Evaluation of Satellite Imager Ice Cloud Retrievals using CALIPSO and CloudSat Data

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Background

- Satellite remote sensing of ice cloud radiative and microphysical properties requires assumptions regarding shape and size distribution of ice particles.
- CERES cloud algorithms continue to evolve as we gain better understanding of ice clouds and of our retrieval uncertainties based on comparisons with other data (e.g. active sensors, in situ).
- Daytime solar reflectance methods assuming single habit smooth and roughened hexagonal columns both appear to overestimate optical thickness (which leads to height underestimates for optically thin clouds).
- But, nighttime estimates (COT, Z_t) are quite good.

Need more representative ice crystal models and optical properties to improve daytime ice cloud properties and improve spectral (day/night) consistency.
Objectives

• Test passive sensor retrievals derived using 3 ice scattering models
  1) SHM - single habit model (smooth hexagonals)
  2) SHM - single habit model (roughened hexagonals)
  3) THM - two habit model (roughened hexagonals + aggregates)
• Evaluate passive satellite sensor ice cloud properties with CALIPSO/Cloudsat data
• Focus on cirrus: COT, Z, IWP
DATA

**Passive Sensor**
- **CERES GEO** cloud properties (Feb 2017)
  - Himawari-8
  - 1-hr temporal resolution
  - Subset to 6-km spatial res
  - +/-15 min of CALIPSO obs

**Active Sensor**
- **CALIPSO** V4.10 5-km Cloud Layers products
  - Optical depth and IWP for $\tau < \sim 3$
  - Cloud heights also from 333-m CLAY
- **Cloudsat 2C-ICE (P1_R04)** (Future Work!!)
  - Combines CALIPSO/CloudSat in variational analysis
  - Retrieves wider range of $\tau$
CERES Ice Crystal Models for MODIS and GEO Cloud Retrievals

<table>
<thead>
<tr>
<th>Ice cloud particle model</th>
<th>CERES edition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth hexagonal columns</td>
<td>Ed2.0 and Ed3.0</td>
</tr>
<tr>
<td>Roughened hexagonal columns</td>
<td>Ed4.0</td>
</tr>
<tr>
<td>Two-habit model</td>
<td>Ed5.0 (planned)</td>
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</tbody>
</table>

- Smooth and Roughened are single habit models assuming hexagonal columns with various sizes and aspect ratios.
- Roughened model smooths out the scattering maxima and peaks, leading to a featureless phase function, smaller retrieved COT and larger retrieved particle size compared to Smooth.
- New two habit model combines roughened columns with ensemble of aggregates as shown.
A few other details

- THM uses continuous particle size distributions (discrete PSD’s used in SHM versions)
- THM development guided by comparisons with in situ measurements (IWC, $D_{\text{median-mass}}$)

REFERENCES

Loeb et al. 2017, J. Climate
Optical Properties for Smooth, Rough, THM (De = 65 µm)

From Loeb et al. 2017
Asymmetry Parameter vs Ice Particle Size
\[ \lambda = 0.65 \, \mu m \ (VIS) \]

In the VIS, the asymmetry parameter, \( g \) is largely determined by the effective aspect ratio. THM has smaller effective aspect ratio than the Smooth and Rough models leading to smaller \( g \). Smaller \( g \) yields lower retrieved COT. \( g \), COT dependence on particle size also different – slightly decreases for THM but increases for Smooth and Rough with increasing size.
Optical Properties for Smooth, Rough, THM (De = 65 µm)

- Smaller $\omega_0$ for THM than for SHM at 3.7 µm
- $\omega_0$ similar for all models at 1.2, 1.6, 2.1 µm
- Larger $g$ for THM at 3.7 µm
- Smaller $g$ for THM at 1.2, 1.6, 2.1 µm

Similarity theory (Van de Hulst, 1974):

Radiance proportional to $S= (1- \omega_0) / (1- \omega_0 g)$

3.7 µm: $S(\text{THM}) > S(\text{SHM})$ for a given De
- need smaller De to match radiance with THM

Opposite true at shorter NIR wavelengths
- So De diffs (e.g. 1.6 minus 3.7 µm) larger for THM
Ice Cloud Property Differences (THM – Smooth)

March 2008, Aqua-MODIS

- THM yields lower COT (-28% globally)
- Larger diffs (> 5) at higher latitudes
  - scattering closer to PP
  - more sensitive to g

- Lower COT (IR emissivity) yields positive height diffs everywhere
  - Global mean increase 290m
  - Increases up to 1km some areas

- Particle size differences also large and negative
  - Global mean diff -3.9 µm (-16%)
  - Larger diffs at mid and high latitudes

Note: Cloud fraction and cloud phase differences were very small (not shown)
Cloud Optical Thickness Comparison with CALIPSO

Himawari daytime Ice Clouds;  CALIPSO extinction QC = 1 (constrained retrieval)

Mean Tau difference
= 1.1 +/- 5.3

Mean Tau difference
= 0.7 +/- 3.9

Mean Tau difference
= 0.6 +/- 1.5

THM COT agrees better with CALIOP and with nighttime (IR only) method
Cloud Top Height Comparison with CALIPSO

Himawari daytime Ice Clouds; excludes CALIPSO 20km & 80 km detections

**Single-habit**

**Non-opaque clouds**

- **SHM**
  - Mean difference: $-3.5 \pm 4.8$ km

- **THM**
  - Mean difference: $-3.2 \pm 4.5$ km

Yikes, overall

Modest improvement with THM

**Opaque clouds**

- **SHM**
  - Mean difference: $-1.3 \pm 2.1$ km

- **THM**
  - Mean difference: $-1.2 \pm 2.0$ km

ML clouds contribute to the bias

Modest improvement with THM
Cloud Height Comparison with CALIPSO

Daytime Ice Clouds; Himawari (left) and MODIS (right)

**non-opaque clouds**

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- MODIS better than HIM-8

**opaque clouds**

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- ML clouds contribute to the bias
Cirrus Cloud Property Comparison with CALIPSO

Daytime

Main takeaways:

- COT and height differences reduced using THM
- IWP differences increase using THM
- Height differences decrease with increasing COT
- IWP differences increase with increasing COT
- MODIS compares better to CALIPSO than HIM-8
Summary

• The CERES CWG has been evaluating a new two-habit ice model (planned for next Edition 5)

• The goal here was to examine our retrieval differences using the various models and evaluate their relative accuracies with CloudSat/CALIPSO data

• Passive sensor retrievals of ice cloud optical depth and effective particle radius exhibit strong dependence on what ice particle model is assumed
  
• Daytime cloud optical thickness and heights derived with THM are in better agreement with CALIPSO/CloudSat data than those derived with previous SHM’s
  
• Improved spectral consistency also achieved (Day/Night retrievals agree better)
  
• 3.7 μm effective radius retrievals also quite different using THM (smaller)
  
• IWP accuracies more difficult to assess due to vertical homogeneity assumption ($R_e(z) =$const).
    - Future comparisons planned w/ CloudSat 2CICE product (combined Cloudsat/CALIPSO)

• More work needed to understand angular dependencies. GEO validation with CALIPSO/CloudSat provides some new insights (off nadir tests)
QUESTIONS ?
Cloud Optical Thickness Comparison with CALIPSO

Himawari Daytime Ice Clouds; CALIPSO extinction QC = 1 (constrained retrieval)

Very Preliminary - need more data
Himawari Cloud Height Comparison with CALIPSO

Cloud effective height can vary with VZA for several reasons:

1. Increased path length with VZA tends to raise radiating layer
2. 3-D effects
   - Increased cloud amount at higher VZA (less contamination by PC pixels)
   - Less impact of lower clouds in ML conditions
MODIS Cloud Height Comparison vs VZA (2004)

- **b) ice**

![Graph of Cloud Effective Height vs Viewing Zenith Angle](image)

- **Cloud Effective Height (km)**
- **Viewing Zenith Angle (°)**

- **ocean**
- **land**
- **total**