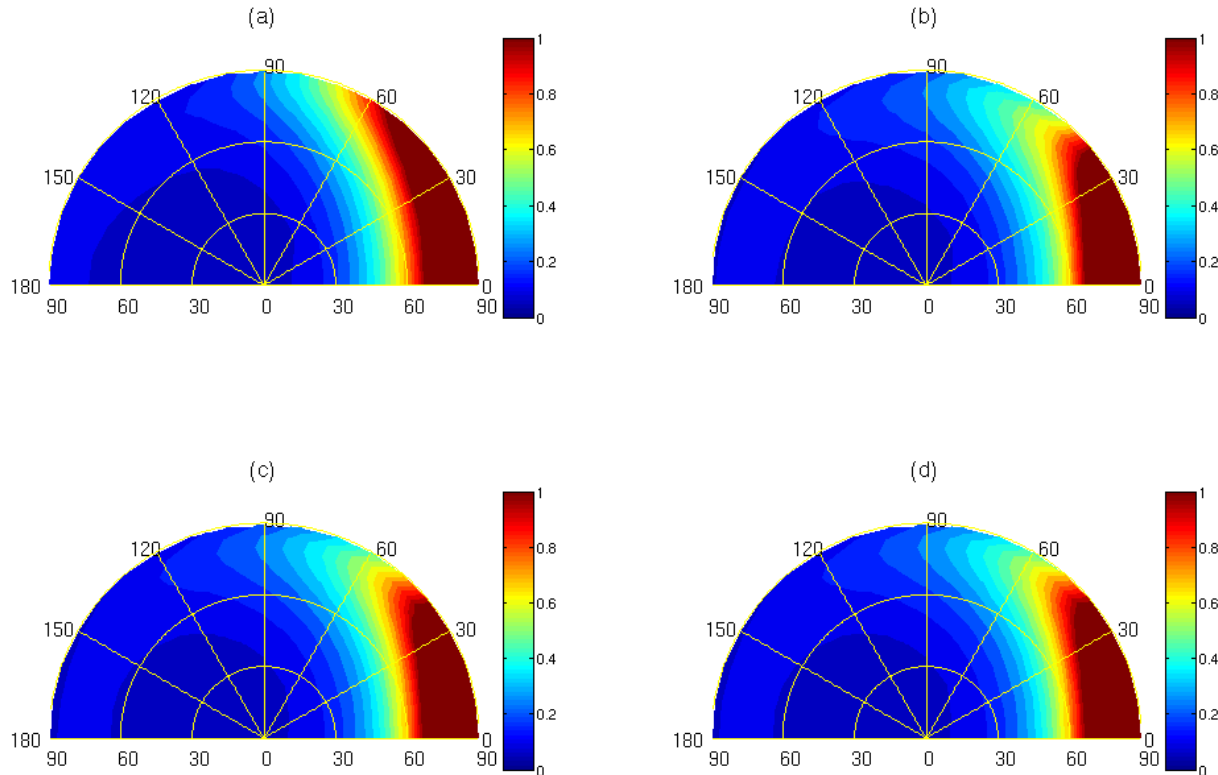
Where f_δ is the δ -fit truncation factor.

The Bidirectional Reflectances (1)



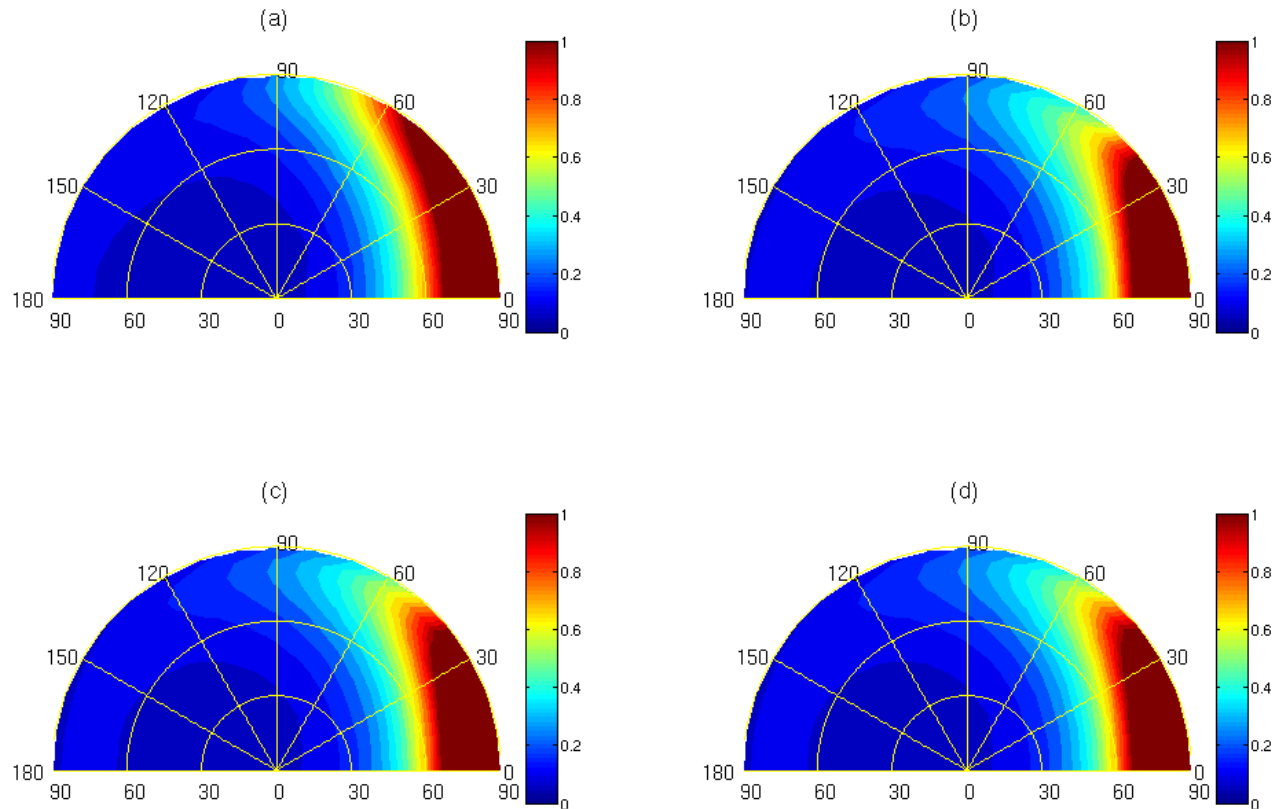
Dust aerosol bidirectional reflectances simulated by using the bulk scattering phase functions fitted by 128 terms of the Legendre Polynomials at wavelengths of (a) 0.55, and (b) 3.75 μm . The dust effective particle radius R_e , optical depth τ , and the solar zenith angle are 2 μm , 1.0 and 60°, respectively.

The Bidirectional Reflectances (2)



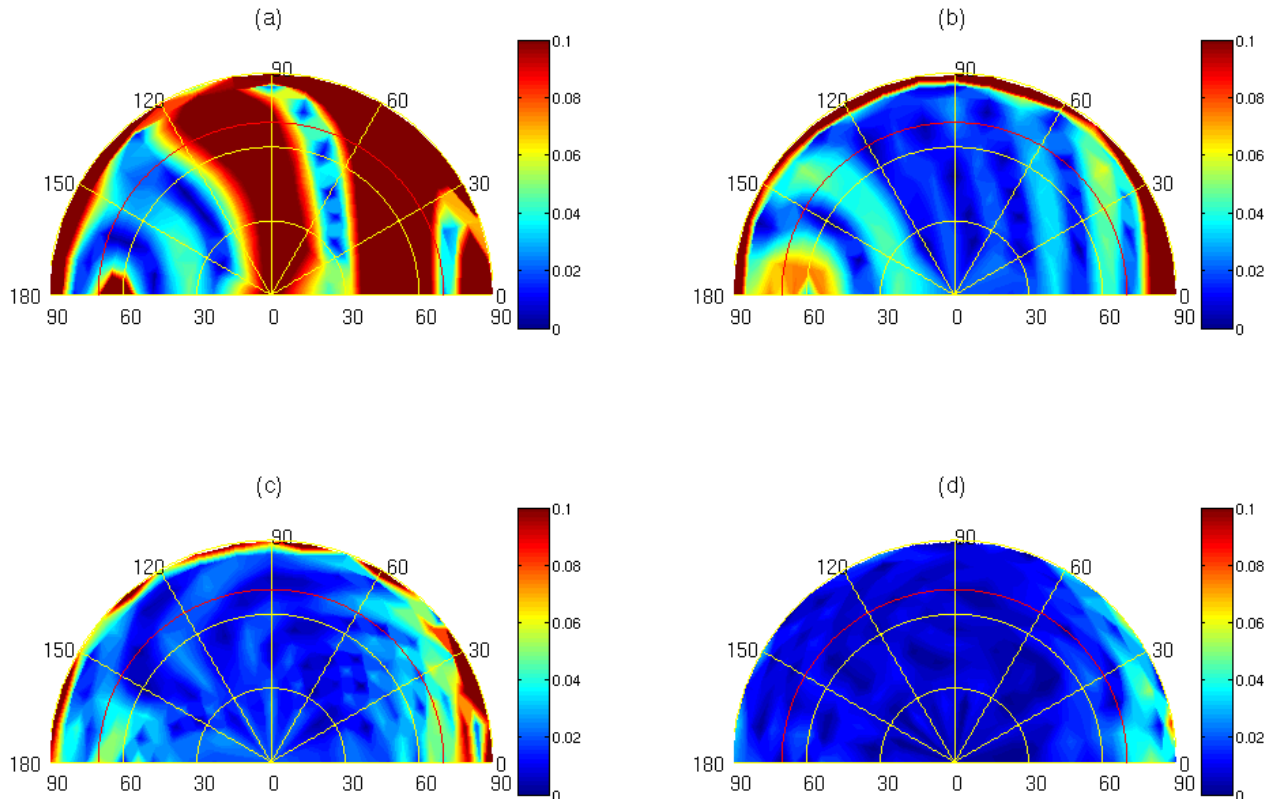
- Simulated dust aerosol bidirectional reflectances using the bulk scattering phase functions fitted by (a) 4, (b) 8, (c) 16, (d) 32 terms of the Legendre Polynomials at wavelength of $0.55 \mu\text{m}$. The dust effective particle radius R_e , optical depth τ , and the solar zenith angle are $2 \mu\text{m}$, 1.0 and 60° , respectively.

The Bidirectional Reflectances (3)



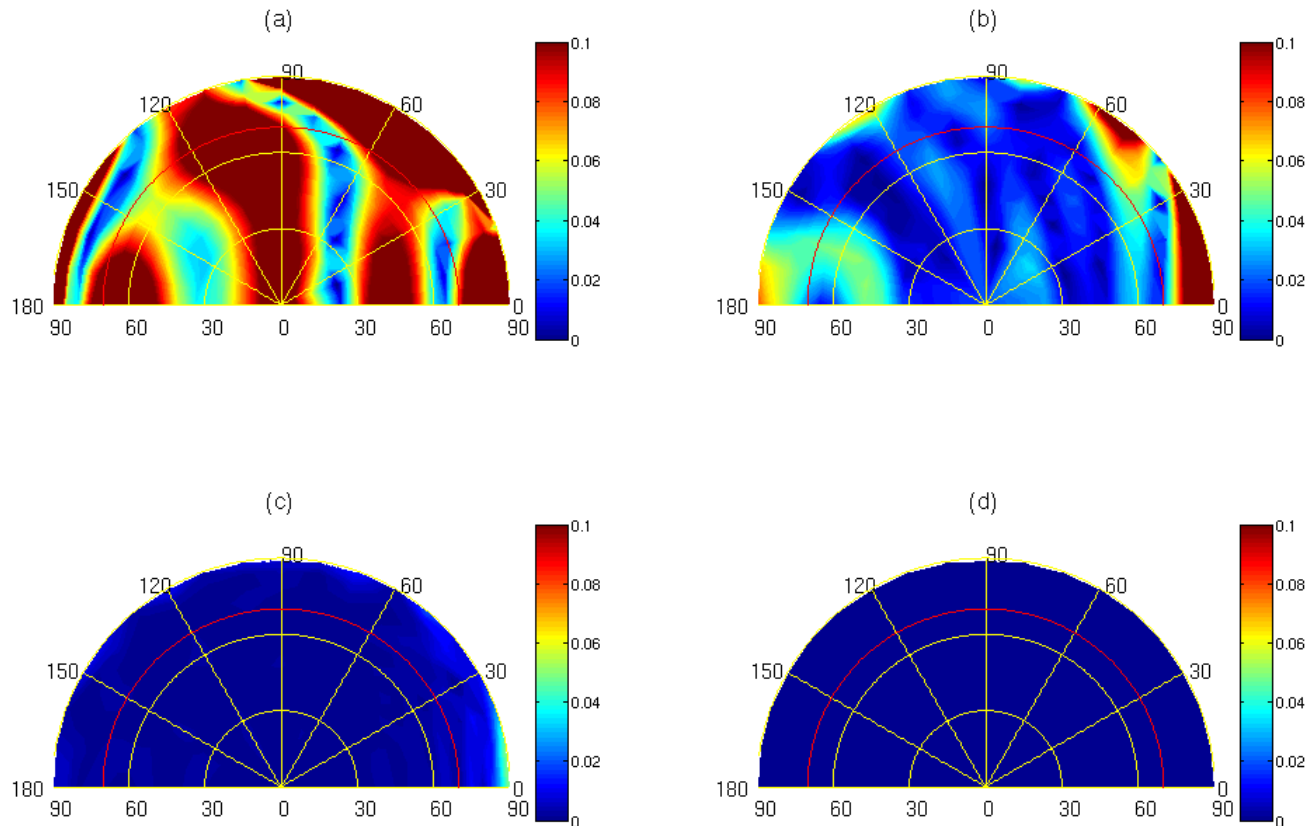
- Simulated dust aerosol bidirectional reflectances using the bulk scattering phase functions fitted by (a) 4, (b) 8, (c) 16, (d) 32 terms of the Legendre Polynomials at wavelength of $3.75 \mu\text{m}$. The dust effective particle radius R_e , optical depth τ , and the solar zenith angle are $2 \mu\text{m}$, 1.0 and 60° , respectively.

Relative Error (1)



Relative errors of bidirectional reflectances for (a) 4, (b) 8, (c) 16, (d) 32 terms of the Legendre polynomials at the wavelength of $0.55 \mu\text{m}$.

Relative Error (2)



Relative errors of bidirectional reflectances for (a) 4, (b) 8, (c) 16, (d) 32 terms of the Legendre polynomials at the wavelength of $3.75 \mu\text{m}$.

Summary

- ❑ The bulk scattering properties of nonspherical dust aerosol are computed and interpolated to 3001 wavelengths between 0.225 and 20.0 μm .
- ❑ The δ -fit method (Hu et al., 2000) is used to remove the strong forward scattering peak from the phase functions and derive the 4, 8, 16, and 32 terms Legendre polynomials at all wavelengths mentioned above.
- ❑ The bidirectional reflectance lookup tables are simulated by using the DISORT.

The single-scattering properties of ice crystals

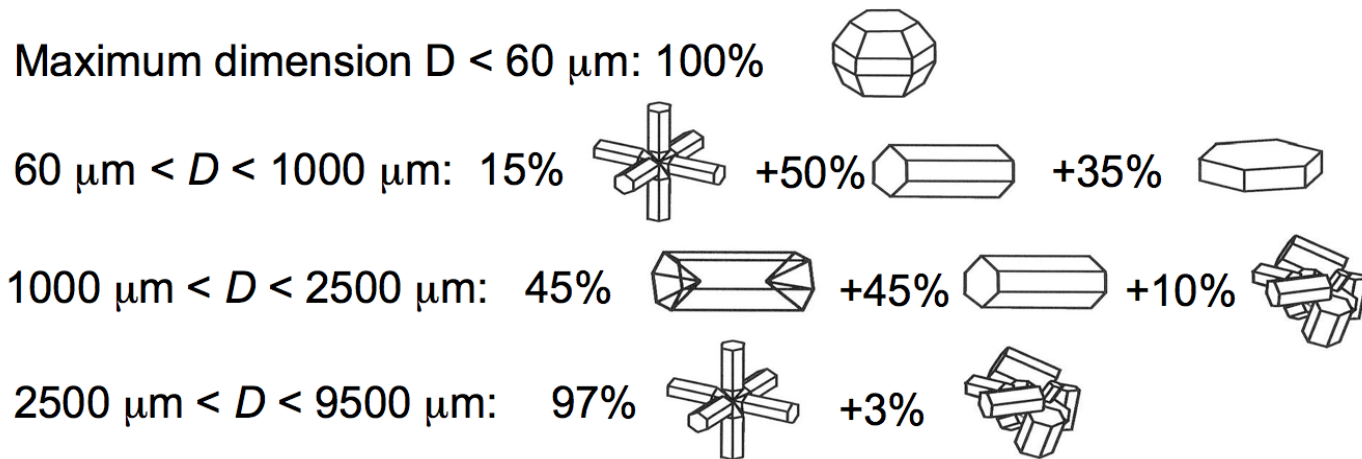
- Computed from a composite method based on the finite-difference time domain (FDTD) technique, an improved geometric-optics method (IGOM)
- The ice cloud particles include droxtals, hexagonal plates, solid columns, hollow columns, aggregates and 3D bullet rosettes with particle maximum dimensions ranging from 2 to 9500 μm
- The database contains particle volume, projected area, asymmetry factor, single scattering albedo, extinction cross section and the scattering phase function at 498 scattering angles from 0° to 180° .

Ice cloud particle size distributions

- The data of individual ice cloud particle size distributions are derived from the following five field campaigns: a) FIRE-I; b) FIRE-II; c) ARM-IOP; d) TRMM; e) CRYSTAL, which are filtered by cloud temperature to ensure that the particle is ice.

Ice clouds

The percentage of each shape used in the integration of a given property over a particle size distribution based on the particle's maximum dimension. The mixed scheme is given as follows (Baum et al., 2005):



Ice clouds

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Contours of extinction efficiency, single-scattering albedo and asymmetry factor as functions of wavelength and effective particle size for ice crystals.

Ice clouds

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are needed to see this picture.

Comparison of single-scattering phase functions for ice crystals: original phase function (black), 8-term, 16-term, and 32-term Legendre polynomial fits. $\lambda=0.65 \mu\text{m}$, $D_e=60 \mu\text{m}$.

Ice clouds

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Comparison of scattering phase functions for ice crystals: original phase function (black), 8-term, 16-term, and 32-term Legendre polynomial fits. $\lambda=12.0 \mu\text{m}$, $D_e=10 \mu\text{m}$.

The adjustment of optical properties

To achieve the same accuracy result in multiple scattering calculations with the truncated phase functions as those with nontruncated phase functions, an adjustment must be made to the optical depths and single-scattering albedos.

The adjustments of single-scattering albedo and optical depths for ice clouds include two steps:

(1) adjustment for δ transmission

$$\begin{aligned}\tau' &= \tau(1 - f\omega) \\ \omega' &= \frac{(1 - f)\omega}{1 - f\omega}\end{aligned}$$

(2) adjustment for truncation of the phase function

$$\begin{aligned}\tau'' &= \tau(1 - f_{\delta}\omega') \\ \omega'' &= \frac{(1 - f_{\delta})\omega'}{1 - f_{\delta}\omega'}\end{aligned}$$

where f_{δ} is the δ -fit truncation factor.

Ice clouds

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Simulated cloud bi-directional reflectances using the scattering phase functions fitted by (a) 4, (b) 8, (c) 16, and (d) 128 terms of the Legendre Polynomials. $\lambda=0.65 \mu\text{m}$, $D_e=10 \mu\text{m}$, $\mu_0=0.65$, and $\tau=1.0$.

Ice clouds

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Simulated cloud bi-directional reflectances using the scattering phase functions fitted by (a) 4, (b) 8, (c) 16, and (d) 128 terms of the Legendre Polynomials. $\lambda=3.75 \mu\text{m}$, $D_e=10 \mu\text{m}$, $\mu_0=0.65$, and $\tau=1.0$.

Summary

- Computed the single-scattering properties of dust aerosols and both ice and water cloud particles
- Generated bulk scattering property databases for dust aerosols and both ice and water cloud particles
- Interpolated the bulk scattering property databases to 3001 wavelengths between 0.225 and 20.0 μm
- Compared the truncated phase functions and corresponding bidirectional reflectances.

Conclusion

In order to account for the phase functions with a reasonable amount of CPU time in radiative transfer models

- 8-term Legendre polynomial expansions of the phase functions are preferred at visible and near infrared wavelengths
- 4 terms are preferred at infrared wavelengths
- More terms are needed to be truncated if the higher degree of accuracy (relative error $<1\%$) is required.

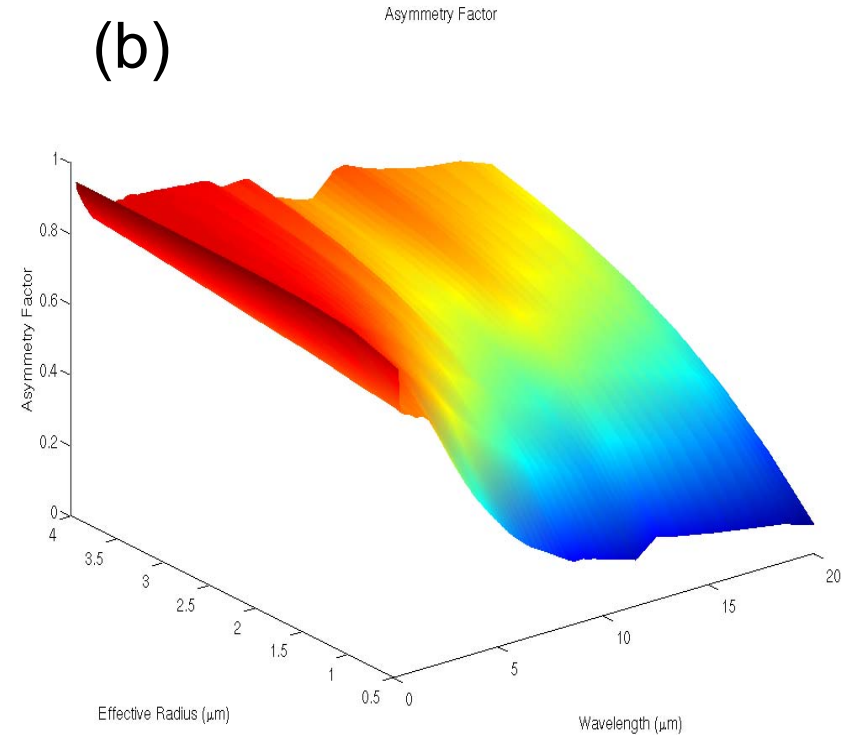
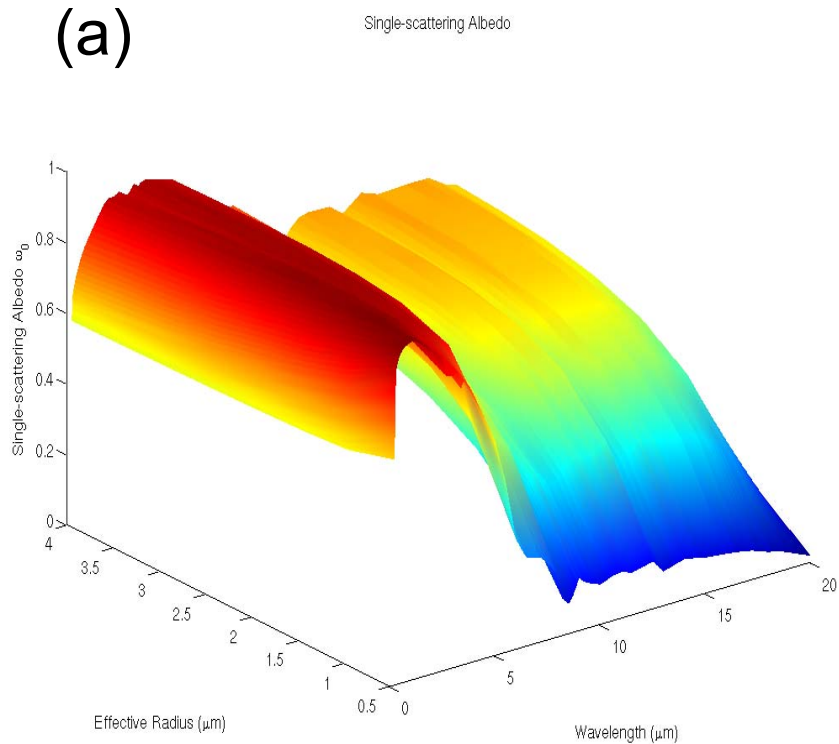
Future plan

- Re-compute single-scattering property database of ice clouds by using the latest ice refractive index data.
- Consider the roughness of ice particles
- Adding the shape distribution of spheroidal dust aerosols

Backup slides

Dust aerosol

Optical properties of nonspherical dust aerosols



Variation of (a) the single-scattering albedo, and (b) Asymmetry factor, versus wavelength and effective radius for dust aerosols.

Ice clouds

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are needed to see this picture.

Contours of brightness temperature at the top of the atmosphere as functions of the surface and cloud temperatures. $\lambda=12.0 \mu\text{m}$, $D_e=10 \mu\text{m}$, $\mu=1.0$, and $\tau=1.0$.

The single scattering properties of water droplets

- shape of water droplet is assumed to be spherical. The single scattering properties of water droplets are calculated by using Mie theory.
- The database provides single-scattering properties of water droplets over the spectral range from 0.225 and 20.0 μm , The database contains asymmetry factor, single scattering albedo, extinction efficiency, and the scattering phase functions at 498 scattering angles form 0° to 180° .

The size distribution of water clouds

- For water clouds, we employ a standard size distribution given by Hansen (1971):

$$n(r) = r^{(1-3b)/b} e^{-r/ab}$$

where $a=Re$, $b=v_{\text{eff}}$. Re is the effective radius and v_{eff} is the effective variance. Here we choose $b=0.1$. The details of the technique for the water droplet size distribution can be found in the literature of Hansen and Travis (1974).

Water clouds

Simulated bi-directional reflectances using the scattering phase functions fitted with 4, 8, 16, 32 and 128 terms of the Legendre Polynomials. $\lambda=0.65 \mu\text{m}$, $r_e=20 \mu\text{m}$, $\mu_0=0.65$, $\mu=0.65$, and $\phi-\phi_0=125^\circ$.

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Water clouds

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Simulated water cloud bi-directional reflectances using the scattering phase functions fitted with (a) 4, (b) 8, (c) 16, and (d) 128 terms of the Legendre Polynomials. $\lambda=0.65 \mu\text{m}$, $r_e=20 \mu\text{m}$, $\mu_0=0.65$, and $\tau=1.0$.

Water clouds

Contours of the brightness temperature at the top of the atmosphere as functions of the surface and cloud temperatures. $\lambda=3.90 \mu\text{m}$, $r_e=20 \mu\text{m}$, $\mu=1.0$, and $\tau=1.0$.

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