Understanding Effective Diameter and Its Application to Terrestrial Radiation in Ice Clouds

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Common Parameterization Approach for Ice Optics

1. Calculation of single ice crystal optical properties from electrodynamic theory, geometric optics and “bridging” parameterization.

2. Integrate (1) over selected ice particle size distributions (PSDs) to obtain PSD optical properties.

3. Relate PSD optical properties to PSD effective diameter ($D_e$) and ice water content (IWC) => parameterization

Caution: For step 3 to be valid, $D_e$ and IWC must uniquely define the PSD optical properties, regardless of PSD shape. How valid is this assumption?
1. Recent research shows that historical PSD measurements suffered from small ice particle artifacts due to shattering of ice particles on the probe inlet tube.

2. Improvements in probe design and electronic detection of shattered ice appear to have removed most of the shattering artifacts. Peak concentrations of small ice crystals are often $10^2$ times lower than historical PSD measurements indicate.

3. What effect, if any, will this change in PSD shape have on parameterized optical properties?
Experiment: Select a 2D-S measured PSD (less shattering) and compare its optical properties with PSD having the same $D_e$ but attributes of historical PSD.
Conserve ice particle shape while changing PSD shape

Derive m-D and A-D power laws from 2D-S data to conserve particle shape

TC4 aged anvil cirrus, 5 August
Ice spheres
T < –60 C
Changing the ice crystal shape changes the PSD for constant $D_e$ (red curve).

Shattering often increases small crystals by $10^2$.
Calculate optical properties for (1) measured PSD; (2) altered PSD with same particle shapes; (3) altered PSD with bullet Rosettes. All use ice optics database of Yang et al. (2005).

PSD #1 & #2 assume droxtals for optics
Extinction efficiencies for (1) measured PSD; (2) altered PSD with same particle shapes; (3) altered PSD with bullet rosettes.

![Graph showing extinction efficiencies for different PSDs.]

- PSDD #1 & #2 assume droxtals for optics
- $D_e = 39 \, \mu m$
- PSD #3 = rosettes

$Q_{ext}$ vs Wavelength (\(\mu m\))
Errors when only PSD shape changes and ice particle shapes remain constant.
Errors when both PSD shape and ice particle shape change

\[ \frac{\text{PSD\#3} - \text{PSD\#1}}{\text{PSD\#1}} \]

\( \text{PSD\#3} = \text{rosettes} \)
Physical Processes Responsible for Ice Optics Dependence on PSD Shape at Constant $D_e$

Up to ½ or more of the error can be due to differences in tunneling contributions. But where does the other error come from?
Area dependent, mass dependent, and transition absorption
Transition Absorption

Percent Absorption Error

Ice Penetration Depth (μm)

Area Dependence

Mass Dependence

D_e \sim 40 \, \mu m
$D_e = 100 \mu m$

$D_e \sim 40 \mu m$

Maximum error when penetration depth $\sim \frac{1}{2}$ to $\frac{1}{3} D_e$
CONCLUSIONS

1. Changes in PSD shape alone (while holding $D_e$ and particle shape constant) substantially affects IR ice optical properties.

2. For constant $D_e$, changing the ice particle shape assumption further changes the PSD shape, which further changes optical properties relative to the reference (i.e. measured) PSD.

3. “Transition absorption” and absorption by tunneling depend on the PSD shape in addition to $D_e$ and IWC.

4. Some GCMs treat terrestrial radiation using $\omega_o$ while others use emissivity (related to $Q_{abs}$). Errors for both quantities vary rapidly with wavelength and may introduce significant errors into both the magnitude and spectral dependence of fluxes.

5. Recent, more reliable PSD measurements may prove useful in revising existing ice cloud optics parameterizations.
6. Between 100 and 1000 µm wavelength, for the same $D_e$ and IWC, PSD extinction efficiencies and coefficients can vary by a factor of 2 or 3 (Mitchell et al. 2002). This should be considered when proposing retrieval algorithms using the MMCR.
The success of $D_e$ in cloud optics suggests this photon path concept should be found in optics theory:

$$Q_{abs} \approx 1 - \exp(-4 \pi n_i d_e / \lambda), \text{ where } d_e = V/A.$$  

For $n_i d_e / \lambda << 1$ (often true for liquid water clouds), absorption cross-section $C_{abs} = A Q_{abs} = 4 \pi n_i V/\lambda$.

For $n_i d_e / \lambda > 1$, $C_{abs} \approx A$ (often true for ice clouds in IR).

Working hypothesis: When $C_{abs} \rightarrow A$, $D_e$ looses its skill in predicting cloud optical properties.