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 Edition 4 MODIS** cloud properties
  (March 2008, Feb 2017)
- **CERES GEO** cloud properties (Feb 2017)
  - **Himawari-8**
  - 1-hr temporal resolution
  - Subset to 6-km spatial res
  - +/-15 min of CALIPSO obs

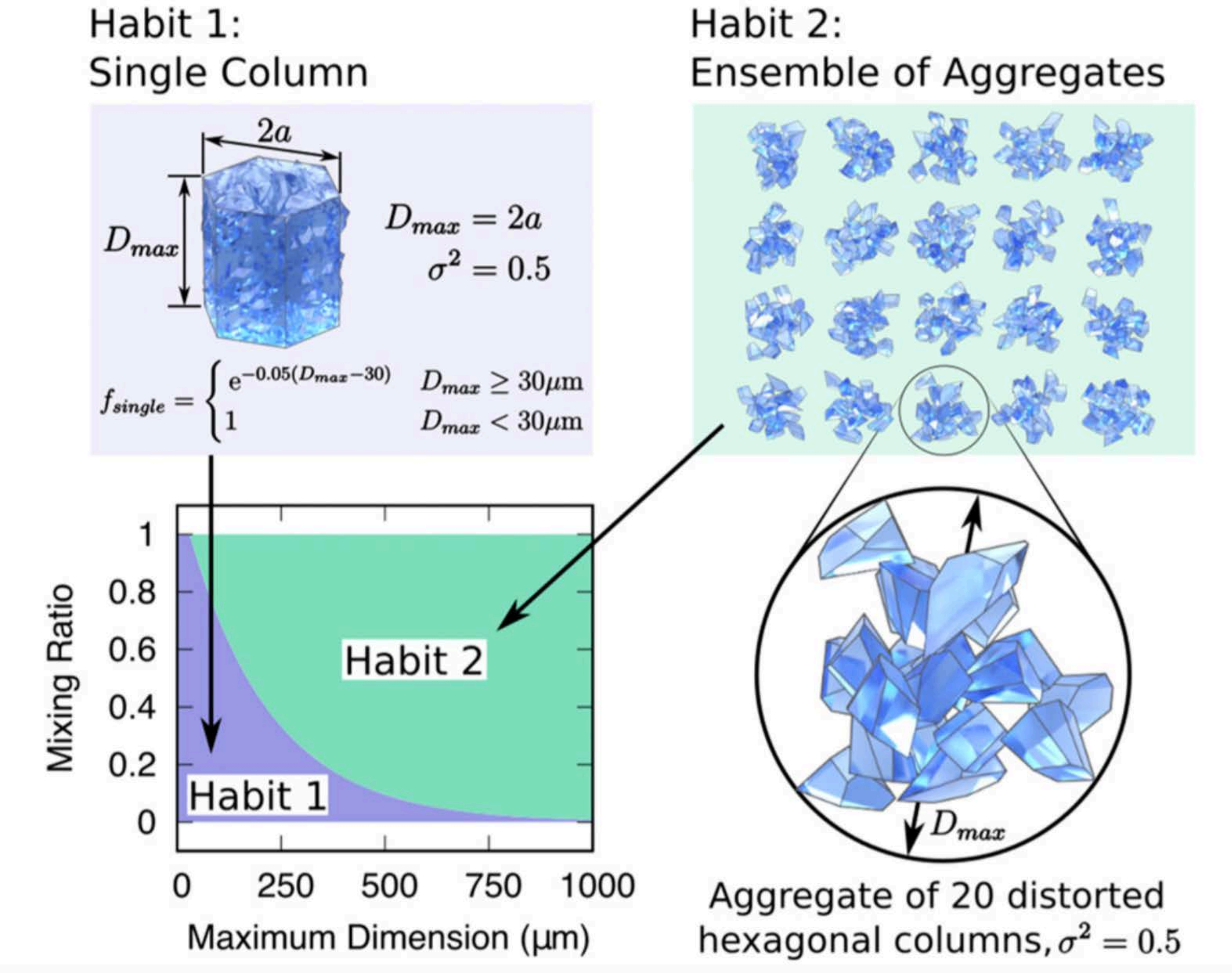
Active Sensor

- **CALIPSO** V4.10 5-km Cloud Layers products
  - Optical depth and IWP for τ < ~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 τ

CERES Ice Crystal Models for MODIS and GEO Cloud Retrievals

Ice cloud particle model	CERES edition
Smooth hexagonal columns	Ed2.0 and Ed3.0
Roughened hexagonal columns	Ed4.0
Two-habit model	Ed5.0 (planned)

- 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



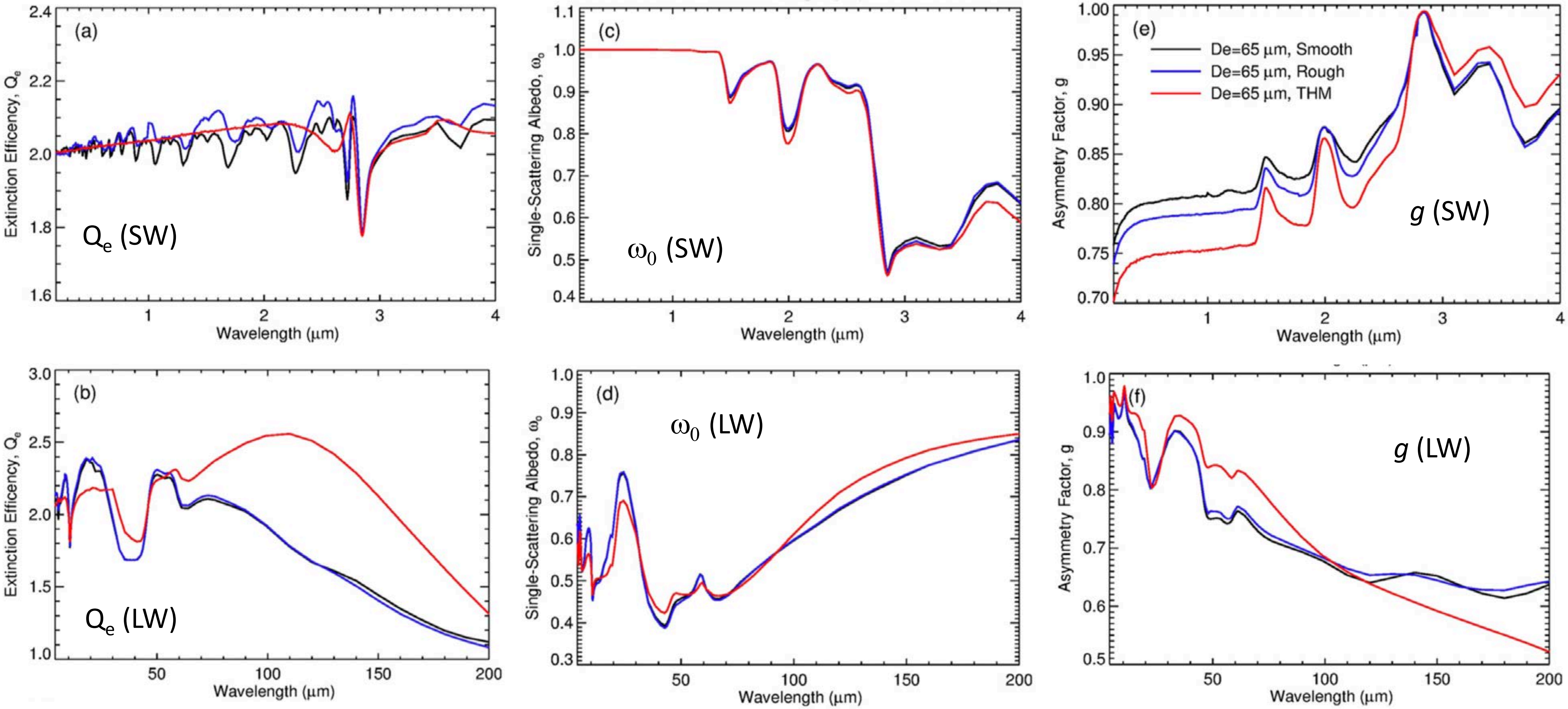
A few other details

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

REFERENCES

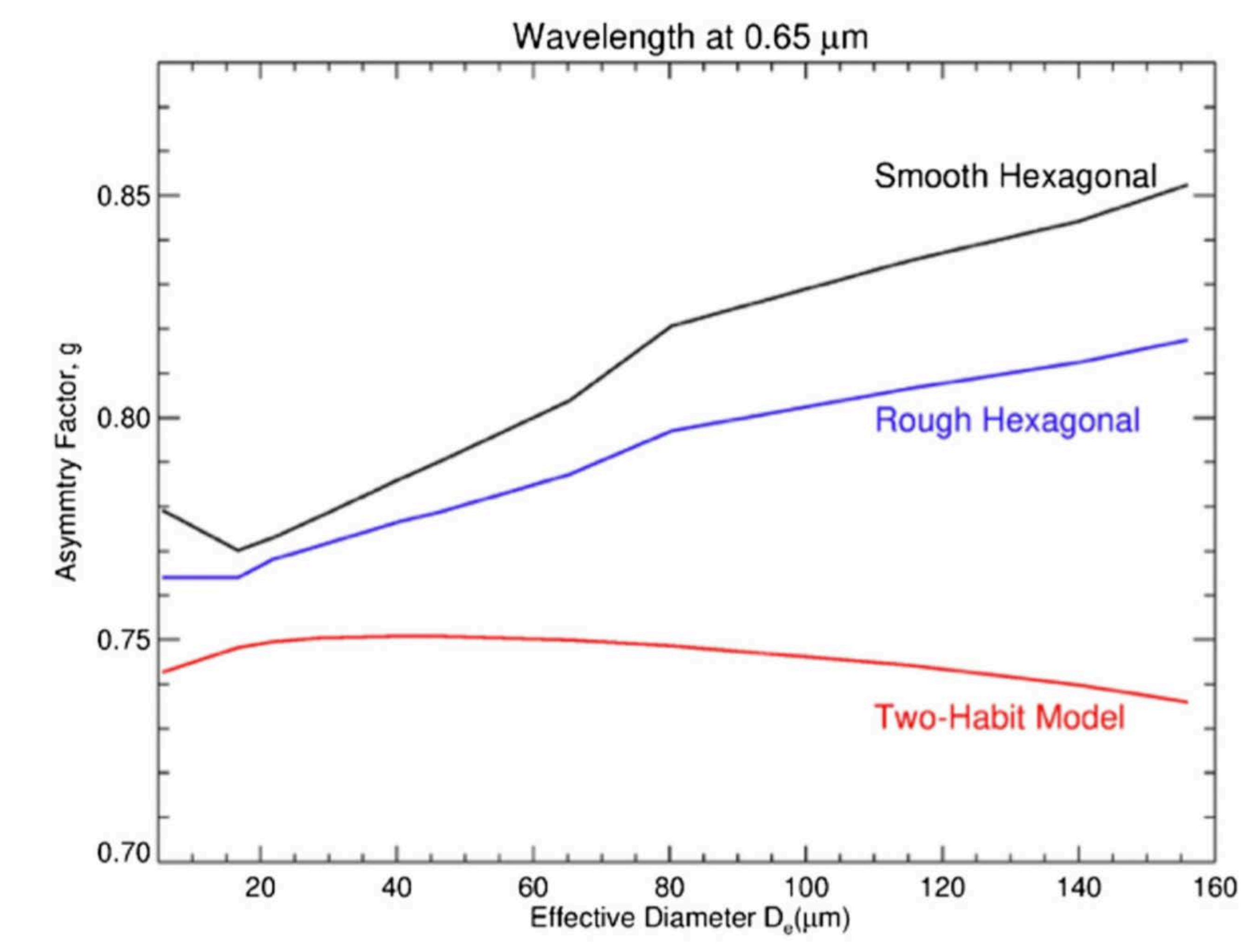
Yang et al. 2008a and 2008b, IEEE Trans. Geosci. Remote Sens.
Liu et al. 2014, Atmos. Chem. Phys.
Loeb et al. 2017, J. Climate

Optical Properties for Smooth, Rough, THM (De = 65 μm)



From Loeb et al. 2017

Asymmetry Parameter vs Ice Particle Size
λ = 0.65 μm (VIS)



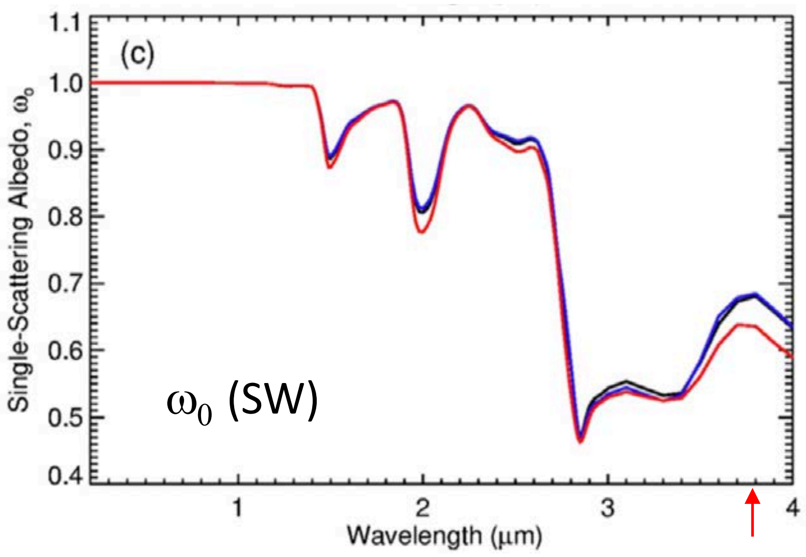
In the VIS, the asymmetry parameter, g is largely determined by the effective aspect ratio

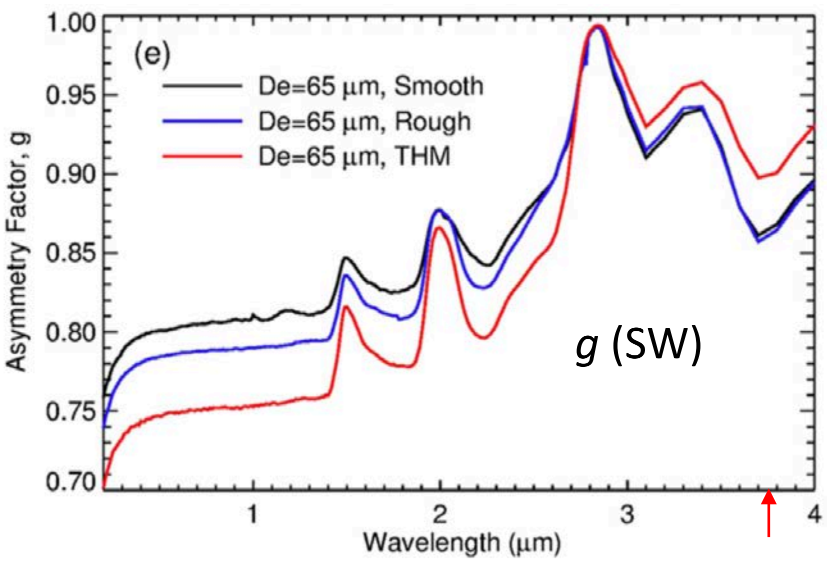
THM has smaller effective aspect ratio than the Smooth and Rough models leading to smaller *g*

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 ω_0 for THM than for SHM at 3.7 μm
ω_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 $S = (1 - \omega_0) / (1 - \omega_0 g)$

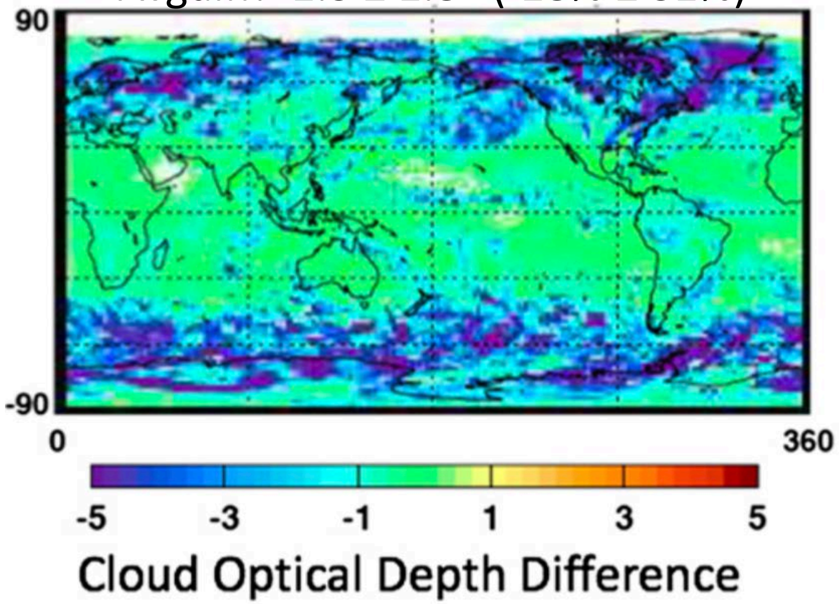
3.7 μm: S(THM) > S(SHM) for a given De
- need smaller De to match radiance with THM

Opposite true at shorter NIR wavelengths
- So De diffs (e.g 1.6 minus 3.7 μm) larger for THM

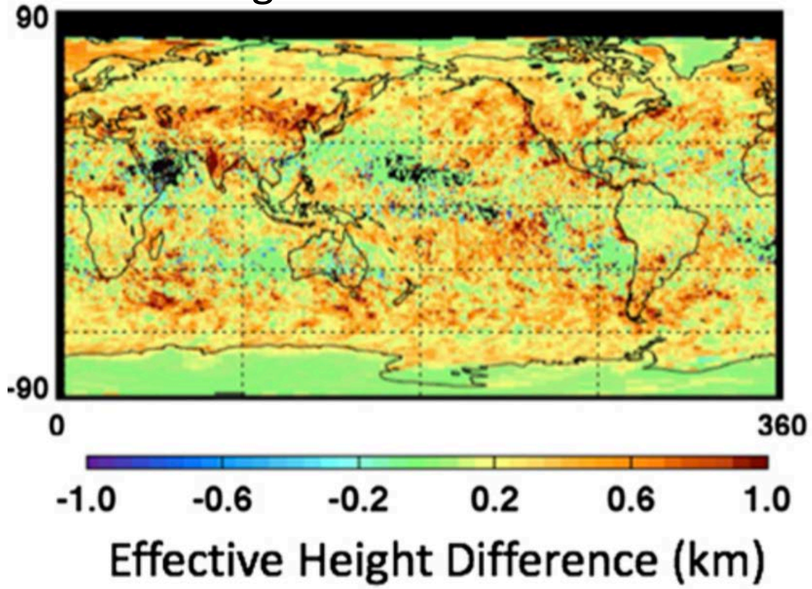
Ice Cloud Property Differences (THM – Smooth)

March 2008, Aqua-MODIS

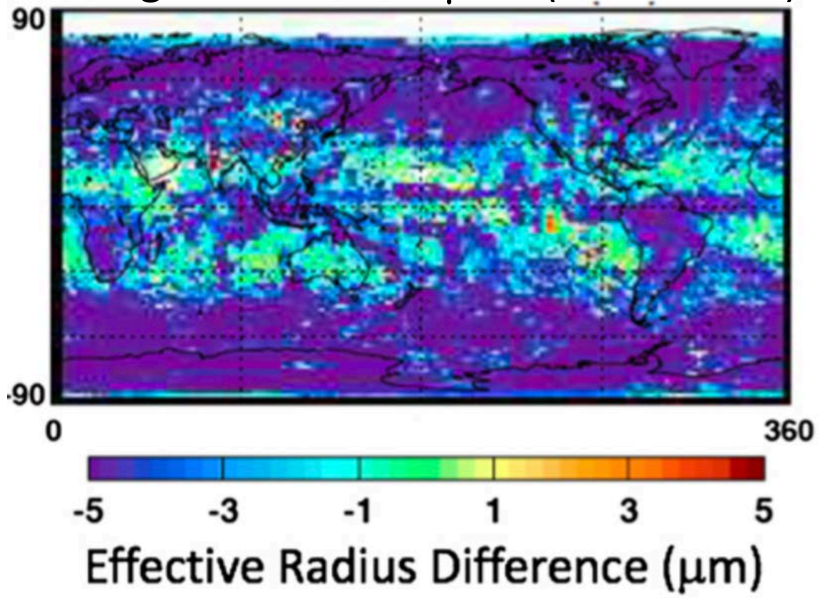
Avgdiff: -2.3 ± 2.8 (-28% ± 32%)



Avgdiff: 290 ± 375 m



Avgdiff: -3.9 ± 5.2 μm (-16% ± 21%)



3.7 μm

- THM yields lower COT (-28% globally)
- Larger diffs (> 5) at higher latitudes
  - scat angs 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

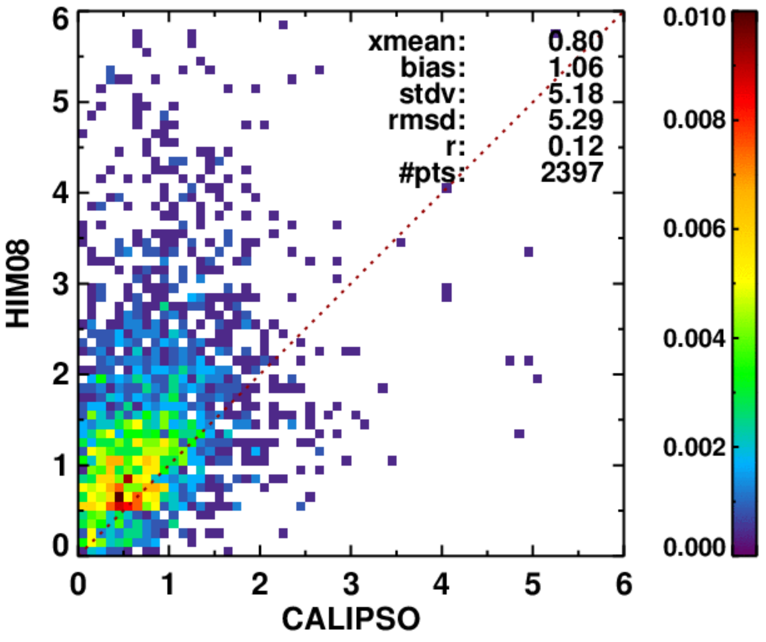
- Particle size differences also large and negative
  - Global mean diff -3.9 μm (-16%)
  - Larger diffs at mid and hi Lats

Note: Cloud fraction and cloud phase differences were very small (not shown)

Cloud Optical Thickness Comparison with CALIPSO

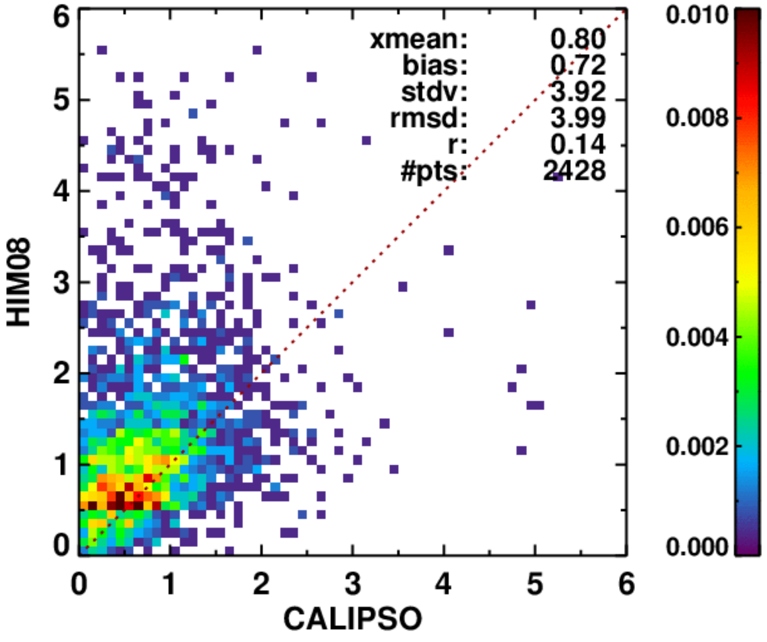
Himawari daytime Ice Clouds; CALIPSO extinction QC = 1 (constrained retrieval)

single-habit



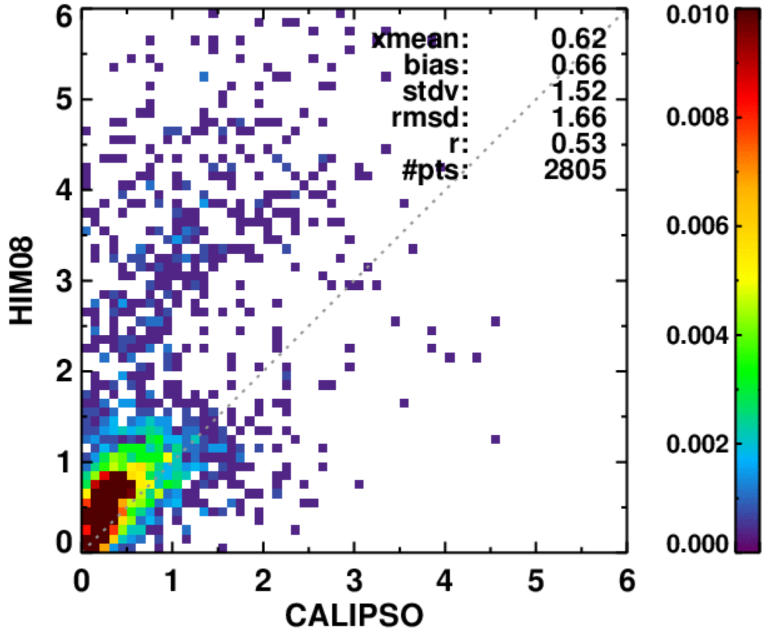
Mean Tau difference
= 1.1 +/- 5.3

two-habit



Mean Tau difference
= 0.7 +/- 3.9

Nightime (IR)



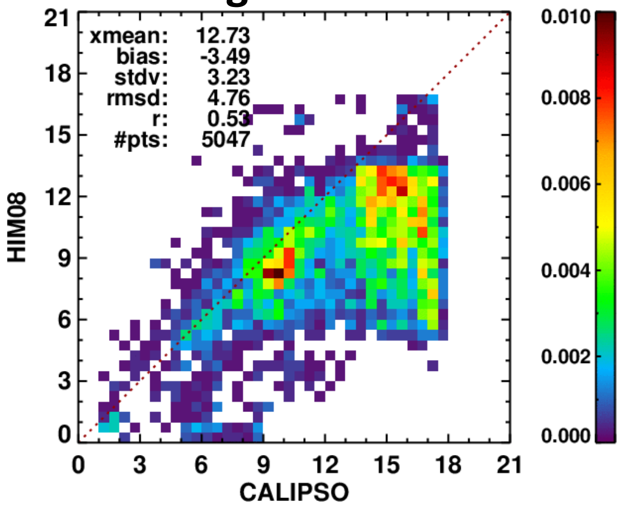
Mean Tau difference
= 0.6 +/- 1.5

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



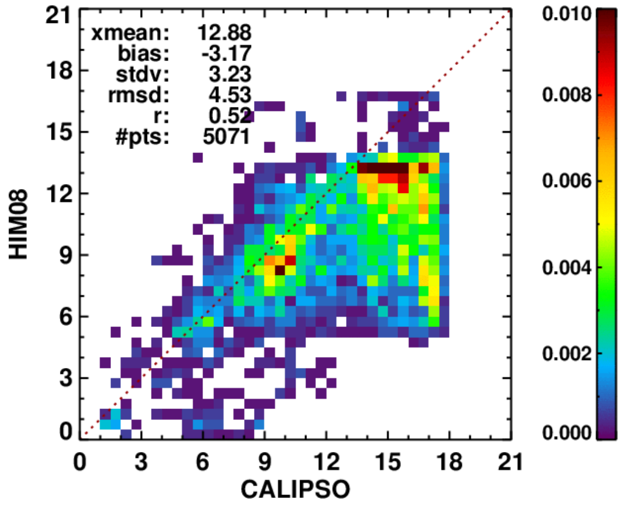
non-opaque clouds

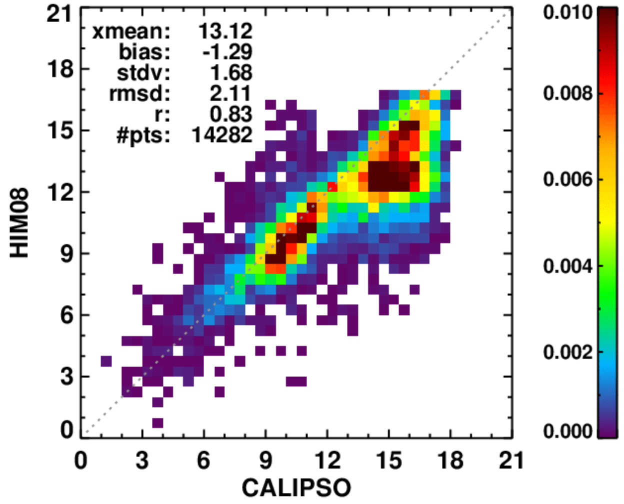
SHM
Mean difference
= -3.5 +/- 4.8 km

THM
Mean difference
= -3.2 +/- 4.5

Yikes, overall
Modest improvement with THM

two-habit



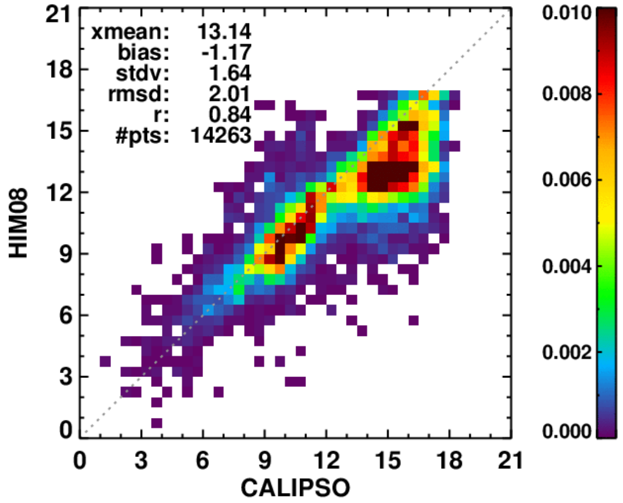


opaque clouds

SHM
Mean difference
= -1.3 +/- 2.1 km

THM
Mean difference
= -1.2 +/- 2.0 km

ML clouds contribute to the bias
Modest improvement with THM

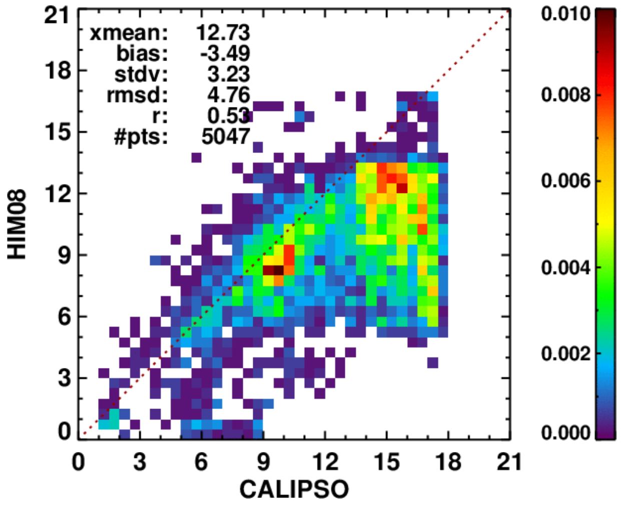


Cloud Height Comparison with CALIPSO

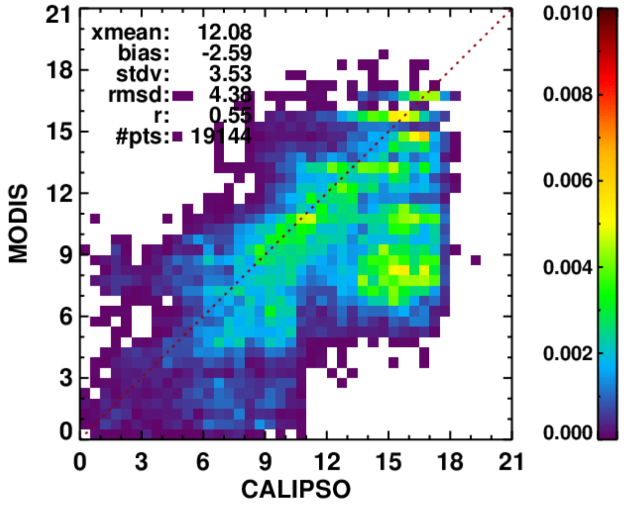
Daytime Ice Clouds; Himawari (left) and MODIS (right)

non-opaque clouds

Him-8



MODIS

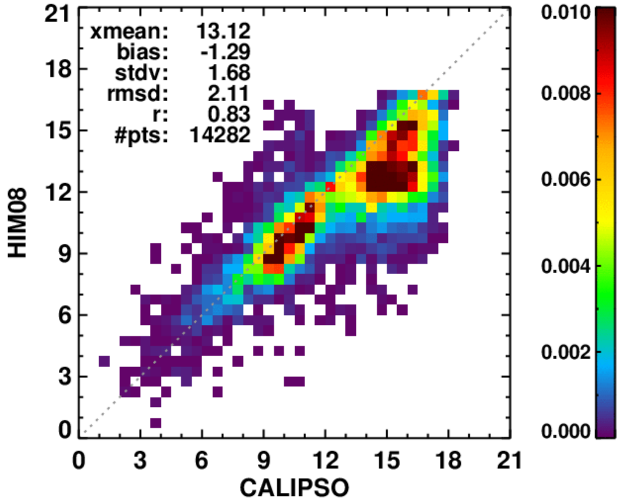


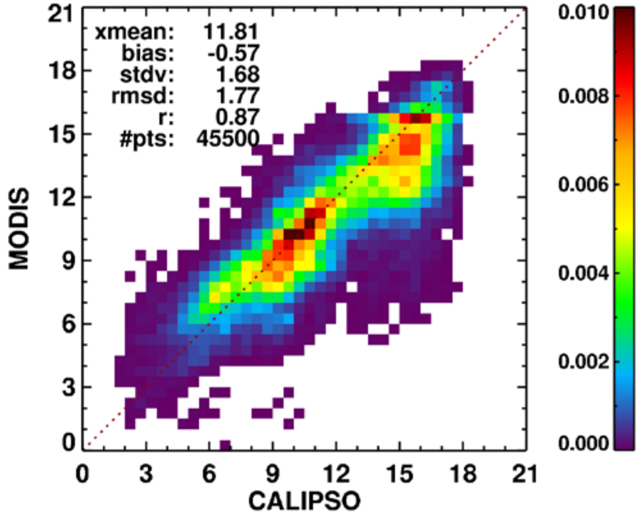
HIM-8
Mean difference
= -3.5 +/- 4.8 km

MODIS
Mean difference
= -2.6 +/- 4.3

- MODIS better than HIM-8

opaque clouds





HIM-8
Mean difference
= -1.3 +/- 2.1 km

MODIS
Mean difference
= -0.6 +/- 1.8 km

- ML clouds contribute to the bias

Cirrus Cloud Property Comparison with CALIPSO

Daytime

HIMAWARI-8

COT

COT BIN	CALIPSO MEAN	SHM BIAS	THM BIAS	N
0-1	0.5	1.1	0.8	3766
1-2	1.4	1.0	0.6	1241
2-3	2.4	1.3	0.7	199
ALL	0.8	1.0	0.7	5265

Z_{top} (km)

COT BIN	CALIPSO MEAN (km)	SHM BIAS	THM BIAS	N
0-1	13.0	-4.1	-3.8	3356
1-2	12.8	-2.5	-2.2	1241
2-3	11.8	-1.8	-1.4	199
ALL	12.7	-3.5	-3.1	4996

IWP (gm^{-2})

COT BIN	CALIPSO MEAN (gm^{-2})	SHM BIAS	THM BIAS	N
0-1	15.3	3.4	-2.7	3745
1-2	56.0	-24.4	-34.2	1239
2-3	114.5	-51.3	-75.8	199
ALL	28.8	-5.3	-13.0	5183

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

MODIS

COT BIN	CALIPSO MEAN	MODIS BIAS
0-1	0.4	1.7
1-2	1.4	1.9
2-3	2.4	2.6
ALL	0.8	1.8

COT BIN	CALIPSO MEAN (km)	SHM BIAS
0-1	12.4	-3.1
1-2	11.6	-2.2
2-3	10.3	-1.3
ALL	12.1	-2.6

COT BIN	CALIPSO MEAN (gm^{-2})	SHM BIAS
0-1	15.2	25.2
1-2	61.3	-3.9
2-3	121.0	-32.7
ALL	32.5	14.6

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)

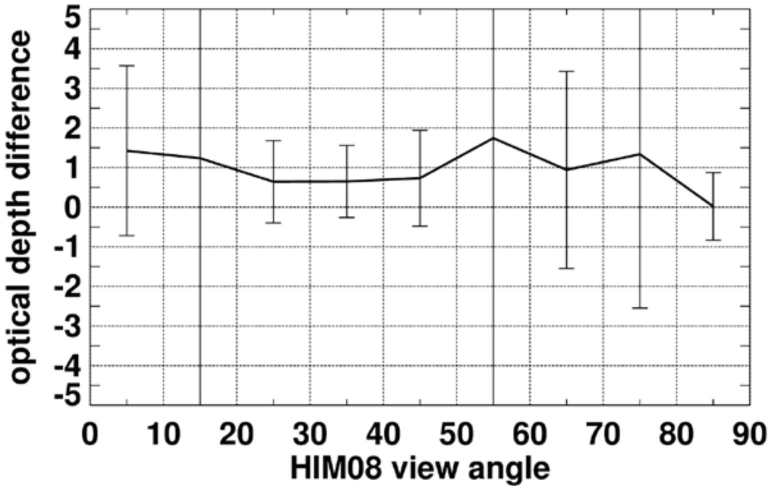
QUESTIONS ?

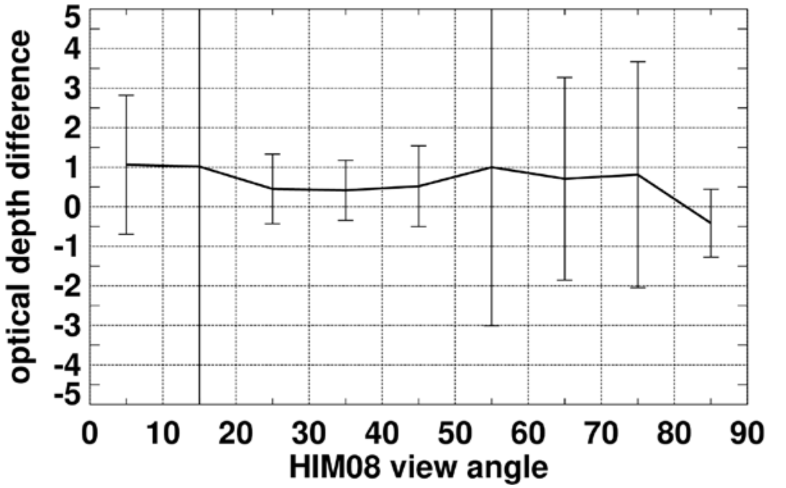
Cloud Optical Thickness Comparison with CALIPSO

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

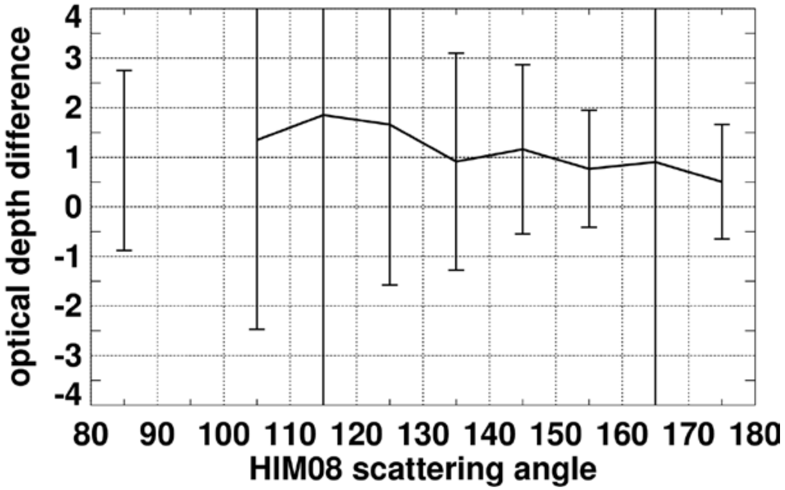
single-habit | **two-habit**

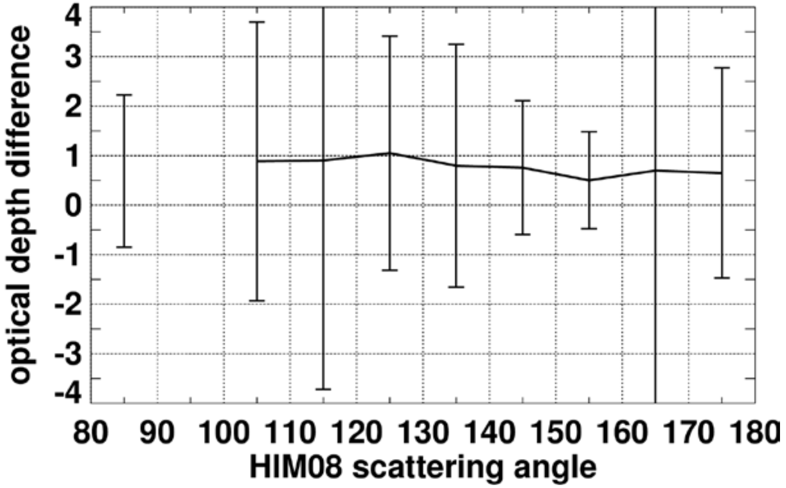
View Angle





Scattering Angle



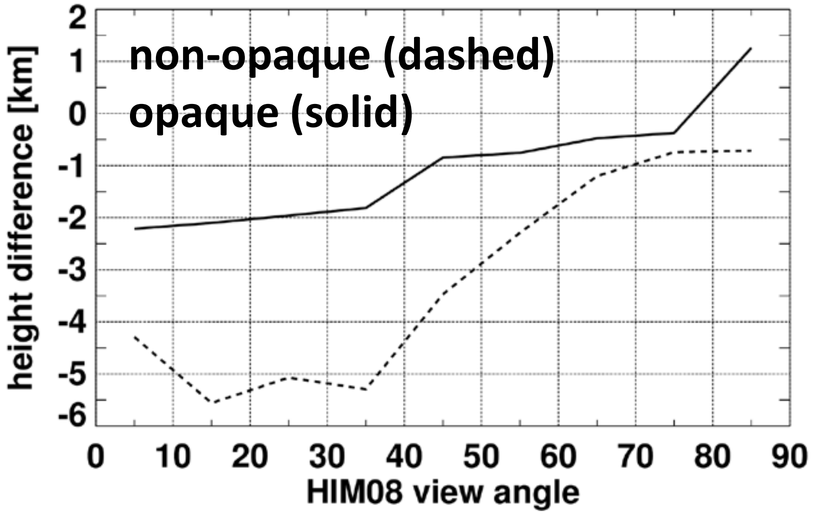


Very Preliminary
- need more data

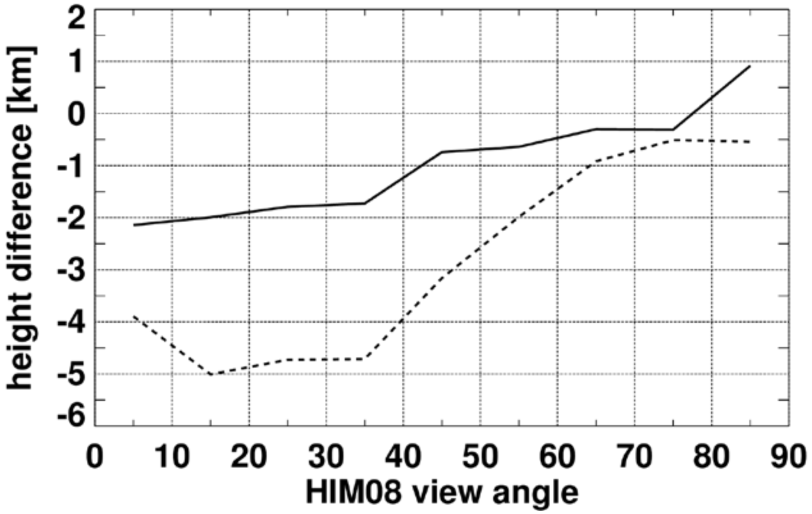
Himawari Cloud Height Comparison with CALIPSO

DAY

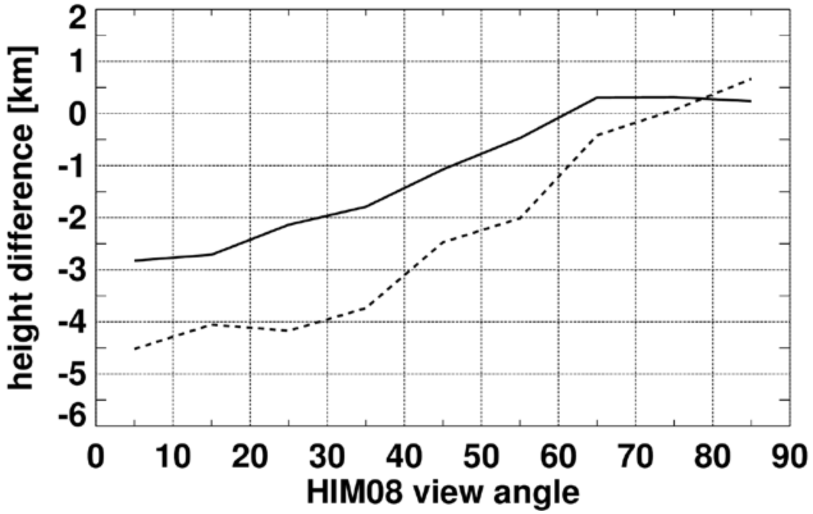
single-habit



two-habit



NIGHT

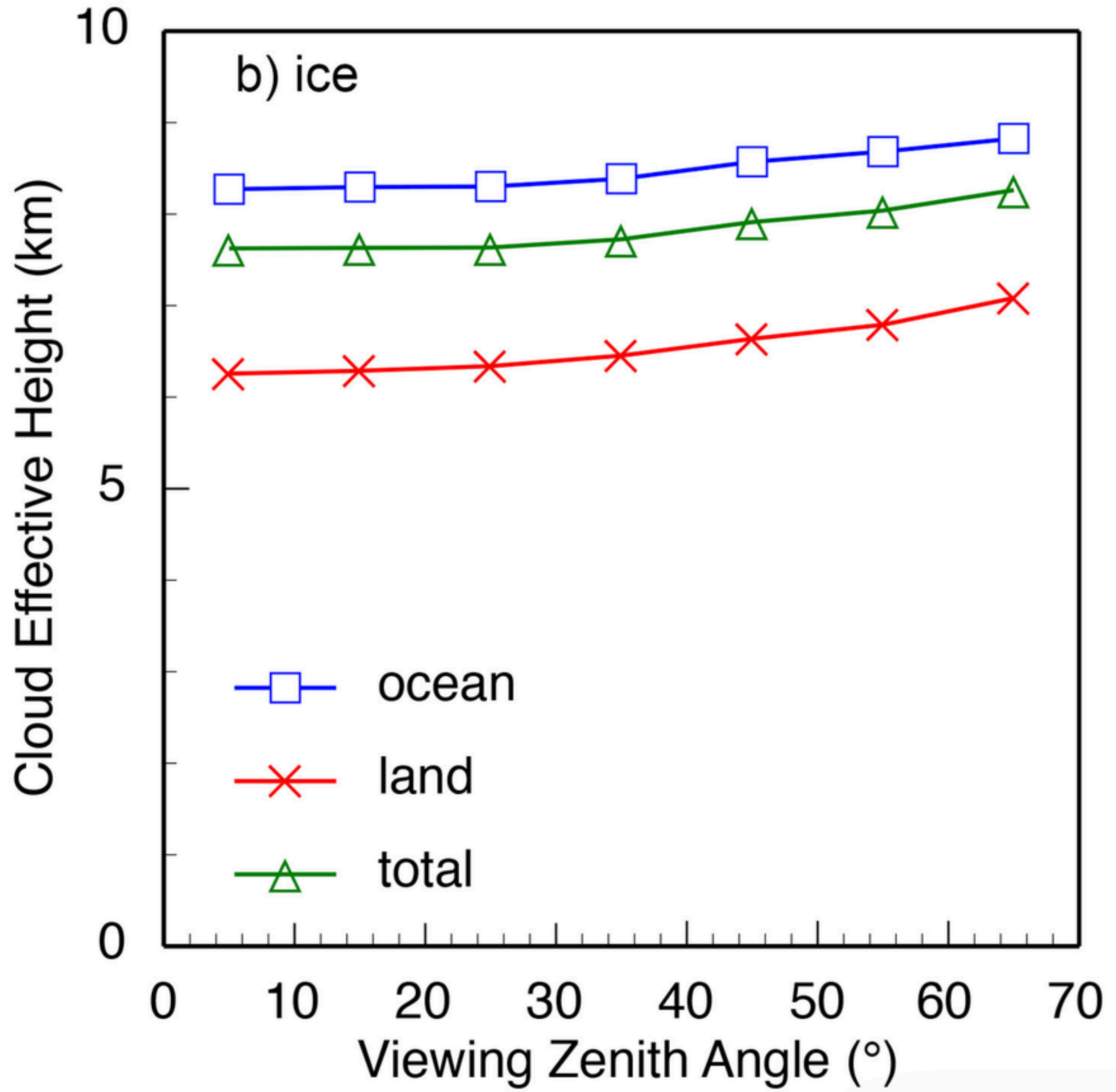


Cloud effective height can vary with VZA for several reasons:

(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)



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CLOUDS AND THE EARTH'S RADIANT ENERGY SYSTEM
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