The Consistency of Ice Clouds Optical Models for Spaceborne Active and Passive Remote Sensing Applications

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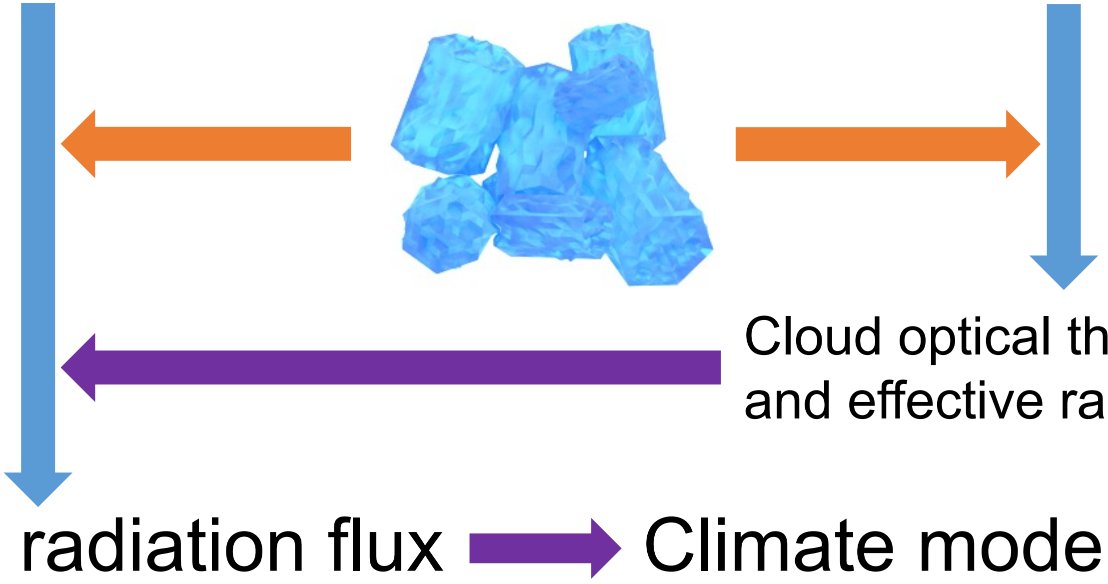
CERES Meeting May 9-11, 2023

A NASA consistency project

Loeb et al. (2018) suggested the same ice optical model be used in a broadband radiation computation and retrieving the cloud description input to the broadband radiation model.



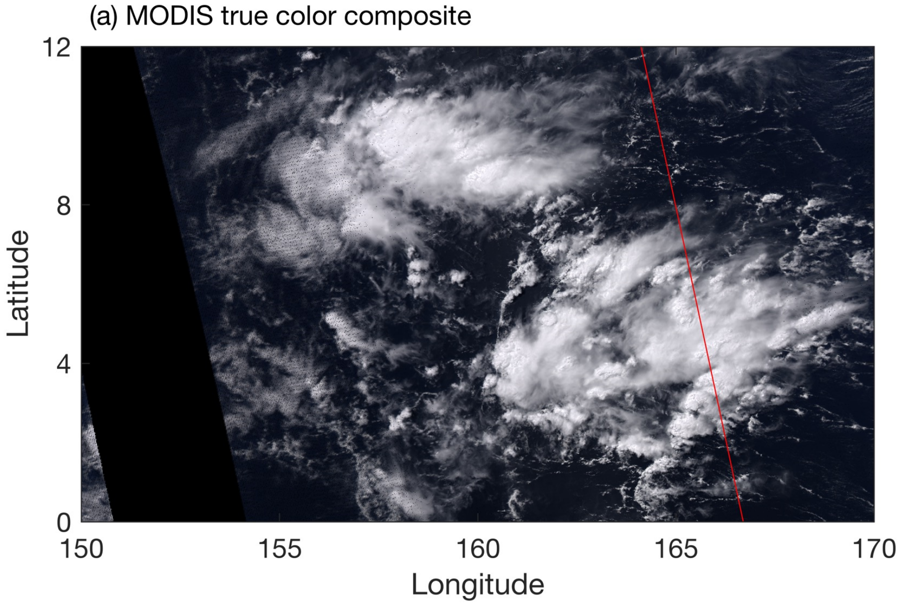
Broadband radiation model

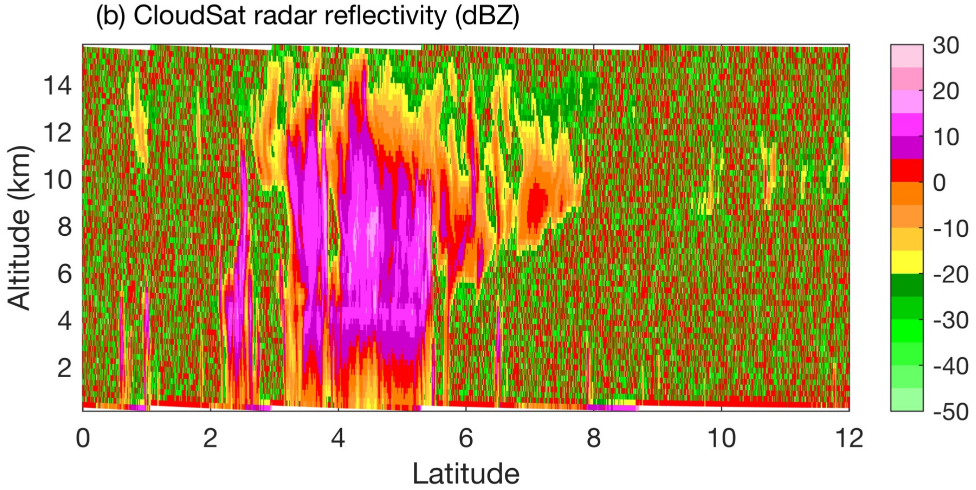
Satellite observations

Cloud optical thickness (τ) and effective radius (r_{eff})

Broadband radiation flux → Climate model evaluation

Influence of ice cloud optical model consistency in passive ice cloud retrieval and broadband radiation parameterization





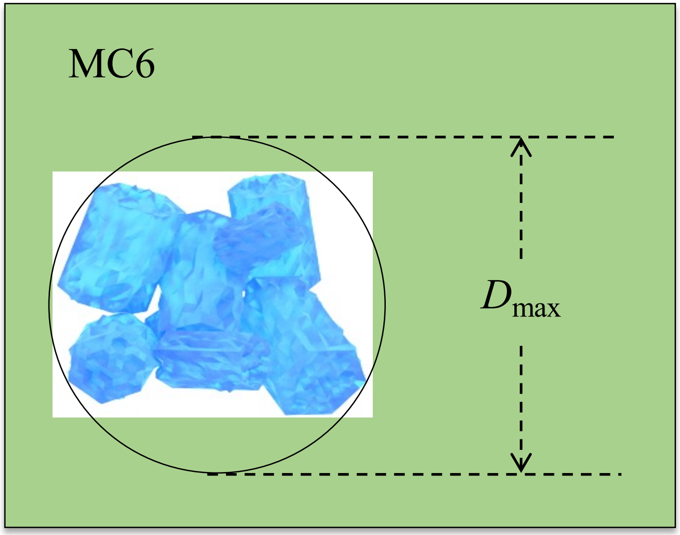
Study area: Equatorial western Pacific Ocean region [0 12˚N] × [150˚E 170˚E]

Time period: July 2008

Observational data: Aqua MC6 cloud retrieval, CERES Single Satellite Footprint (SSF)

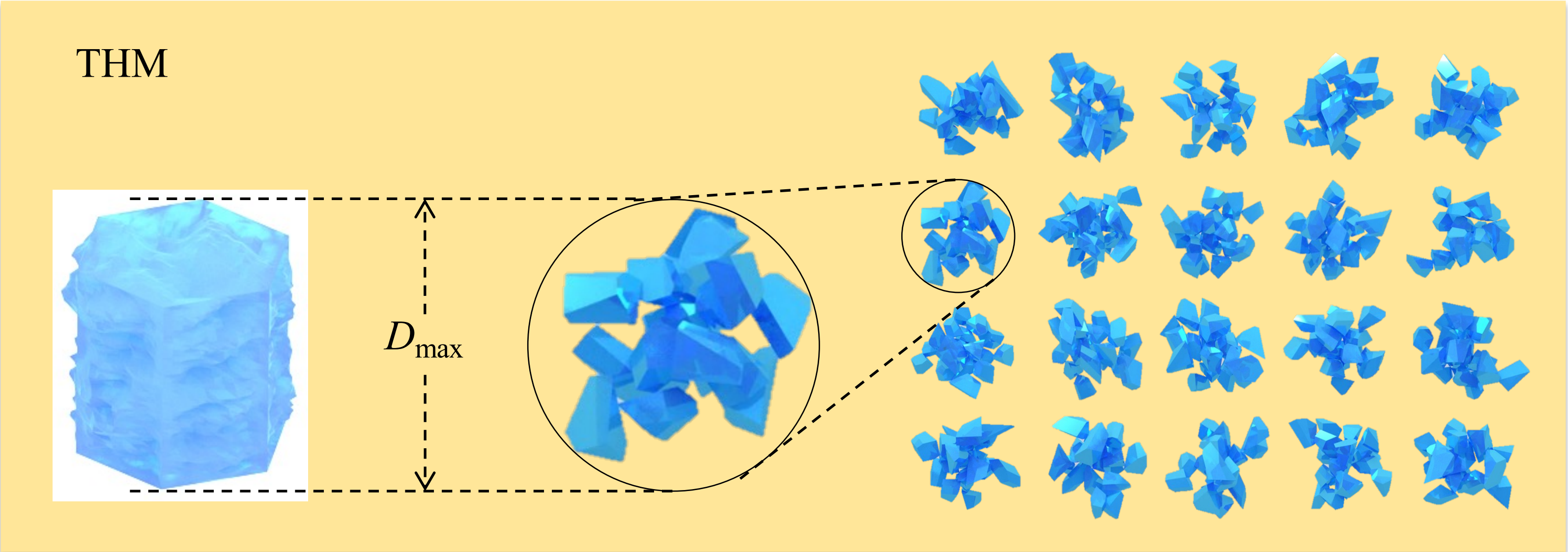
Model: ECMWF (*ecRad)* 1.4.0 with new ice cloud parameterization added (Ren, Yang, et al. 2022)

Two ice optical models of interest

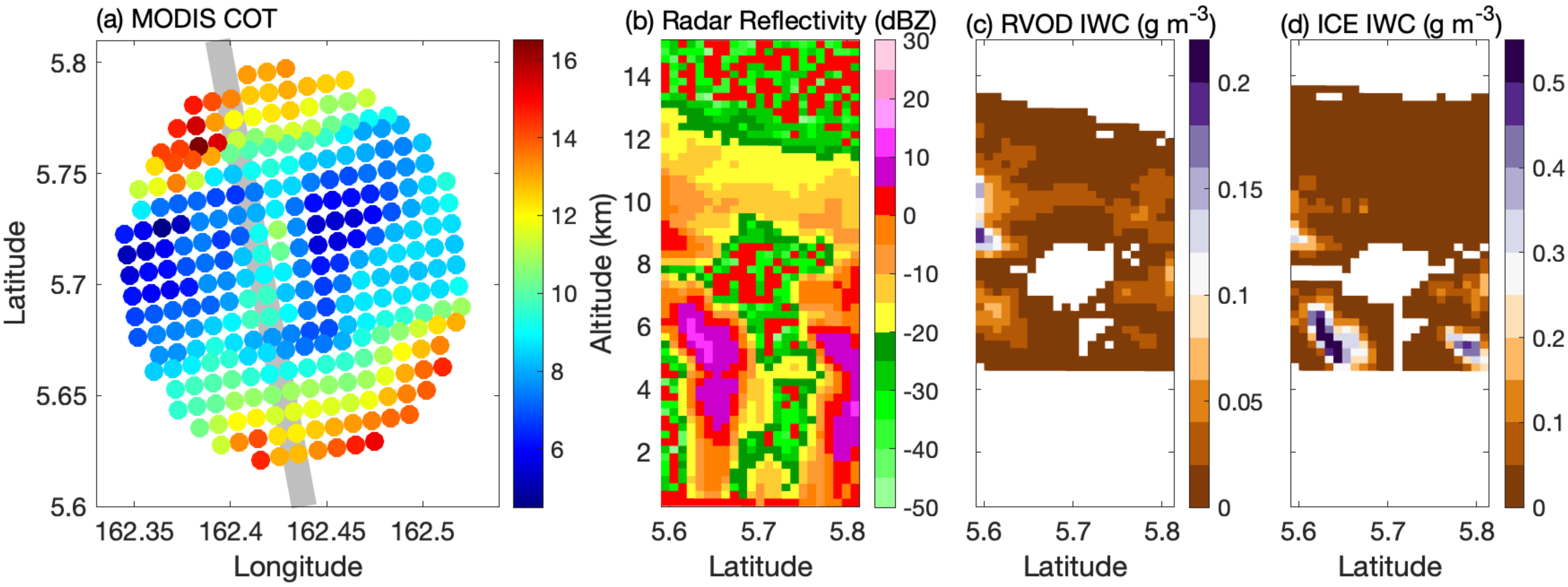


Eight-piece surface roughened hexagonal column aggregate model adopted in the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 (MC6) cloud retrieval product (Platnick et al. 2017)

The two-habit model (THM; Loeb et al. 2018)

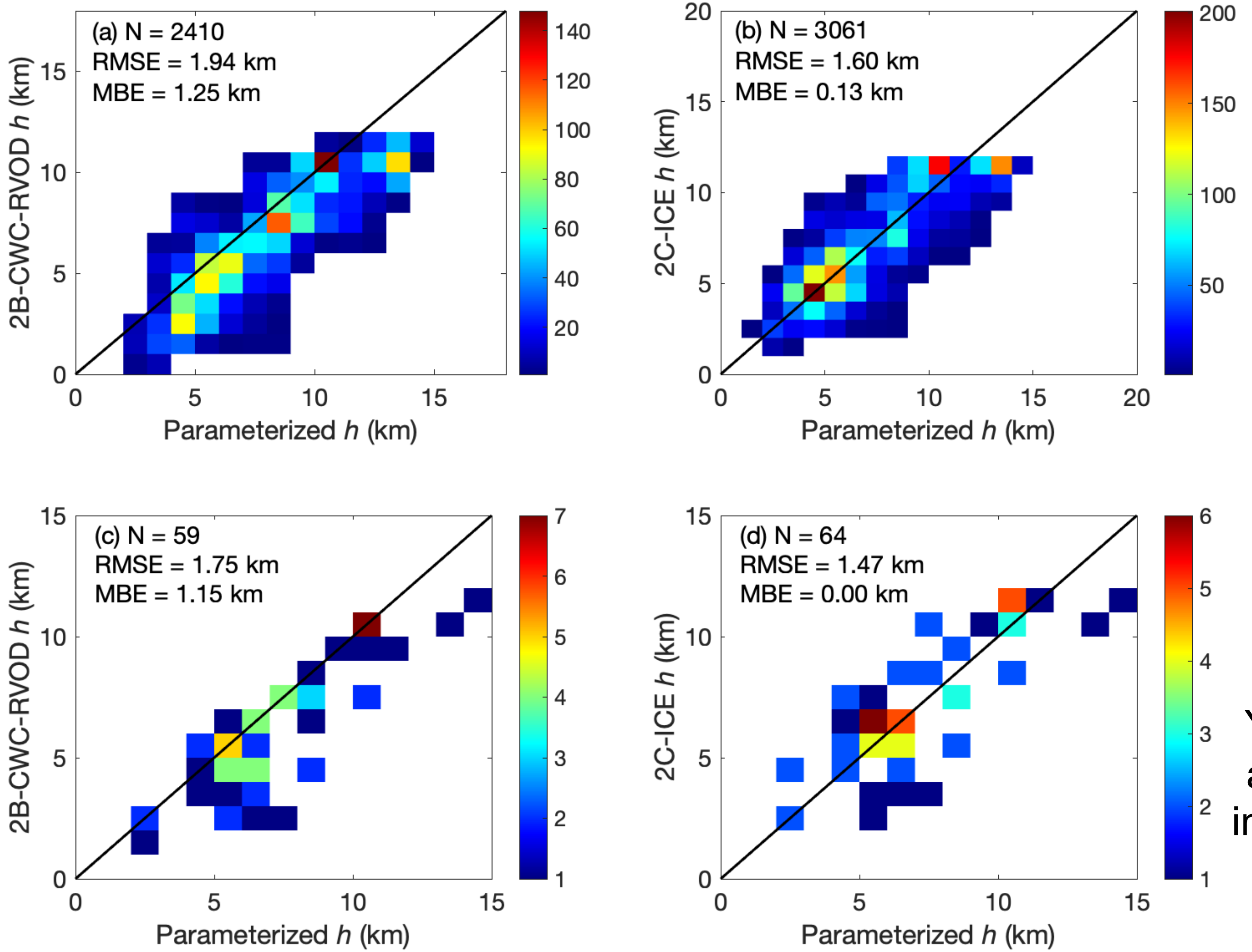


CloudSat 2B-CWC-RVOD and 2C-ICE data are used to test Minnis's cloud vertical extent parameterization



(Ren, Yang, et al. 2023 in review)

Minnis's parameterization agrees with both 2B-CWC-RVOD and 2C-ICE



(Ren, Yang, et al. 2023 in review)

Both MC6 and THM overestimate SW and LW cloud radiative effects at the TOA

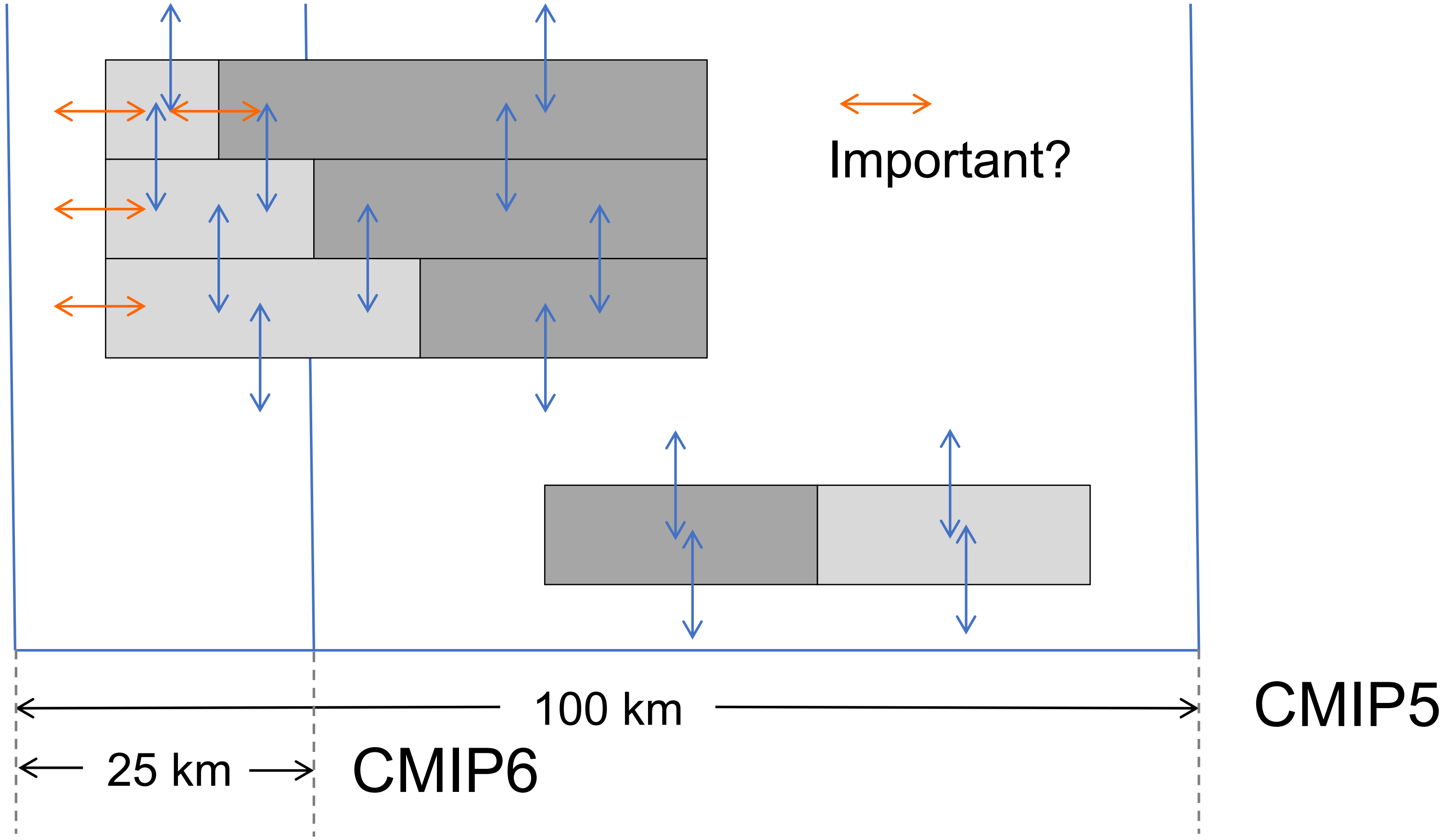
	RMSE (W m^{-2})	MAPE	MBE (W m^{-2})
$F_{SW,M,M}$	52.1	9.9%	43.0
$F_{SW,M,T}$	50.5	9.4%	40.9
$F_{SW,T,M}$	61.7	12.4%	54.4
$F_{SW,T,T}$	59.7	11.8%	52.1
$F_{LW,M,M}$	13.1	6.7%	-8.1
$F_{LW,M,T}$	12.9	6.6%	-7.7
$F_{LW,T,M}$	13.6	7.0%	-8.8
$F_{LW,T,T}$	13.4	6.9%	-8.4

MC6 or THM ice cloud broadband radiation scheme is used in the computations

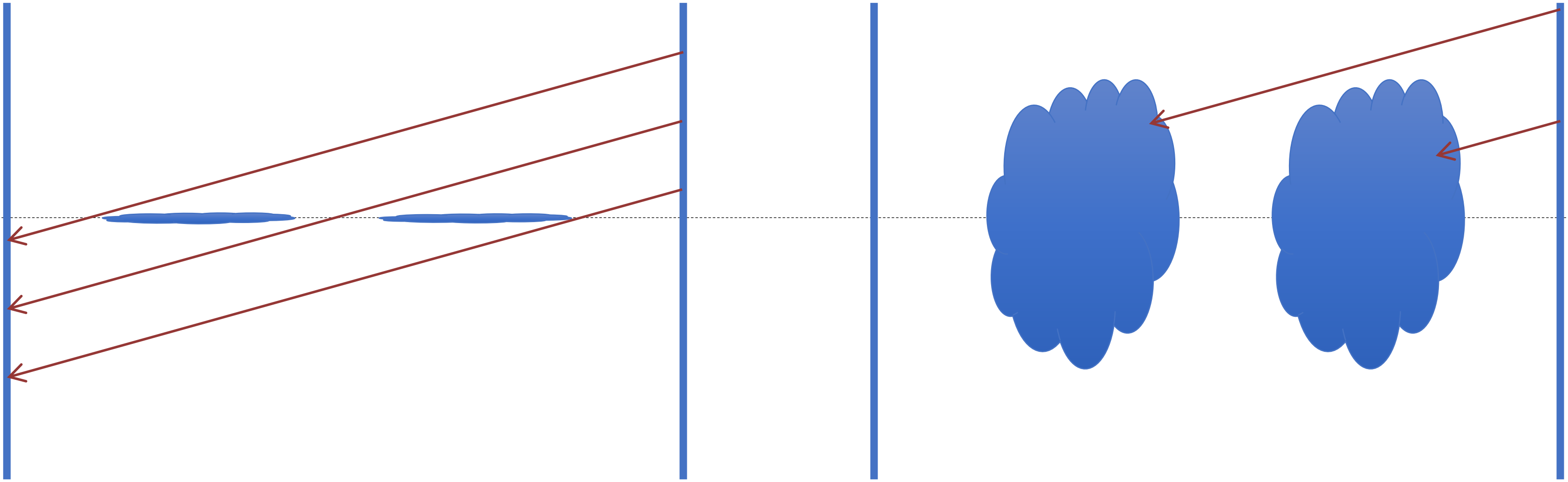
MC6 or THM-based MODIS ice-cloud retrievals serve as inputs for the simulation

(Ren, Yang, et al. 2023 in review)

Lateral radiation exchanges may become more important in finer resolution models.



The Speedy Algorithm for Radiative Transfer through Cloud Sides (SPARTACUS)



Plane-parallel

SPARTACUS

Linearization of the lateral exchange of incident solar radiation

$$\begin{cases} \dfrac{dF^a}{dz} = -\dfrac{\beta_e^a}{\mu_0} F^a \underline{- f_{\mathrm{dir}}^{ab} F^a + f_{\mathrm{dir}}^{ba} F^b} \\ \dfrac{dF^b}{dz} = -\dfrac{\beta_e^b}{\mu_0} F^b \underline{- f_{\mathrm{dir}}^{ba} F^b + f_{\mathrm{dir}}^{ab} F^a} \end{cases}$$

$$f_{\mathrm{dir}}^{ab} = \underline{L_{\mathrm{dir}}^{ab}} \tan(\theta_0) / c_a$$

normalized cloud perimeter length

(Hogan and Shonk 2013)

Weaker SW CRE and stronger LW CRE in the SPARTACUS simulations

Independent column-based

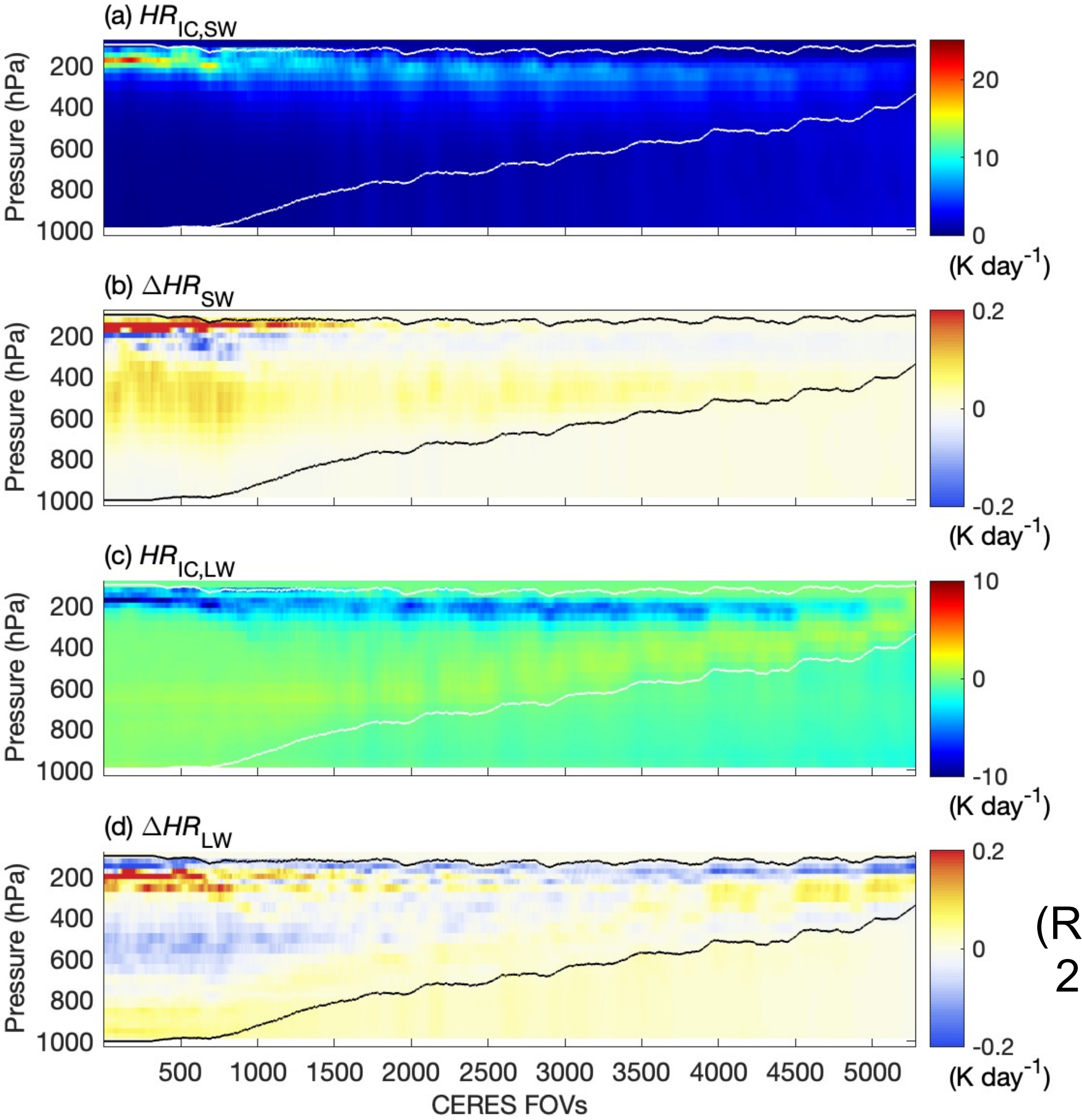
	RMSE (W m^{-2})	MAPE	MBE (W m^{-2})
$F_{SW,M,M}$	52.1	9.9%	43.0
$F_{SW,M,T}$	50.5	9.4%	40.9
$F_{SW,T,M}$	61.7	12.4%	54.4
$F_{SW,T,T}$	59.7	11.8%	52.1
$F_{LW,M,M}$	13.1	6.7%	-8.1
$F_{LW,M,T}$	12.9	6.6%	-7.7
$F_{LW,T,M}$	13.6	7.0%	-8.8
$F_{LW,T,T}$	13.4	6.9%	-8.4

SPARTACUS

	RMSE (W m^{-2})	MAPE	MBE (W m^{-2})
$F_{SW,M,M}$	51.0	9.5%	41.2
$F_{SW,M,T}$	49.4	9.0%	38.9
$F_{SW,T,M}$	60.3	11.9%	52.4
$F_{SW,T,T}$	58.2 ↓	11.4%	49.9
$F_{LW,M,M}$	13.7 ↑	7.0%	-8.7
$F_{LW,M,T}$	13.5	6.9%	-8.3
$F_{LW,T,M}$	14.2	7.3%	-9.4
$F_{LW,T,T}$	14.0	7.2%	-9.0

(Ren, Yang, et al. 2023 in review)

Radiation horizontal transfer adds vertical radiative heating/cooling gradients to cloud top and base



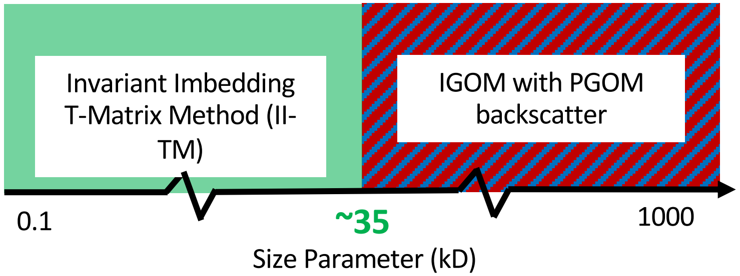
(Ren, Yang, et al. 2023 in review)

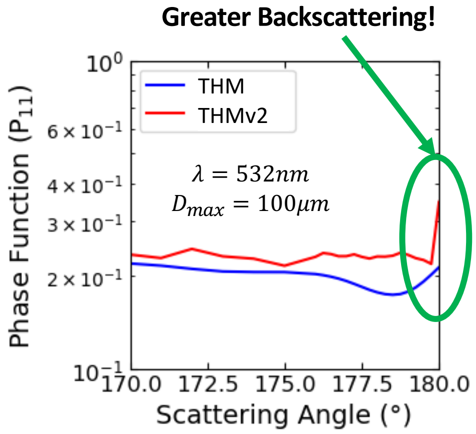
New Full Resolution Two Habit Model (THMv2)

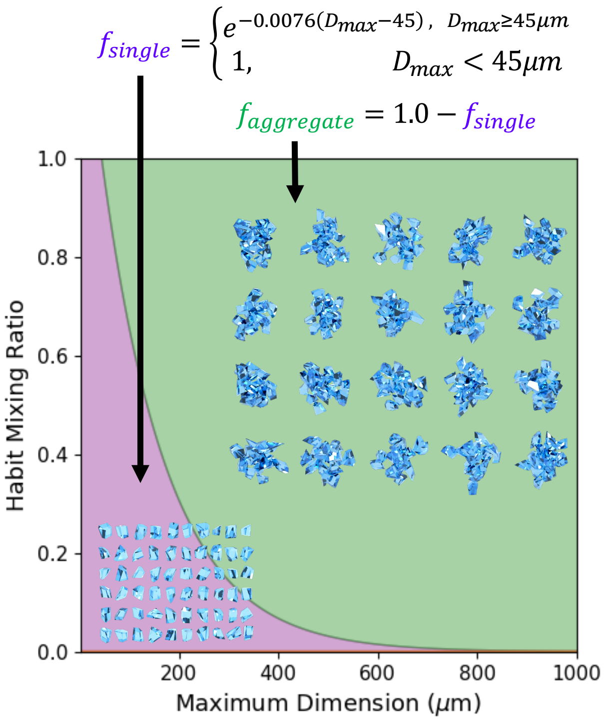
- 60-particle distorted single column and 20-particle distorted 20-column aggregate ensembles.
- Builds on the concept of the previously developed THM (Loeb et al. 2018).
- More accurate phase matrix backscattering calculations provided by Physical Geometric Optics Method (PGOM).
  - Replaces existing IGOM backscattering calculations.
  - **Available for 94 wavelengths**: 0.2 – 1.1µm (includes Lidar wavelengths).

	THMv2
Wavelength	470 bins **(0.2 – 200µm)** 3 Lidar bins: **355, 532, 1064nm**
Size (D_{max})	189 bins **(2.206 – 11031.337µm)**

THMv2 Computation Methods



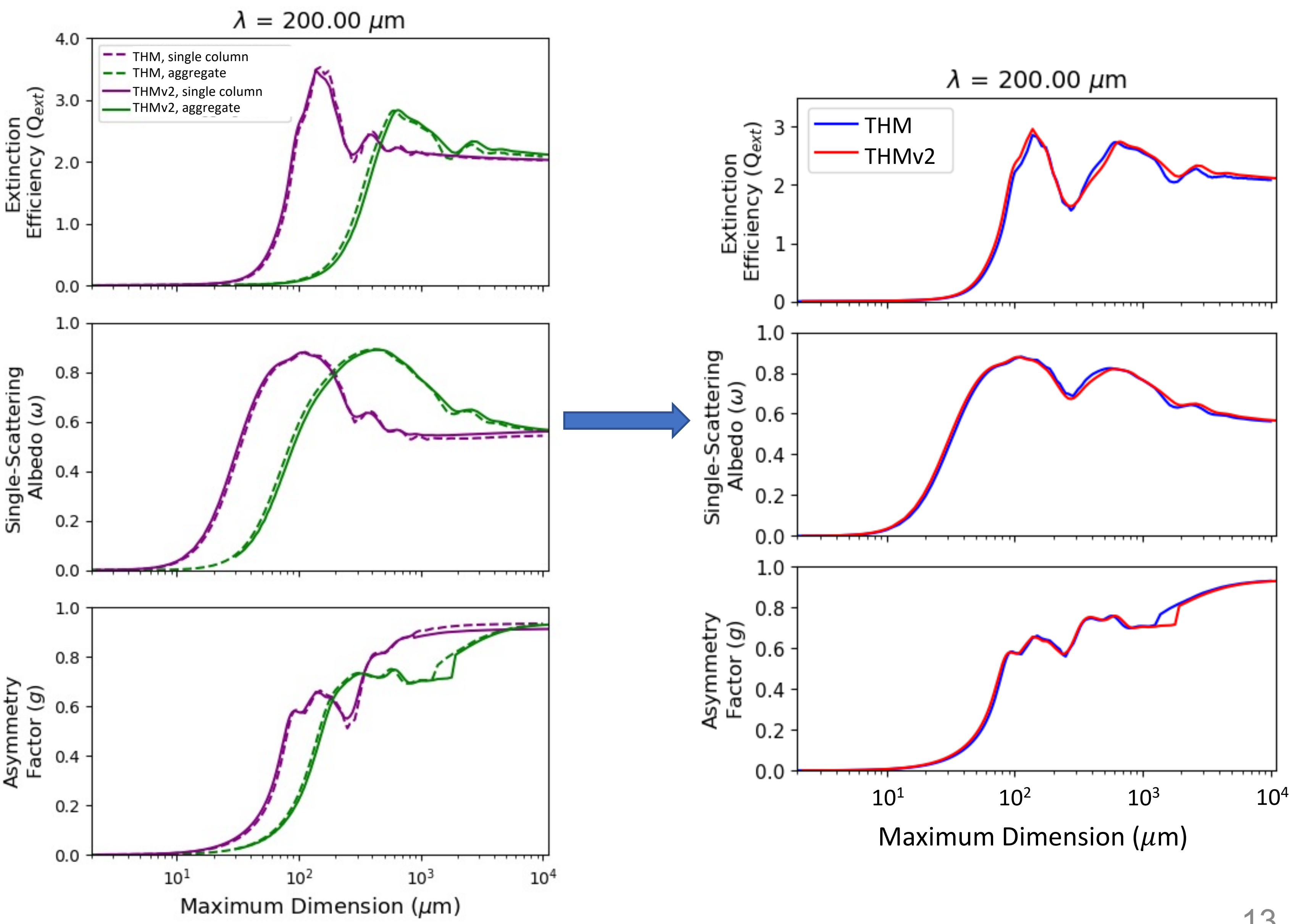




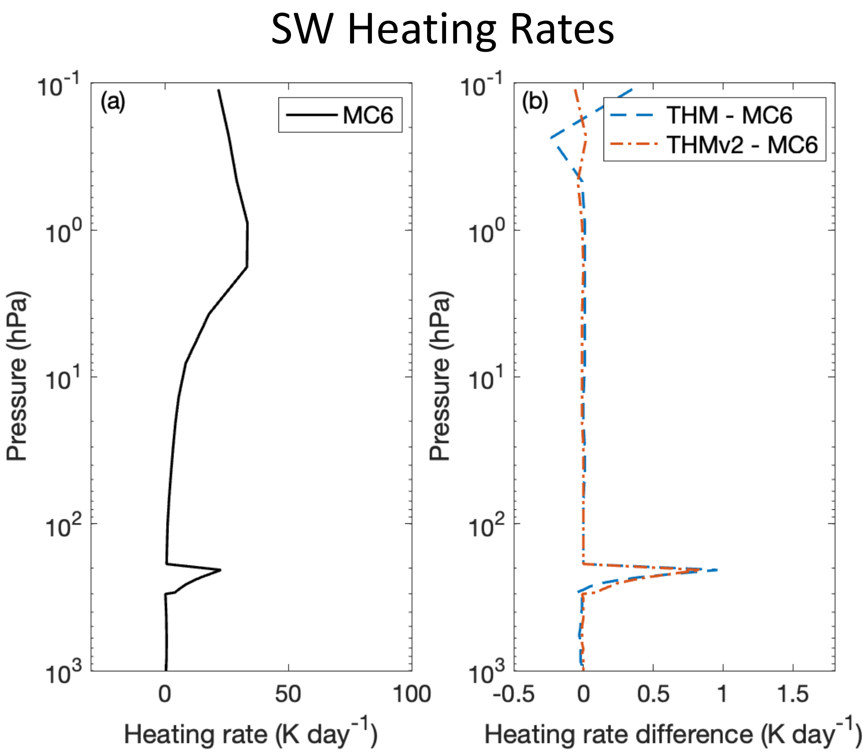
$$f_{single} = \begin{cases} e^{-0.0076(D_{max}-45)}, & D_{max} \geq 45\mu m \\ 1, & D_{max} < 45\mu m \end{cases}$$

$$f_{aggregate} = 1.0 - f_{single}$$

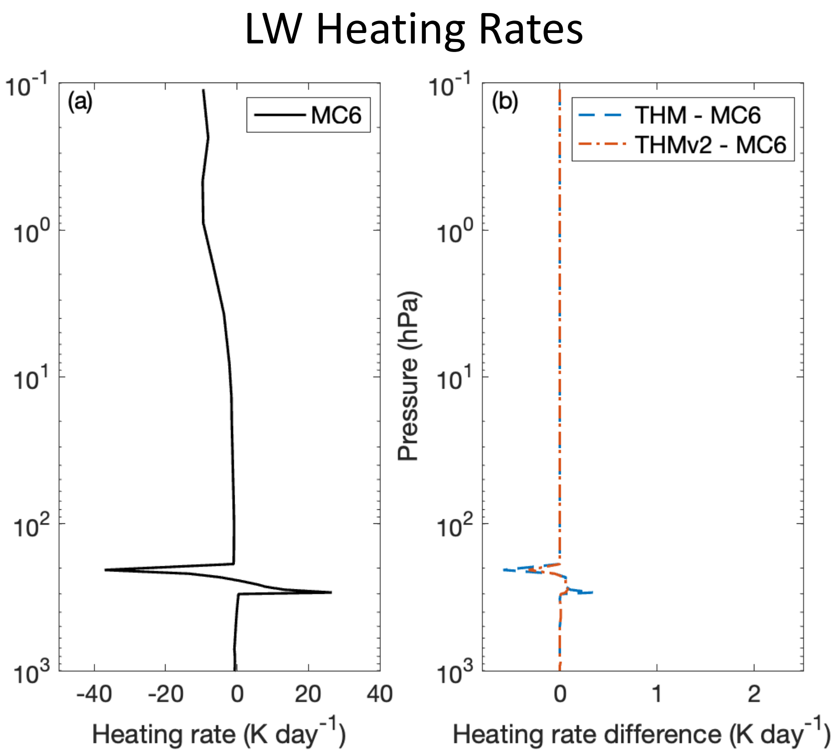
THM vs. THMv2 Optical Consistency



THMv2 Radiative Parameterization added to Langley Fu-Liou RTM



SW Heating Rates

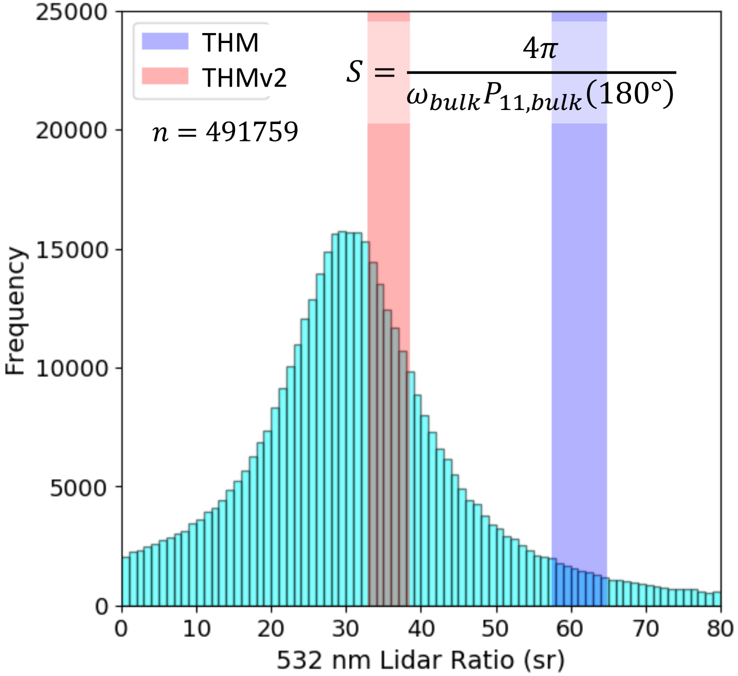


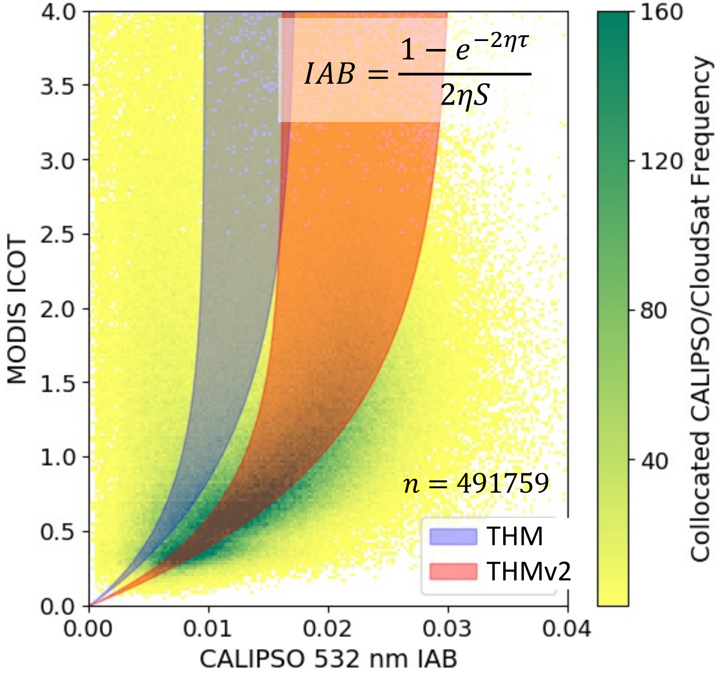
LW Heating Rates

Standard midlatitude winter; SW surface albedo of 0; LW emissivity of 1; Cloud layer between 300 – 200 hPa; Visible optical thickness of 7; Cloud particle effective radius of 32 micron.

Lidar-Based Retrieval Consistency

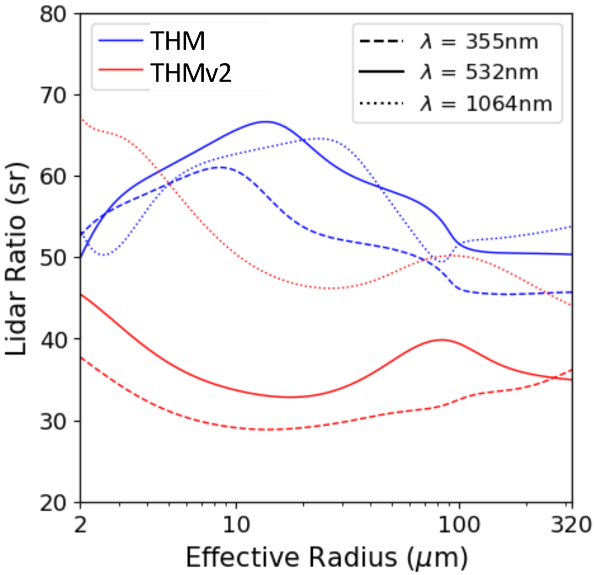
- 532nm Integrated Attenuated Backscatter (IAB) can be calculated from ice cloud optical thickness (ICOT;τ) and Lidar Ratio (S).
- Lidar Ratios calculated by THM and THMv2 P_{11} backscatter and compared against collocated CALIOP IAB and CloudSat ICOT of ice cloud cases.
  - Entire year of 2009, 2010, 2013, 2014.
  - Multiple scattering factor (η) ranges from 0.5 to 0.8 to account for temperature and particle size.
- THMv2 has significantly improved consistency.

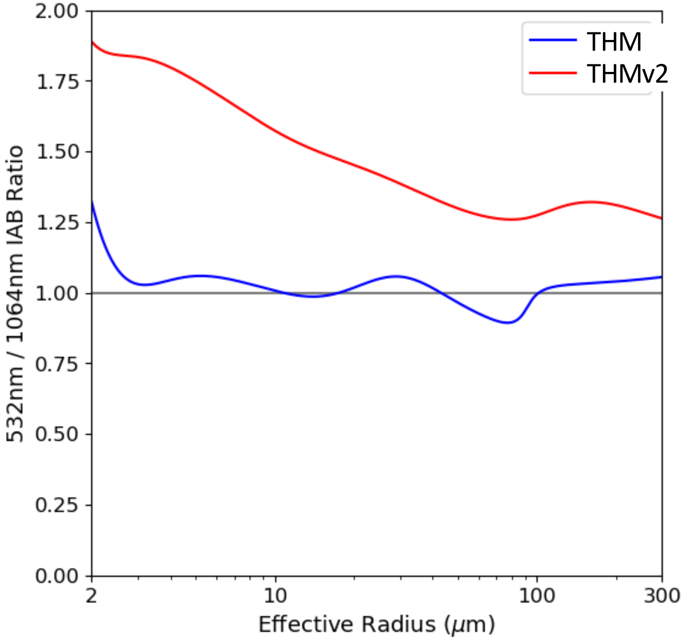


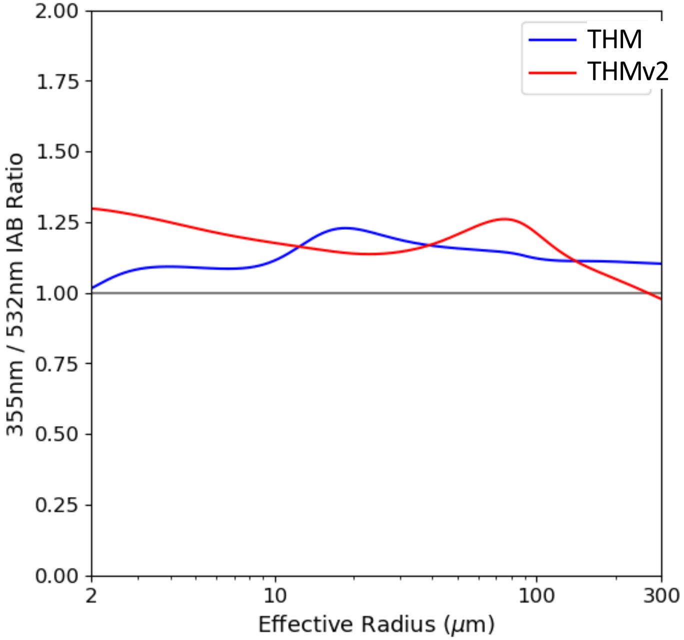


IAB Comparisons between Two Wavelengths

- CALIOP assumes opaque ice clouds have same IAB for 532 and 1064nm wavelengths.
- THMv2 532/1064nm IAB ratios disagree with assumption.
  - ○ 1064nm has significantly higher imaginary refractive index (greater absorption).
- THMv2 355/532nm IAB ratios remain mostly close to 1:1 value.







$$IAB = \frac{1}{2\eta S}$$

Summary

- Investigated the influence of ice cloud optical model consistency in passive ice cloud retrieval and broadband radiation parameterization
  - MC6 and THM ice particle models overestimate SW and LW ice CREs.
  - Horizontal radiative transfer increases vertical radiative heating/cooling gradients near cloud top.
- Further expanded THMv2 lidar consistency study.
  - THMv2 remains consistent to collocated IAB-ICOT observations over a multiple scattering factor range.
  - THMv2 532/1064 IAB ratios disprove CALIOP assumption that IABs are equal for both wavelengths of observed opaque ice clouds.

Upcoming Manuscripts

Ren, T., Yang, P., Loeb, N. G., Smith Jr., W. L., and Minnis, P. (2023). On the consistency of ice optical models for spaceborne remote sensing applications and broadband radiative transfer simulations. *Journal of Geophysical Research Atmospheres.* (Forthcoming-submitted)

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Coy, J., Saito, M., Yang, P., Liu, X., and Hu, Y. (2023) Improved ice cloud backscattering with physical geometric optics method for lidar-based remote sensing applications. *Institute of Electrical and Electronics Engineers.* (Forthcoming-not submitted)

jcoy93@tamu.edu (James Coy)