Updates on the Two Habit Model Optical Property Database: Full Resolution and Improvements Compared to Previously Developed Databases

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Importance of Ice Cloud Particle Models

- Ice cloud properties still least understood atmospheric parameters in remote sensing and radiative transfer calculations due to uncertainties in ice cloud microphysical and optical properties.

- **Ice cloud particle models** help to describe microphysical (e.g., particle habit) and optical properties (e.g., scattering phase matrix) of ice clouds.
  - These properties are fundamental to applications in remote sensing, radiative transfer, and general circulation models.
  - New ice cloud particle models being developed/improved upon to provide more accurate downstream calculations.

Loeb et al., 2018
Reasons for a new Two-Habit Model Database

- Observations of ice particles that comprises ice clouds show that particles can be irregularly shaped rather than being idealized such as a hexagonal column.
- Conventional particle size classification of maximum dimension do not represent irregular particle shapes leading to physical and optical inconsistency.
- Previously developed Two-Habit Model databases lack accurate backscattering which is important for applications for lidar-based radiative transfer simulations.

Weak Backscattering for non-absorbing wavelengths
Reasons for a new Two-Habit Model Database

• The Two-Habit Model (THM) follows the Thompson et al. 2008 cloud ice scheme than other commonly used single-scattering databases.

• Improvements to the THM should maintain the consistency with the cloud ice scheme.
Recap: Preliminary New Two Habit Model

- Same size-dependent, and continuous mixing ratio as the last version THM (Loeb et al., 2018) (Figure 1a).
- New 60-particle ensemble of distorted single columns.
- Volume-projected area equivalent sphere diameter ($D_{VA}$) size characterization (Figure 1b).
- Physical Geometric Optics Model (PGOM)-based enhanced backscattering calculations applied to existing Improved Geometric Optics Model (IGOM) single-scattering calculations (Figure 1c).

\[
f_{\text{single}} = \begin{cases} 
e^{-0.005(D_{VA} - 30)}, & D_{VA} \geq 30 \mu m \\ 1, & D_{VA} < 30 \mu m \end{cases}
\]

\[
f_{\text{aggregate}} = 1.0 - f_{\text{single}}
\]

\[
D_{max} = \frac{3V}{2A_p}
\]

$V$: Particle volume

$A_p$: Projected area

<table>
<thead>
<tr>
<th>Preliminary THM (Version 3)</th>
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<tbody>
<tr>
<td>Wavelength</td>
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<tr>
<td>42 bins (0.2 – 20 µm)</td>
</tr>
<tr>
<td>Size</td>
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<tr>
<td>59 bins (2.0 – 1000.0 µm)</td>
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THM Computation Methods

- Invariant Imbedding T-Matrix Method (II-TM)
- IGOM with PGOM backscattering enhancement

THM: Two Habits Model

1a: Same size-dependent, and continuous mixing ratio as the last version THM (Loeb et al., 2018) (Figure 1a).
1b: New 60-particle ensemble of distorted single columns.
1c: Volume-projected area equivalent sphere diameter ($D_{VA}$) size characterization (Figure 1b).

IGOM: Improved Geometric Optics Model

PGOM: Physical Geometric Optics Model
Recap: THM New Size Characterization

- Upon transitioning from roughened particle to distorted particle ensemble, $D_{\text{max}}$ size characterization results in optical and physical inconsistency (Warren and Grenfell, 1999).
  - Particle distortion causes changes in particle volume and projected area.
- 3 other size characterizations considered for replacing $D_{\text{max}}$.
  - Volume-projected area equivalent sphere diameter ($D_{VA}$) selected to replace $D_{\text{max}}$ as new size characterization for new THM (Figure 2).

\[
D_{vol} = \left(\frac{6}{\pi} V_{\text{particle}}\right)^{1/3}
\]

\[
D_{VA} = \frac{3V_{\text{particle}}}{2A_{\text{particle}}}
\]

\[
D_{\text{sur}} = \left(\frac{6}{\pi} S_{\text{particle}}\right)^{1/2}
\]

Extinction Efficiency ($Q_{\text{ext}}$) Size Characterization Comparison

- $\lambda = 0.80 \mu m$
  - Roughened, $\sigma^2 = 0.15$
  - Distorted Ensemble, $\sigma^2 = 0.15$
Recap: PGOM-Based Backscattering Enhancement

• PGOM provides accurate backscattering calculations but significantly more computationally demanding than IGOM and IITM.
  
  o PGOM fully considers the vector properties and phase difference characteristics of ice particles while IGOM summarizes it for faster computation time.

• The PGOM-based backscattering enhancement, calculated from lookup table from selected refractive indices and size parameters, was applied to the preliminary THM.

3a
THM IGOM-only P11 vs. THM IGOM/PGOM-merged P11

3b
THM PGOM-enhanced P11 vs. THM IGOM/PGOM-merged P11

\[ \lambda = 0.40 \, \mu m \]
\[ D_{VA} = 200 \, \mu m \]
Recap: Major Changes in Lidar-based Radiative Transfer Simulations

- Conducted lidar-based radiative transfer simulations utilizing CALIOP/CALIPSO data and the cloud optical thickness (COT) – integrated attenuated backscattering (IAB) retrieval approach.
  - Validate changes in simulation results for non-absorbing wavelengths (532 nm) caused by using the new THM with enhanced backscattering.
- New Preliminary THM showed significantly higher IAB for larger effective radii and COT.
  - New THM reveals more COT information in the COT – IAB retrieval approach.
Recap: Preliminary THM Active – Passive Consistency Check

- 532 nm CALIOP/CALIPSO IAB and 8.65, 10.6, and 12.05 µm IIR/CALIPSO Split-Window technique COT retrieval methods utilized to validate active-passive consistencies between the previous and preliminary THM databases.
- New THM showed to achieve active-passive consistency in COT retrievals due to more IAB COT information provided by improved backscattering.

![Graphs comparing CALIOP/CALIPSO and IIR/CALIPSO COT values between THMv2 and THMv3.](image-url)
Current Progress: Full Resolution THM Developed

- Full resolution THM database has been developed.
  - 60-particle irregular single column and 20-particle irregular 20-column aggregate ensembles.
  - Volume-projected area equivalent sphere diameter size characterization.
  - Same wavelength and size resolution and range as previous THM.
  - Only IGOM calculations for size parameters > 25.

<table>
<thead>
<tr>
<th>New THM (Version 3)</th>
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<tr>
<td>Wavelength</td>
<td>470 bins (0.2 – 200 µm)</td>
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<tr>
<td>Size</td>
<td>189 bins (2.0 – 10000.0 µm)</td>
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THM Computation Methods

- Invariant Imbedding T-Matrix Method (II-TM)
- Improved Geometric Optics Method (IGOM)
Absorptive wavelengths at about 2.9, 11, and 46 µm have significantly low extinction efficiencies, single-scattering albedo (Figure 8a) (due to sharp declines in real part of refractive index).

Most significant THM version differences in extinction efficiency (Figure 8b).

- Likely caused by small particle habit change and IITM calculation size parameter limit reduction (THMv2 IITM < 40; THMv3 IITM < 25).
• Bulk scattering calculations with effective radius eliminate obvious size characterization differences between the two THM versions.
  o Reveals how irregular single column ensemble affected results.
• For small wavelengths (< 4 µm), bulk $Q_{\text{ext}}$ (Fig. 9a) for THMv3 less sensitive to absorptive wavelengths.
• THMv3 bulk $\omega$ (Fig. 9b) slightly greater than THMv2 throughout nearly all wavelengths (except shortwave).
• THMv3 bulk $g$ (Fig. 9c) slightly less than THMv2 for nearly all wavelengths.
• Overall, distorted single column ensemble more reflective and less sensitive to absorptive wavelengths.
Current Progress: Lidar Version of New THM In Development

- Performing PGOM calculations for the full resolution THM not computationally feasible.
  - Each PGOM calculation takes around 10 min – 1 hour to complete for each wavelength and size.
  - Using backscattering enhancement parameterization like in preliminary THM likely to lead to errors.
- Want to focus on wavelengths commonly used for lidar applications.
  - 355, 532, and 1064 nm considered for the lidar version of the new THM.
  - Will use PGOM calculations to replace IGOM-calculated backscattering region (160 degrees and greater).

### Lidar THM

| Wavelength | 3 bins (355, 532, 1064 nm) |
| Size       | 189 bins (2.0 – 10000.0 µm) |
Since the new THM has higher backscattering, the denominator of the lidar ratio will be higher thus reducing the ratio value.

The THMv3 532 nm lidar ratio ranges from 30 – 40 sr.
- In agreement with Seifert et al. 2007: lidar ratio of 29 – 33 sr over Indian Ocean.
- In agreement with Josset et al. 2012: lidar ratio of 33 ± 5 sr over the global ocean.

Lidar Ratio

\[ S = \frac{4\pi}{\omega_{\text{bulk}} P_{11,\text{bulk}}(180°)} \]

\( \omega_{\text{bulk}} \): bulk single-scattering albedo
\( P_{11,\text{bulk}} \): bulk scattering phase function
Summary

• Successfully developed the full resolution new THM with a new size characterization and particle habit change.
  o Bulk scattering calculations indicate no abnormalities in the new THM.
  o Testing/validation will be conducted using the database in remote sensing applications and broadband radiative transfer simulations.

• Lidar version of the THM is currently in development and will be completed in June.
  o Will demonstrate the improvements in retrievals provided by the accurate PGOM backscattering calculations.
  o Will be compared against the previous THM and a lidar version of the Fu 1996 database that will also have PGOM backscattering calculations.
References


