Progress in simulating the optical properties of ice clouds and graupel/Snow in support of the CERES Science Team

James Coy, Jiachen Ding, Masanori Saito

Ping Yang (presenting author)

Texas A&M University
An Ice clouds model is needed for remote sensing implementation and flux computation.

A consistent Ice optical property model is essential to a reliable estimation of fluxes at the surface and TOA from satellite observations.

Ice cloud property retrieval
- Passive shortwave measurements
- Passive thermal infrared measurements
- Lidar measurements

Broadband RT calculation
- Radiative parameterization
- Mass-diameter relationship

Loeb, Yang et al., 2018 JClim
Flux Biases due to neglecting LW scattering

An Improved Two Habit Model (THM)

- Major updates in the improved THM
  1. The improved THM uses an ensemble of 20 irregular hexagonal columns with a tilting parameter \((\sigma_t)\) of 0.15 instead of a severely roughened hexagonal column \((\sigma_r = 0.5)\) used in current Current THM (Loeb, Yang et al., 2018). This choice is to avoid some challenges in light scattering computations concerning ice crystal’s surface roughness.
  2. Substantial improvement in backscattering resulting from using rigorous calculations.
  3. Refined the geometry of 20-column aggregates.

Loeb, Yang et al., 2018 JClim
An Improved Two Habit Model (THM)

- Same size-dependent, a continuous mixing ratio similar to the current THM (Loeb et al., 2018).
- A preliminary version of an improved THM database has been developed.
- Uses Volume-Projected Area Equivalent Diameter ($D_{VA}$) size characterization.

$$D_{VA} = \frac{3V_p}{2A_s}$$  

$V_p$: Particle volume  
$A_s$: Projected area

$$f_{single} = \begin{cases} 
    e^{-0.005(D_{VA}-30)}, & D_{VA} \geq 30 \\
    1, & D_{VA} < 30 
\end{cases}$$

<table>
<thead>
<tr>
<th>Habit 2</th>
<th>Habit 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{aggregate} = 1.0 - f_{single}$</td>
<td></td>
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<table>
<thead>
<tr>
<th></th>
<th>Current THM</th>
<th>Improved THM (preliminary version)</th>
<th>Improved THM (final version)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>470 bins (0.2 – 200 µm)</td>
<td>42 bins (0.2 – 20 µm)</td>
<td>470 bins (0.2 – 200 µm)</td>
</tr>
<tr>
<td>Size</td>
<td>189 bins (2.0 – 10000.0 µm)</td>
<td>59 bins (2.0 – 1000.0 µm)</td>
<td>189 bins (2.0 – 10000.0 µm)</td>
</tr>
</tbody>
</table>
The single column ensemble of the improved THM has $\sigma_t = 0.15$.

- $\sigma_t = 0.50$ results in inconsistent magnitudes of the extinction efficiency ($Q_{ext}$) compared to severely roughened hexagonal columns ($\sigma_r = 0.50$).
- A smaller $\sigma_t$ results in more consistent magnitudes of $Q_{ext}$.
- Further investigation would need to further optimize $\sigma_t$ for irregular single column ensemble.
Development of an improved THM involves a huge burden from the perspective of numerical computation; in particular, PGOM is computationally expensive for 20-column aggregate calculations.

- Combination of IGOM calculations and PGOM-based backscattering parameterizations
  - IGOM calculations: Entire scattering angle range.
  - Parameterization: Correct IGOM calculations for $170^\circ - 180^\circ$ scattering angles.
Improvement in Backscattering

- The backscattering enhancement ($\xi_{PGOM}(\theta)$) is parameterized with the Cauchy distribution ($F(\theta)$):

$$\xi_{PGOM}(\theta) = \frac{P_{11,PGOM}(\theta)}{P_{11,PGOM}(170^\circ)} = 1 + F(\theta) - F(170^\circ), \quad (1)$$

where

$$F(\theta) = c_1 \frac{1}{\{c_2 \pi \left(1 - \frac{\theta}{180^\circ}\right)\}^2 + 1}. \quad (2)$$

- $\theta$ is the scattering angle, ranged from $170^\circ - 180^\circ$; $P_{11,PGOM}$ is the PGOM calculated $P_{11}$ phase function; and $c_1$ and $c_2$ are parameters represented as:

$$c_1 = d_1 \ast \left[1 - \tanh(a_0 \ast V_{abs} + a_1)\right] \quad (3)$$

$$c_2 = d_0 \ast kD \quad (4)$$

- $kD$ is the size parameter and $V_{abs}$ is dependent on the imaginary part of the refractive index ($m_i$) and $kD$.

- $d_0$, $d_1$, $a_0$, and $a_1$ are constants estimated from regressions.
• With optimized coefficients of the parameterization, the phase function is obtained from

\[ P_{11,\text{enhanced}}(\theta) = \xi_{\text{PGOM}}(\theta) \times P_{11,\text{IGOM}}(\theta) \]  

• \( P_{11,\text{enhanced}} \) has been shown to be fairly consistent with PGOM calculations.

• Reduced substantial computational burden

→ Feasible to develop the future THM single-scattering property database that covers entire size and spectral ranges.
The backscattering enhancement is applied to single column and 20-column aggregate ensembles separately.

After the application, the THM database calculations are conducted.

Bottom figure shows THM $P_{11}$ between single column and aggregate $P_{11}$s at $D_{VA} = 100 \ \mu m$.

THM backscattering is shown to be enhanced compared to IGOM-only.
Active–Passive Consistency Check

IIR=Imaging Infrared Radiometer; COT=Cloud Optical Thickness

Improved THM has reasonably robust backscattering, leading to consistency between passive and active COT retrievals.
Cirrus cloud climatology

- Lidar + IR signals show sensitivity to the whole range of cirrus cloud COT (e.g., $\tau = 0 - 3.6$).

- Decreased average COT for cirrus clouds where optically thin clouds ($\tau < 0.1$) are dominant due to sufficient sensitivity of lidar measurements to these optically thin clouds.

Physics-based active-passive synergistic retrievals of ice cloud properties

CTT $< -40^\circ$C
COT $< 3.6$
Single-layer ice

IR-only retrievals
IR + lidar retrievals
Are ice cloud optical property models applicable to graupel/snowflakes?

→ No, they are not applicable due to various ice mass density values. We need to develop realistic graupel/snow models.
Step 1: generate random points in a certain shape
Step 2: cluster points into some random groups
Step 3: create a convex polyhedron for each point group
Examples: Graupel

Spherical

Conical

Ice mass ratio (MR):

0.1  0.3  0.5  0.7  0.9

Gergely et al. 2017
Examples: Snowflake

Plate

Dendrite

Ice mass ratio (MR):

0.2 0.3 0.5 0.7 0.9

Gergely et al. 2017
IGOM computations

Maximum dimension: 5 mm
Wavelength: 355 nm

Asymmetry factor - Graupel

![Graph showing the asymmetry factor for Graupel with two datasets: Conical and Spherical. The graph plots Ice Mass Ratio on the x-axis and g on the y-axis. The Conical dataset is represented by filled green circles, and the Spherical dataset is represented by red stars.](image-url)
IGOM computations

Maximum dimension: 1 mm
Wavelength: 355 nm
Different Ice Mass Ratio (MR)

Maximum dimension: 5 mm

Wavelength: 355 nm

Conical shapes

Phase matrix
Different Ice Mass Ratio (MR)

Maximum dimension: 1 mm

Wavelength: 355 nm

Dendrite shapes
Different Shapes - Graupel

Maximum dimension: 5 mm
Wavelength: 355 nm
Mass ratio: 0.9
Different Shapes - Snowflake

Maximum dimension: 1 mm
Wavelength: 355 nm
Mass ratio: 0.7

Phase matrix

- $P_{11}$
- $P_{12}/P_{11}$
- $P_{22}/P_{11}$
- $P_{33}/P_{11}$
- $P_{43}/P_{11}$
- $P_{44}/P_{11}$

Graphs showing the variation of phase matrix elements with scattering angle.
Summary and Future Plan

Development of a new ice crystal optical property database is in progress:
- An improved THM
  - Improved ice crystal shape models
  - Improved backscattering computations
  → Active–passive sensor-based retrieval consistency
- Graupel/Snow crystal model
  - Realistic graupel/snow particle shape models
  - Various ice mass density ratios
  → The single-scattering properties of graupel/snow are realistic.
- Near future plan:
  1. Deliver a preliminary improved THM database
  2. Extensive validations and application studies
  3. Develop a database of graupel/snowflakes