Impacts of orientation and morphology of small atmospheric ice crystals on in-situ aircraft measurements: scattering calculations

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I. Introduction

- Sun, energy source
- Sun – cloud interaction
  - reflection
  - absorption
  - transmission
- Cloud properties vary
  - space & time
- For climate system
  - knowledge of cloud radiative properties
Cloud radiative properties depend on particle shape & size
- Low warm clouds, liquid particles spherical
- High cold clouds, ice particles non-spherical
- Mixed clouds, ice & water coexist
II. Background

- Size distribution [#/L/µm]
  # of particles in
  given sample
  volume &
  size range (bin),

Fundamental
input for
numerical
models &
retrieval
algorithms!
Size distribution [#/L/µm]
# of particles in given sample volume & size range (bin),

Fundamental input for numerical models & retrieval algorithms!

Forward scattering probe

FSSP, CDP, CAS, CPSPD, ...

Optical array probe

2D-C/P, CIP, 2DS, PIP, ...

\[ N(D) \text{[#/L/µm]} \]

\[ T = -48.63 \]

\[ N(D) \approx 50 \text{ µm} \]
Forward scattering probes

- convert intensity of scattered light measured in specific angles (e.g., 4-12° and/or 168-176°) to particle size (Mie scattering)
- shape ("sphere") and refractive index of particle
- forward scattering spectrometer probe (FSSP), Knollenberg (1972)
- 1 – 50 µm
- many different probes

FSSP, CDP, CAS,
CAS-DPOL,
CPSPD,
Fast FSSP (FFSSP),
Fast CDP (FCDP)
- **Forward scattering probes**

  Measured scattered light (i.e., scattering cross section) -> Conversion table -> Particle size

  Generate using Mie theory assuming “spherical” particles with known refractive index
- Spherical shape
- Different refractive index
  
  ice (n_r=1.31) &
  liquid (n_r=1.33)
**Forward scattering probes**

- Spherical shape
- Different refractive index
  - ice \((n_r=1.31)\) & liquid \((n_r=1.33)\)
- Multiple solutions
  (i.e., \(D_{\text{max}}\))
  for scat. cros. sec.

This is known problem
(<50%) due to spherical shape.

Nonspherical shape?
II. Key Challenge

- **Nonspherical ice crystals**
  - ice crystals can be spherical shape (fresh, homogeneous freezing),
  - most cases nonspherical shapes
  - hexagonal shapes are fundamental (hexagonal lattice structure)
  - 60% hexagonal shapes (AIDA chamber experiment, Schnaiter et al. 2012)

![Hexagonal crystal](image)

- Spherical frozen droplet becomes hexagonal column crystal
- Aspect ratio ($L/W$) depends on $T$
- Gonda and Yamazaki (1984)

Fig. 1 An example of ice crystals grown from frozen cloud droplets at $-15^\circ$C and a supersaturation of 1–2%.
(a) 2.0, (b) 2.2, (c) 2.7, (d) 3.2, (e) 4.0, (f) 4.7 min.
III. Key Challenge

- **Nonspherical ice crystals**
  - ice crystals can be spherical shape (fresh, homogeneous freezing), most cases nonspherical shapes
  - hexagonal shapes are fundamental (hexagonal lattice structure)
  - 60% hexagonal shapes (AIDA chamber experiment, Schnaiter et al. 2012)

- Few studies (Borrmann et al. 2000; Meyer 2012) have tested uncertainty in forward scattering probes due to nonsphericity of ice crystals, show < 20% error based on $T$-matrix calculations using cylinder or spheroid!
- Impact of nonsphericity have to be quantified with realistic shape!

Aspect Ratio (AR) = \( \frac{L}{W} \)

\( AR = 0.10, 0.25, 0.50, 1.00, 2.00, 4.00 \)

Thin Plate

Long Column

width, \( W \): up to 20 \( \mu m \)

length \( L \): up to 48 \( \mu m \)

- Amsterdam Discrete Dipole Approximation (ADDA)
- Um and McFarquhar (2015, JQSRT)
- Um et al. (2015, ACP)

- Scattering phase matrix
- Forward & backward scattering cross section of CAS

- Assign each or group of dipoles to cores of BW
IV. Accomplishments

New conversion tables
Impact of orientation
- Difference in diameter b/n Mie ice and nonspherical crystals, mean+-stddev
- Up to 72% (170%) in forward (backward) scattering direction
- Increase with nonsphericity (i.e., departure from compact shape)
- Larger than those (<20%) with spheroid or cylinder
Impact of particle orientation

- Scattering properties of nonspherical particle depend on its orientation

- Measurement $< 1.0 \mu\text{sec}$

- Certain orientation!

**Forward scattering (4-12°)**

Baumgardner et al. (2017)
Impact of particle orientation

Scattering properties of nonspherical particle depend on its orientation

Measurement $< 1.0 \mu$sec

Certain orientation!

Large variations in $P_{11}$

Baumgardner et al. (2017)
- Impact of particle orientation
- Scattering properties of nonspherical particle depend on its orientation
- Measurement $< 1.0 \, \mu\text{sec}$
- Certain orientation!
- Large variations in scattering properties
- Euler $\alpha$, $\beta$, $\gamma$ for orientation
- Quasi Monte Carlo method
- 1000 selections of $\beta$ & $\gamma$
- Um and McFarquhar (2013; 2015)
- Impact of particle orientation
- Scattering properties of nonspherical particle depend on its orientation
- Measurement < 1.0 μsec
- Certain orientation!
- Large variations in scattering properties
- Euler $\alpha$, $\beta$, $\gamma$ for orientation
- Quasi Monte Carlo method
- 1000 selections of $\beta$ & $\gamma$
- Um and McFarquhar (2013; 2015)
- $L=48$ μm, $W=12$ μm
- 45 BW XE nodes
- ~28 hours/orientation (hard to get discount!)
- 460 GB mem/orientation
- $45 \times 28 \times 1000 = 1.26$ M node hours
- Impact of particle orientation

- Scattering properties of nonspherical particle depend on its orientation

- Measurement < 1.0 $\mu$sec

- Certain orientation!

- Large variations in scattering properties

- Euler $\alpha, \beta, \gamma$ for orientation

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- $L=48 \, \mu$m, $W=12 \, \mu$m

- 45 BW XE nodes

- ~28 hours/orientation (hard to get discount!)

- 460 GB mem/orientation

- 45 X 28 X 1000 = 1.26 M node hours

- Errors, up to 515% (790%) in forward (backward) scattering direction due to impact of orientation!
Summary & Future Work

- Up to 72% (170%) in forward (backward) scattering direction, increase with nonsphericity (i.e., departure from compact shape)
- Up to 515% (790%) in forward (backward) scattering direction due to orientation of nonspherical shape
- New conversion table is required!
- Building new conversion table (+ polarization) using BW

![Graphs showing depolarization ratio for different shapes](image)

**Linear depolarization ratio**

- **AR=4.0**
- **L=10 \( \mu \text{m} \)**
- **W=2.5 \( \mu \text{m} \)**
- Forward scattering probes

- measured intensity of scattered light is
  “differential scattering cross section”

\[ C_{\text{sca},\theta} = \frac{1}{k^2} \int_0^{2\pi} \int_{\theta_1}^{\theta_2} P_{11} \sin(\theta) d\theta d\phi \]

- CAS
  \[ \theta_1 = 4^\circ \text{ & } \theta_2 = 12^\circ \text{ forward} \]
  \[ \theta_1 = 168^\circ \text{ & } \theta_2 = 176^\circ \text{ backward} \]

- \( P_{11} \): scattering phase function
- spherical shape
- different refractive index
  ice ($n_r=1.31$) & liquid ($n_r=1.33$)
- multiple solutions
  (i.e., $D_{\text{max}}$)
  scat. cros. sec.
  $D_{\text{max}} < 10 \ \mu\text{m}$
- linear fitting,
- avg. over solutions
Forward scattering probes

- Errors due to Mie scat.
even for spherical shape
- $> \pm 20\% \ (D_{\text{max}} < 10 \ \mu m)$
- $< 10\% \ (10 < D_{\text{max}} < 30 \ \mu m)$
- $< 15\% \ (D_{\text{max}} > 30 \ \mu m)$
using “best fitting curve”

This is known errors due
to Mie scattering of
“spherical” particles.

What about ice crystals?
“Non-spherical!”

![Convs. table]
- Nonspherical crystal, Mie sph. liquid, Mie sph. ice, different AR for each panel