A flexible parameterization for shortwave optical properties of ice crystals

Bastiaan van Diedenhoven[1,2], Andrew Ackerman[2], Brian Cairns[2], Ann Fridlind[2]
1: Columbia University, 2: NASA Goddard Institute for Space Studies
Contact: bastiaan.vandiedenhoven@nasa.gov

1: Introduction

The fundamental radiative properties of atmospheric ice crystals for atmospheric models are the extinction cross section (σ_e), single scattering albedo (ω) and the asymmetry parameter (g). Here, we present a simple, yet accurate parameterization for σ_e, ω and g of ice crystals for any combination of

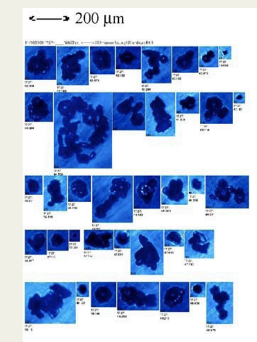
- volume
- projected area
- aspect ratio
- distortion/roughness
- at any wavelength in the shortwave

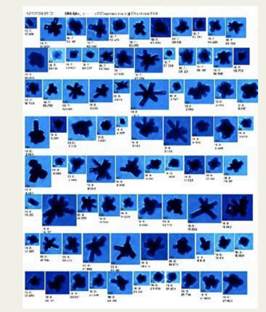
Unlike existing parameterizations, this scheme is flexible enough to obtain ice crystal optical properties that are consistent with any assumptions about ice crystal mass (equivalent to bulk volume), projected area and aspect ratio used in modern cloud and climate model ice microphysics schemes to parameterize, e.g., fall-speeds and capacitances of particles.

Main assumptions are:

- Geometric optics are valid
- Optical properties of complex, aggregated ice crystals can be well approximated by those of single hexagonal crystals with varying size, aspect ratio and distortion.

These assumptions are similar to those of previous parameterizations (e.g., Fu 1996, 2007)





More info: van Diedenhoven et al., *A flexible parameterization for shortwave optical properties of ice crystals*, J. Atmos. Sci., 2014, doi: 10.1175/JAS-D-13-0205.1.
Get the paper and a python version of the code by scanning the QR code or visit: www.columbia.edu/~bv2154/parameterization.html

2: Reference calculations

- Geometric Optics (GO) code developed by Macke et al. (1996).
- Single hexagonal plates and columns with random orientation
- The distortion parameter represents the stochastic large-scale distortion of a collection of ice crystals.
- Microscale particle surface roughness, crystal impurity and large-scale particle distortion all lead to a similar randomization of the angles between crystal facets (Hess et al. 1998, Yang et al. 2008b). Thus, the distortion used here can be considered as a proxy for the randomization of the angles between crystal facets caused by any of these effects.

3: Single scattering albedo and extinction parameterization

This diagram shows the steps to obtain the parameterization of single scattering albedo for particles with any combination of volume, projected area and aspect ratio and at any wavelength in the shortwave.

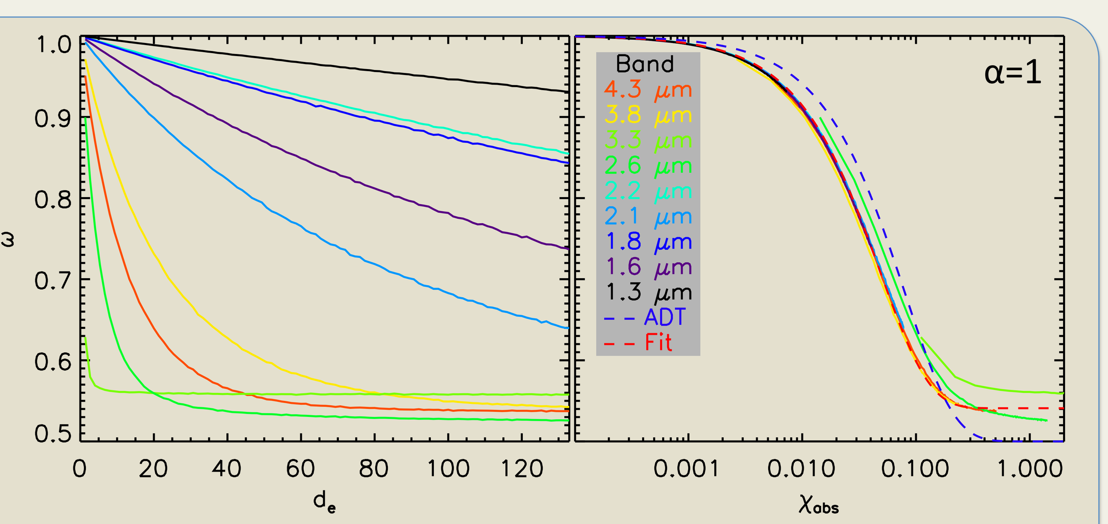
Inputs: A_p Projected area; V Volume; λ Wavelength; m_i Imaginary refractive index; α Aspect ratio

1. $\chi_{abs} = \frac{m_i V}{\lambda A_p}$
2. $\omega_{\alpha=1} = 1 - a_0(1 - e^{-a_1 \chi_{abs}})$; $a_0 = 0.457593$ and $a_1 = 20.9738$
3. $\Delta\omega_\alpha = \frac{l_0}{\sqrt{2\pi}\, l_1\, \chi_{abs}} \exp\left[-\frac{(\ln \chi_{abs} - l_2)^2}{2\, l_1^2}\right]$; $l_i = \sum_{j=0}^{3} c_{i,j} \log^j \alpha$ ($c_{i,j}$ in Table)
4. $\omega = \omega_{\alpha=1} + \Delta\omega_\alpha$
5. $\sigma_e = Q_e A_p$; $Q_e = 2$

	j	$c_{0,j}$	$c_{1,j}$	$c_{2,j}$
Plates	0	0.000527060	0.309748	-2.58028
	1	0.00867596	-0.650188	-1.34949
	2	0.0382627	-0.198214	-0.674495
	3	0.0108558	-0.0356019	-0.141318
Columns	0	0.000378774	0.390452	-2.36821
	1	0.00463283	0.420040	1.07603
	2	0.00593106	-0.0848059	-0.729980
	3	-0.00117167	0.0186601	0.232446

1-2

Single scattering albedos are often parameterized in terms of the ratio of particle volume (V) over projected area (A_p), dubbed effective distance $d_e = V/A_p$ (see left panel of figure).

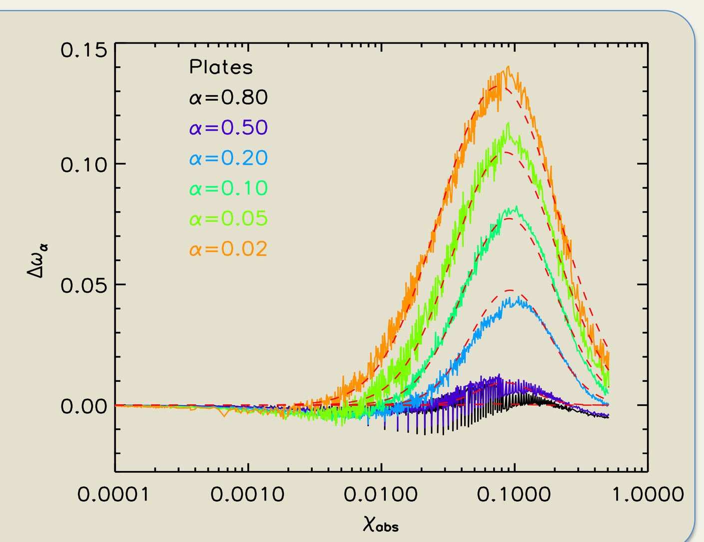


A more fundamental parameter is the absorption size parameter χ_{abs} as defined in box 1 of the diagram. The right panel shows that, for a hexagonal particle with aspect ratio α=1, ω in nearly all bands collapse to a single function of χ_{abs}. This function can be parameterized by the formula given in box 2.

3

The difference $\Delta\omega_\alpha$ between $\omega_{\alpha=1}$ at aspect ratio unity and ω at other aspect ratios (see figure) is parameterized as follows:

1. For various aspect ratios α, $\Delta\omega_\alpha$ is fit by log-normal functions in χ_{abs} with coefficients l_0, l_1, and l_3.
2. Dependence of coefficients l_i on log(α) is fit by polynomial functions for both columns (α>1) and plates (α<1), with coefficient listed in the table.

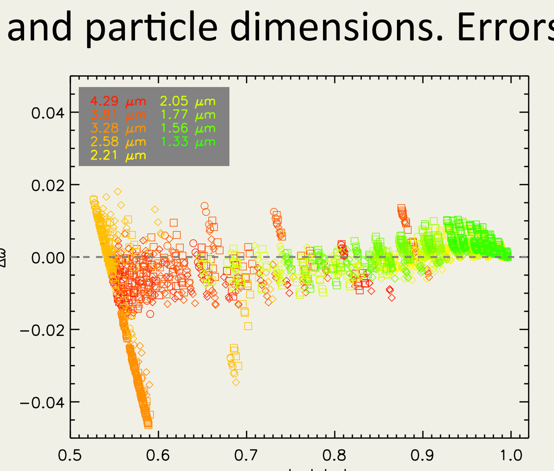


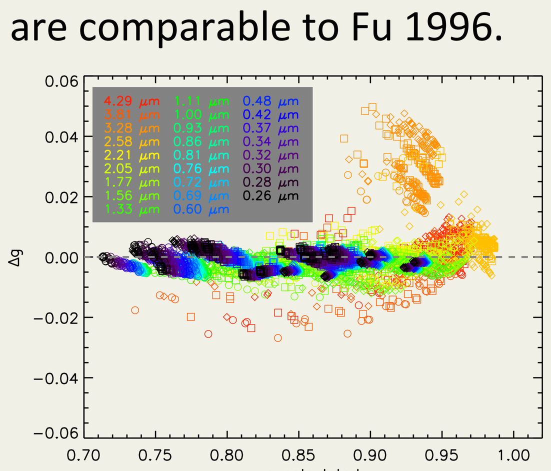
4-5

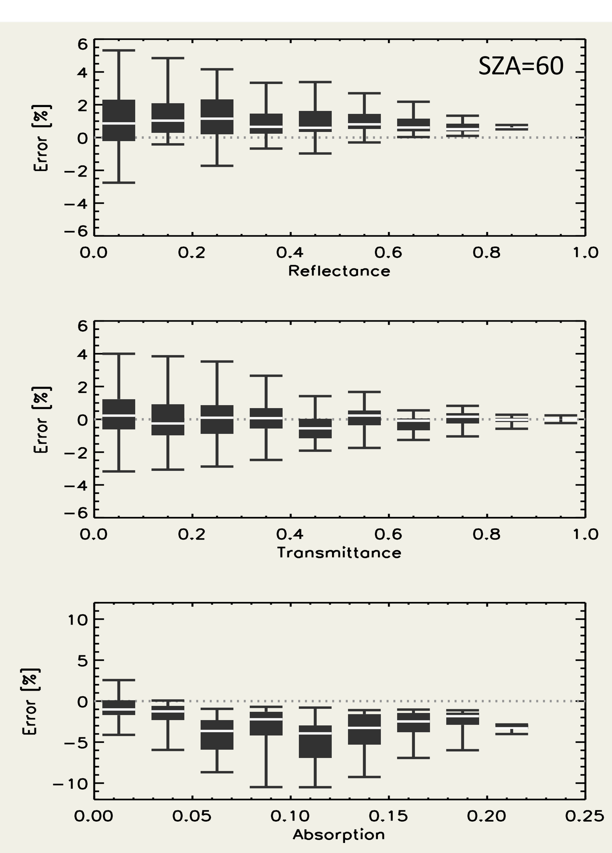
The total single scattering albedo is the sum of $\omega_{\alpha=1}$ and $\Delta\omega_\alpha$. Since we are using geometric optics, the extinction cross section σ_e is assumed to be twice the orientation-averaged projected area of the particle.

5: Evaluation

Differences with reference calculations for a wide range of particle dimensions are shown in the figures below. Only for bands with strong absorption (m_i>0.02) are substantial errors obtained. Resulting errors on shortwave fluxes are shown in the figure on the right using wide ranges of COT, size distributions and particle dimensions. Errors are comparable to Fu 1996.







4: Asymmetry parameter parameterization

This diagram shows the steps to obtain the parameterization of asymmetry parameter for particles with any combination of volume, projected area, aspect ratio and distortion and at any wavelength in the shortwave.

Inputs: λ Wavelength; A_p Projected area; δ Distortion; α Aspect ratio; ω Single scattering albedo; m_r Real refractive index

1. $\chi_{scat} = 2\pi \frac{\sqrt{A_p/\pi}}{\lambda}$
2. $g_{dif} = 1$ when $\chi_{scat} \geq 100$; $g_{dif} = b_0 \cdot e^{b_1 \ln \chi_{scat}} + b_2$ when $\chi_{scat} < 100$; $b_0 = -0.822315$, $b_1 = -1.20125$ and $b_2 = 0.996653$
3. $g_{\alpha=1} = \sum_{i=0}^{4} p_i \log^i \delta$; p_0=0.780550, p_1=0.00510997, p_2=-0.0878268, p_3=0.111549 and p_4=-0.282453
4. $\Delta g_\alpha = \sum_{i=0}^{2} p_{\Delta,i} \log^i \delta$; $p_{\Delta,i} = \sum_{j=0}^{6} q_{i,j} \log^j \alpha$ ($q_{i,j}$ in Table)
5. $g_{tot,\lambda=862\,nm} = g_{\alpha=1} + \Delta g_\alpha$; $g_{RT,\lambda=862\,nm} = 2\, g_{tot,\lambda=862\,nm} - 1$
6. $C_{m_r} = \frac{(m_{r,1} - \epsilon)}{(m_{r,1} + \epsilon)} \frac{(m_{r,2} + \epsilon)}{(m_{r,2} - \epsilon)}$; $\epsilon = c_0 + c_1 \log \alpha$; $m_{r,1}$ = 1.3038; c_0=0.960251 and c_1=0.429181 for $\alpha \leq 1$; c_0=0.941791 and c_1=-0.216010 for $\alpha > 1$
7. $C_{\omega,1} = \sum_{i=0}^{5} s_i (1-\omega)^i$; $s_0 = 1.00014$, $s_1 = 0.666094$, $s_2 = -0.535922$, $s_3 = -11.7454$, $s_4 = 72.3600$, $s_5 = -109.940$
8. $C_{\omega,2} = u \log(\alpha) \cdot (\omega - 1) + 1$; $u = -0.213038$, for $\alpha \leq 1$; $u = 0.204016$ for $\alpha > 1$.
9. $g_{tot} = \frac{1}{2\omega}\left[(2\omega - 1)\, C_{\omega,1}\, C_{\omega,2}\, C_{m_r}\, g_{RT,\lambda=862\,nm} + g_{dif}\right]$

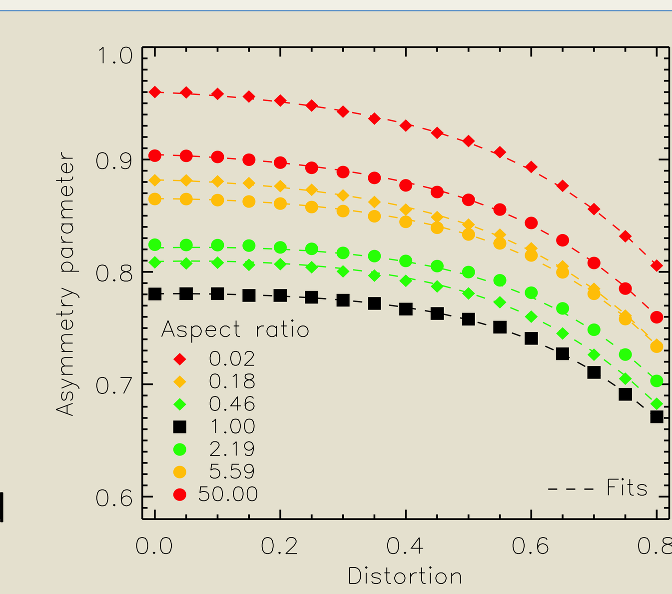
	j	$q_{0,j}$	$q_{1,j}$	$q_{2,j}$
Plates	0	-0.00133106	-0.000782076	0.00205422
	1	0.0408343	-0.00162734	0.0240927
	2	0.525289	0.418336	-0.818352
	3	0.443151	1.53726	-2.40399
	4	0.00852515	1.88625	-2.64651
	5	-0.123100	0.983854	-1.29188
	6	-0.0376917	0.187708	-0.235359
Columns	0	-0.00189096	0.000637430	0.00157383
	1	0.00981029	0.0409220	0.00908004
	2	0.732647	0.0539796	-0.665773
	3	-1.59927	-0.500870	1.86375
	4	1.54047	0.692547	-2.05390
	5	-0.707187	-0.374173	1.01287
	6	0.125276	0.0721572	-0.186466

1-2

For cloud ice crystals, the diffraction asymmetry parameter g_{dif} is generally unity. For small particles, g_{dif} is fit in terms of the scattering size parameter.

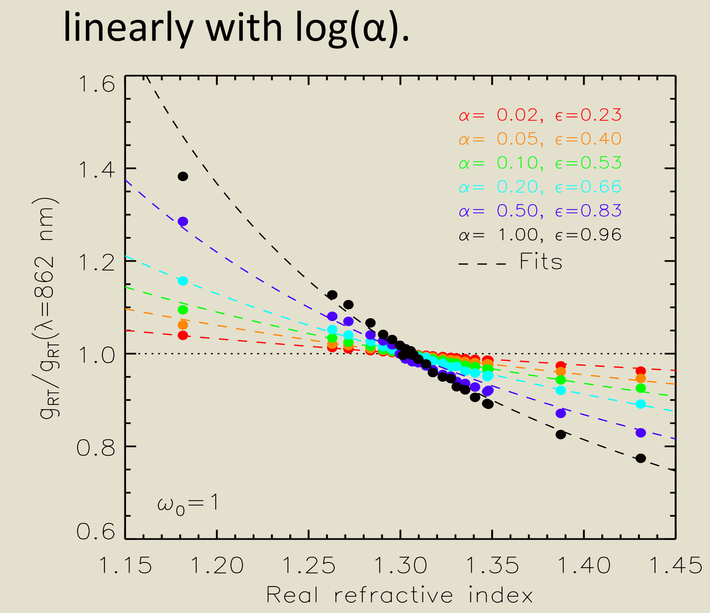
3-5

- The total asymmetry parameter g_{tot} is computed at 862 nm for various aspect ratios α and distortion values δ (symbols in figure).
- For α=1, the dependence of $g_{\alpha=1}$ on distortion is approximated by a polynomial (black line in figure).
- Differences Δg_α between $g_{\alpha=1}$ and the asymmetry parameter at other aspect ratios are approximated by polynomials in δ with coefficients $p_{\Delta,i}$.
- Dependence of coefficients $p_{\Delta,i}$ on log(α) is fit by polynomial functions for both columns and plates, with coefficient listed in the table (colored lines in figure show results).
- The ray tracing asymmetry parameter g_{RT} at 862 nm is obtained by subtracting the diffraction. (g_{dif} = 1 for these calculations).



6

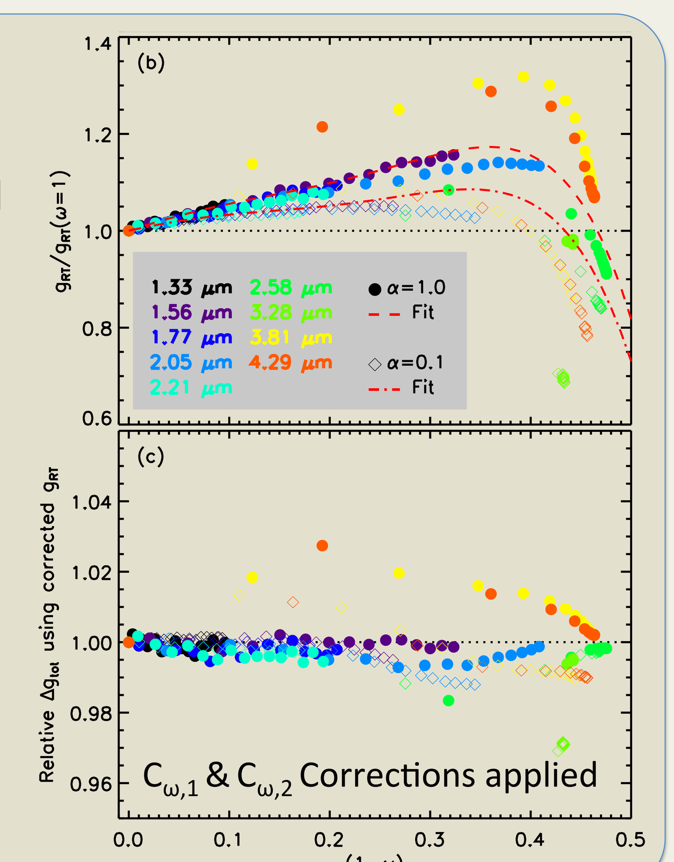
The dependence of g_{RT} on real refractive index is fit by a function inspired by the Fresnel equation for reflection. Fit parameter ε scales linearly with log(α).



7-8

For α=1, the dependence of g_{RT} on absorption ($C_{\omega,1}$) is approximated by polynomial function in (1-ω) (filled dots and dashed line in top figure).

The relative differences $C_{\omega,2}$ between the dependence of g_{RT} on absorption for other aspect ratios and $C_{\omega,1}$ is approximated by a linear function in log(α) (open dots and dashed-dotted line in top figure).



9

According to geometric optics theory, the total asymmetry parameter is obtained by summing the diffraction and ray-tracing contributions, weighted by single scattering albedo.