Updates on ice cloud optical property development and study of cloud radiative effects with the use of spherical harmonic functions

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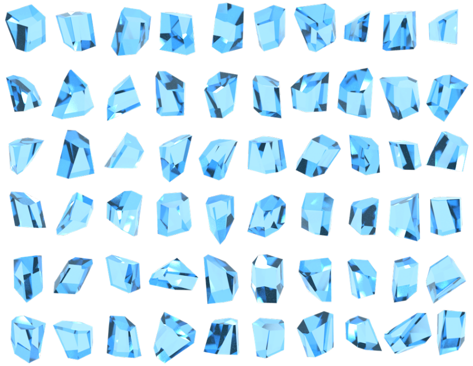
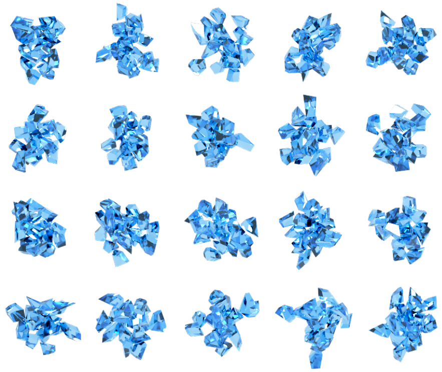
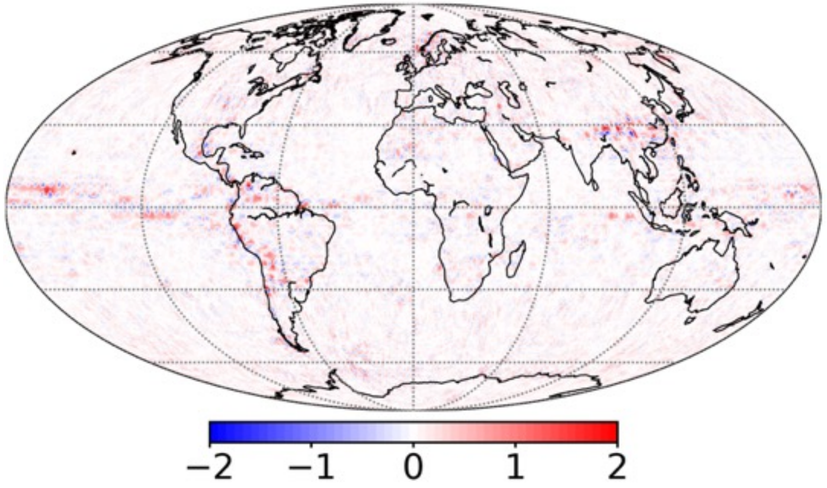






Current Progress Overview

- **Full resolution database of new Two-Habit Model (THM-new) finalized.**
  - Implemented accurate Physical Geometric Optics Method (PGOM) backscattering calculations to shortwave wavelength regime (94 wavelengths).
    - Over 1 year computational effort (January 2021 – February 2022).
    - Estimated Texas A&M HPRC supercomputer service unit (SU) cost:

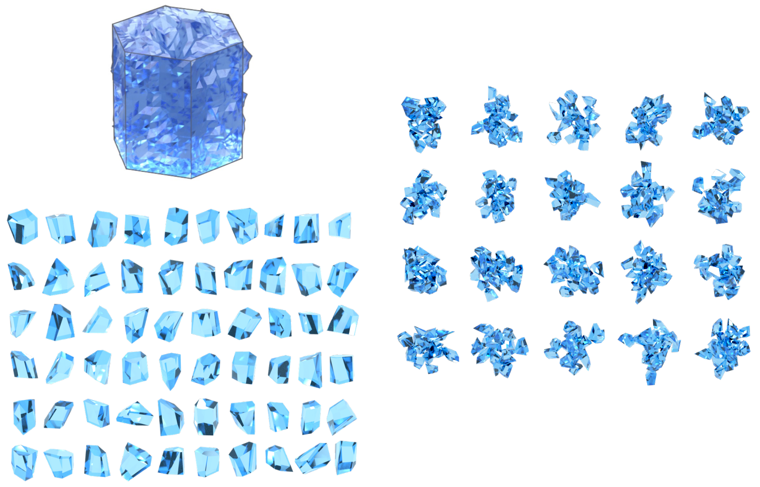
$$(80\ particles)\times(94\ wavelengths)\times(189\ sizes)\times(\sim 5\ SU\ per\ job) = \sim 7{,}000{,}000\ SU\ (822\ years)$$

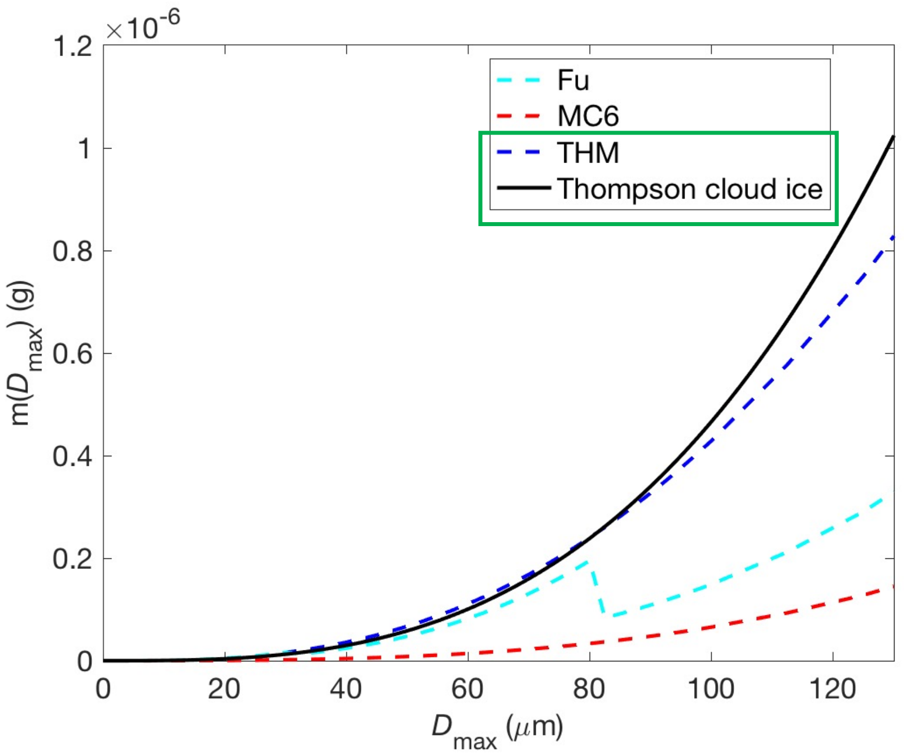
  - Added Lidar-specific wavelengths.
  - Performed preliminary validation of THM-new for active Lidar remote sensing retrieval consistency.

- **Performed expansion of spherical harmonics function to represent global distribution of clouds.**
  - Validated by the computations of the Rapid Radiative Transfer Model for GCMs (RRTMG).

Reasons for a new Two-Habit Model Database

- Current ice cloud models have inaccurate backscattering for moderate size parameters.
  - Improved Geometric Optics Model (IGOM) less accurate.
  - **Affects lidar-based retrievals and assumptions needed to be made.**
- Invariant Imbedding T-Matrix Method (IITM) does not handle small-scale surface roughness.
  - Computationally expensive so only smooth particles used.
- The THM follows the Thompson et al. 2008 cloud ice scheme than other commonly used single-scattering databases.
  - Used with the Weather Research and Forecasting (WRF) Model.

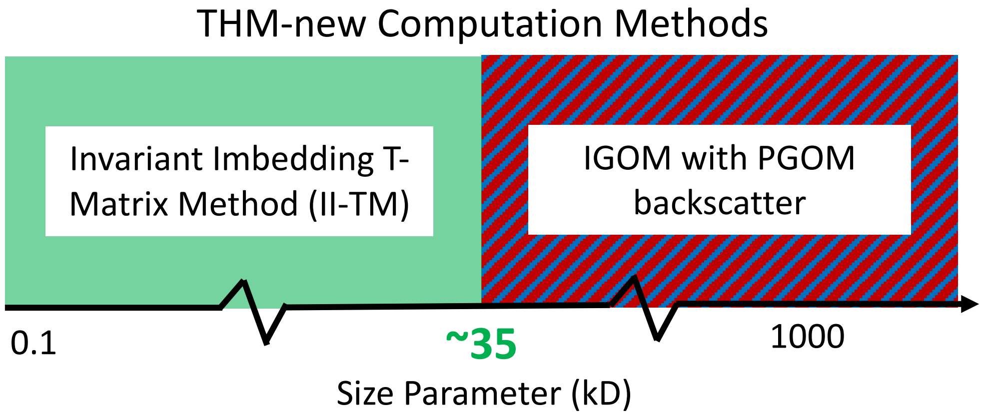


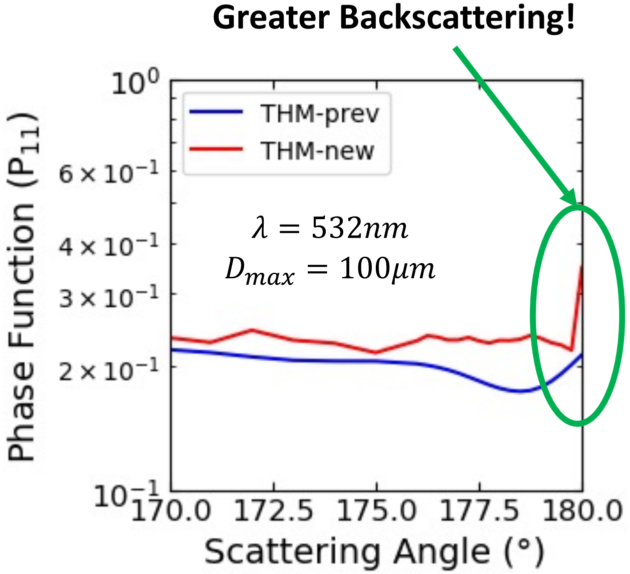


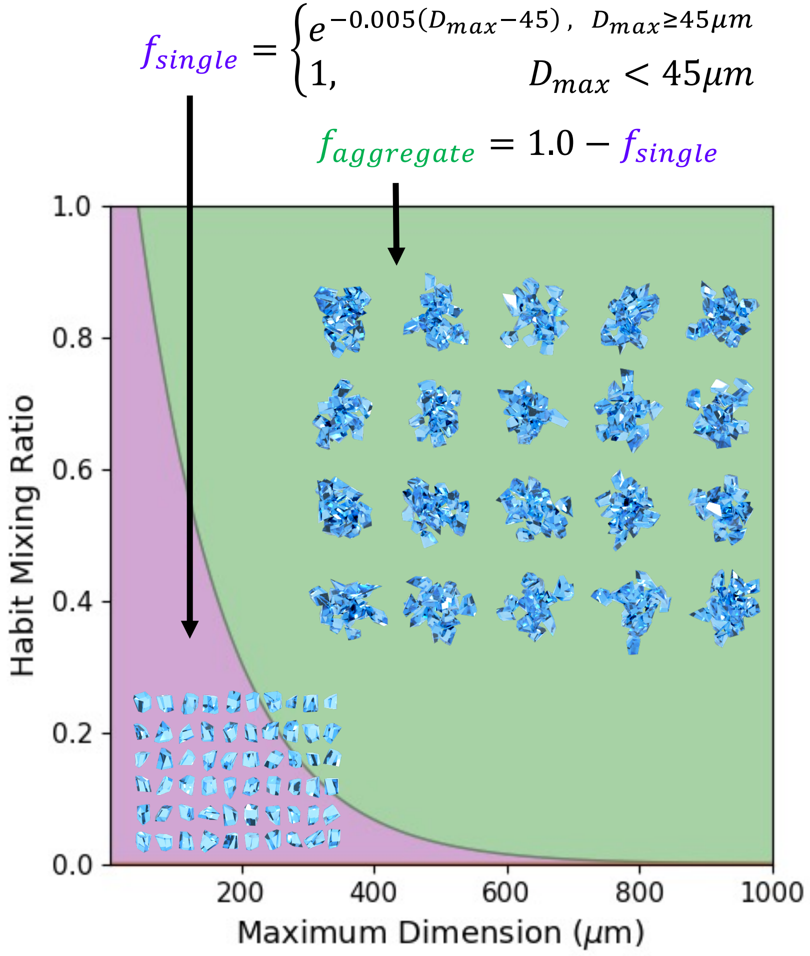
Finalized Full Resolution Two Habit Model (THM-new)

- 60-particle distorted single column and 20-particle distorted 20-column aggregate ensembles.
- Now includes 3 Lidar-specific wavelengths.
- 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).

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

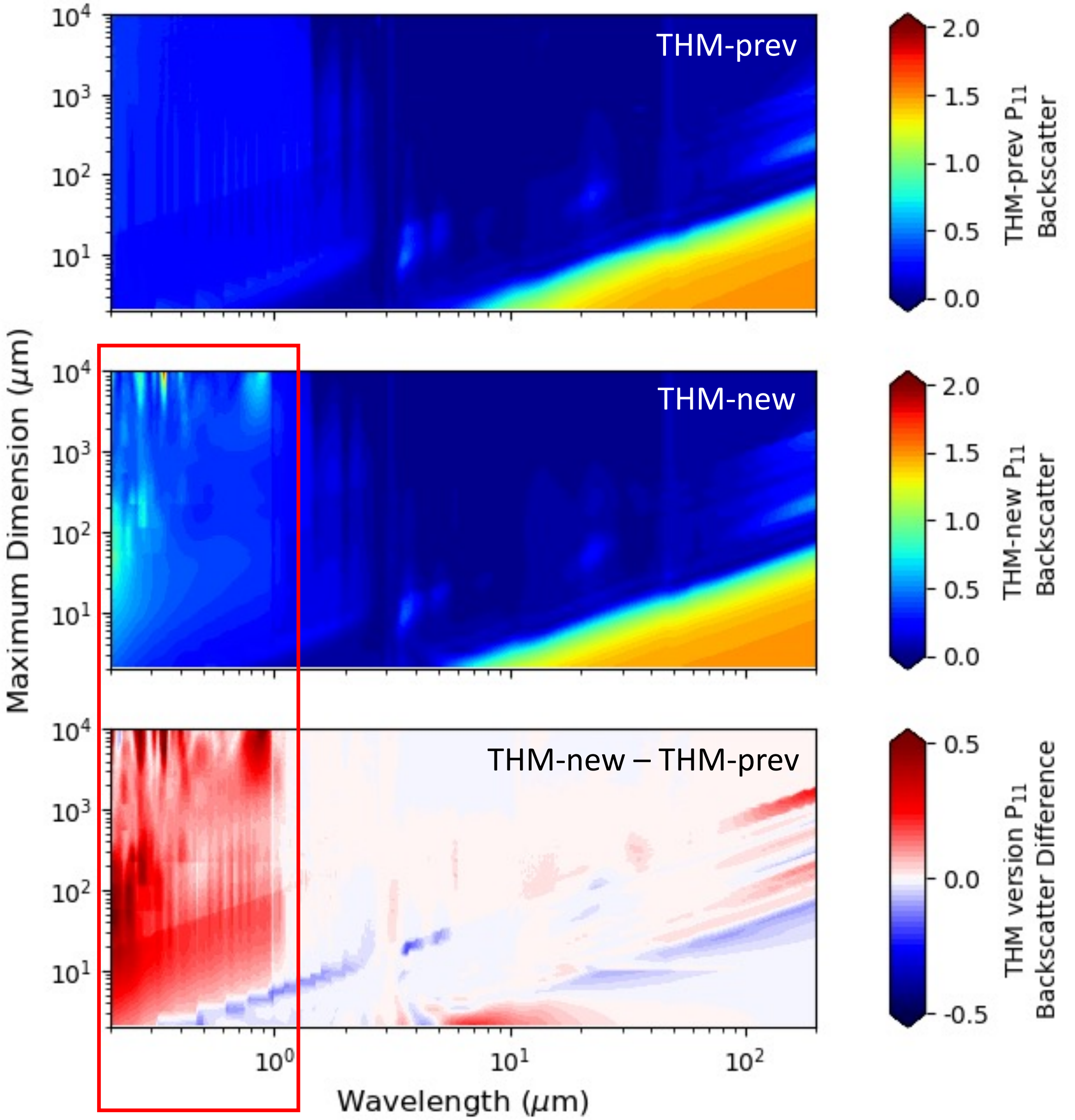






Phase Function Backscattering Comparison

- PGOM phase function (P_{11}) backscattering (180°) calculations compared with previous THM (THM-prev).
  - THM-prev (Loeb et al., 2018) only has IGOM calculations with roughened hexagonal column as "simple" habit.
- $P_{11}(180°)$ differences concentrated within 0.2 – 1.1μm wavelengths.
  - THM-new has generally higher backscatter.

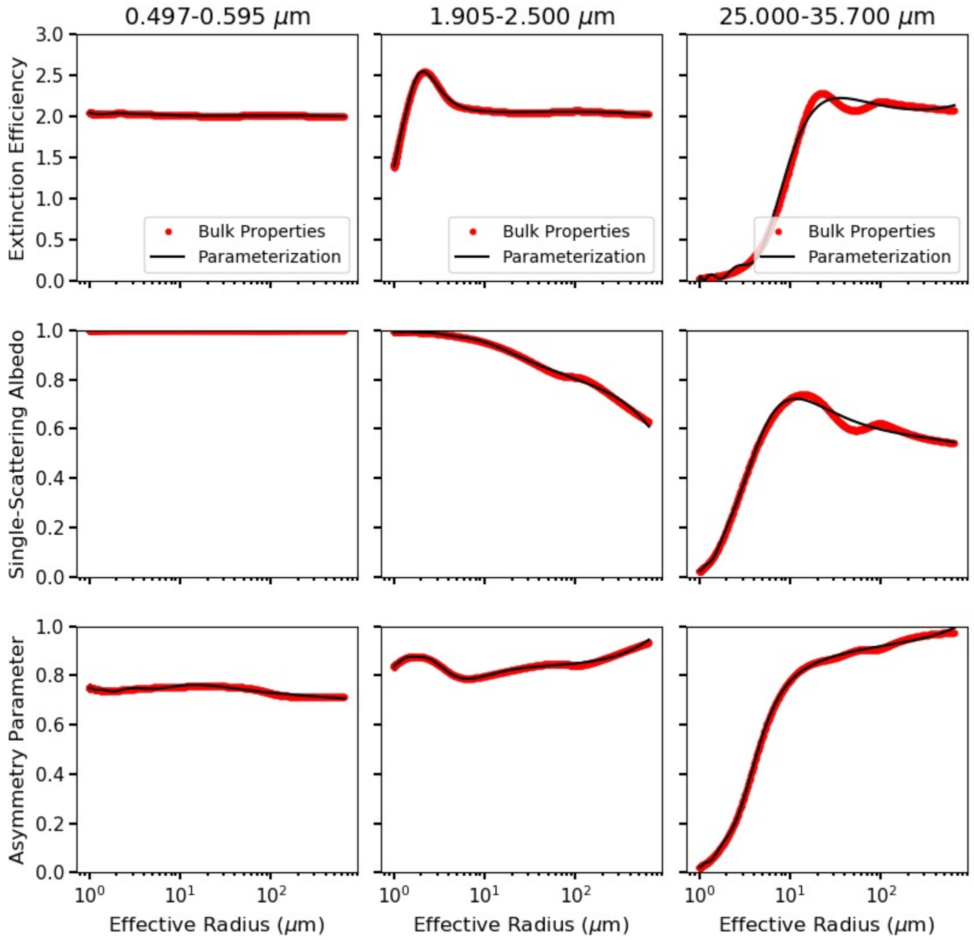


Bulk Radiative Parameterization for Fu-Liou RTM

- Remains unchanged in regards to improved phase matrix backscattering.
- Parameterization performed for **18 shortwave bands and 14 longwave bands**.
- Utilizes a **10-term polynomial equation for bulk extinction efficiency, scattering albedo, and asymmetry parameter**.
    - Coefficients (c_i) derived from least square linear regression.

Fu-Liou Parameterization Formula

$$\langle Qext \rangle, \langle \omega \rangle, \langle g \rangle = \sum_{i=0}^{9} c_i r_{eff}^{1-i}$$



Shortwave Bands			
#	**Bandwidth (μm)**	**Band Avg (μm)**	**Gases**
1	0.175 – 0.224	0.21	O3
2	0.224 – 0.243	0.23	O3
3	0.243 – 0.285	0.26	O3
4	0.285 – 0.298	0.29	O3
5	0.298 – 0.322	0.31	O3
6	0.322 – 0.357	0.33	O3
7	0.357 – 0.437	0.38	O3
8	0.437 – 0.497	0.46	O3 / H2O
9	0.497 – 0.595	0.53	O3 / H2O
10	0.595 – 0.689	0.63	O3 / H2O
11	0.690 – 0.794	0.72	H2O / O2 / O3
12	0.794 – 0.889	0.83	H2O
13	0.889 – 1.042	0.94	H2O
14	1.042 – 1.410	1.16	H2O
15	1.410 – 1.905	1.57	H2O / CO2
16	1.905 – 2.500	2.10	H2O / CO2 / CH4
17	2.500 – 3.509	2.84	H2O / CO2 / O3 / CH4
18	3.509 – 4.000	3.67	H2O / CO2 / CH4

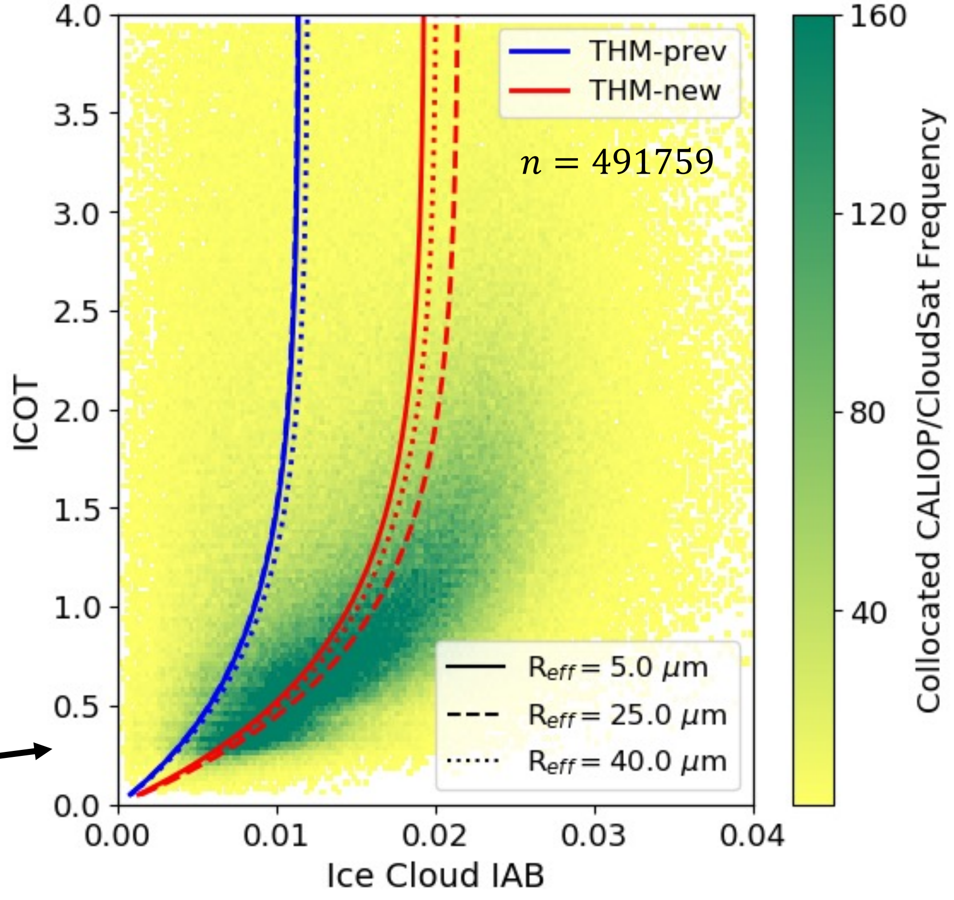
Longwave Bands			
#	**Bandwidth (μm)**	**Band Avg (μm)**	**Gases**
1	4.54 – 5.26	4.78	H2O
2	5.26 – 5.88	5.47	H2O
3	5.88 – 7.14	6.30	H2O
4	7.14 – 8.00	7.43	H2O / CH4 / N2O
5	8.00 – 9.09	8.36	H2O / CH4 / N2O / Cfc
6	9.09 – 10.2	9.46	H2O / O3 / Cfc
7	10.2 – 12.5	10.97	H2O / Cfc
8	12.5 – 14.9	13.30	H2O / CO2
9	14.9 – 18.5	16.10	H2O / CO2
10	18.5 – 25.0	20.67	H2O
11	25.0 – 35.7	28.57	H2O
12	35.7 – 99.0	56.80	H2O
13	3.50 – 4.00	3.67	H2O / CO2
14	4.00 – 4.50	4.18	H2O / N2O / CO2

Lidar-Based Retrieval Consistency

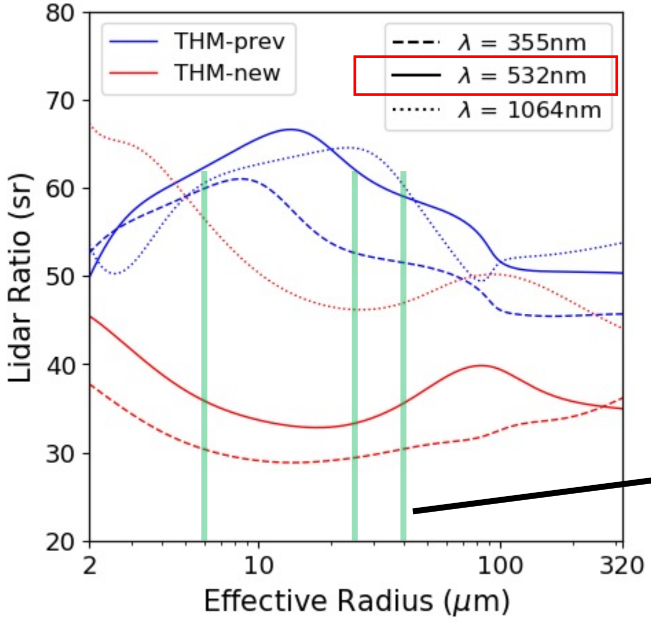
- 532nm Integrated Attenuated Backscatter (IAB) can be calculated from ice cloud optical thickness (ICOT) and Lidar Ratio (S).
- Lidar Ratios calculated by THM-new and THM-prev P_{11} backscatter and compared against collocated CALIOP IAB and CloudSat ICOT of ice cloud cases.
  - Entire year of 2009, 2010, 2013, 2014.
- THM-new has significantly improved consistency.

$$IAB = \frac{1 - e^{-2\eta\tau}}{2\eta S}$$

Collocated 532nm CALIOP IAB and CloudSat ICOT Frequency Distribution

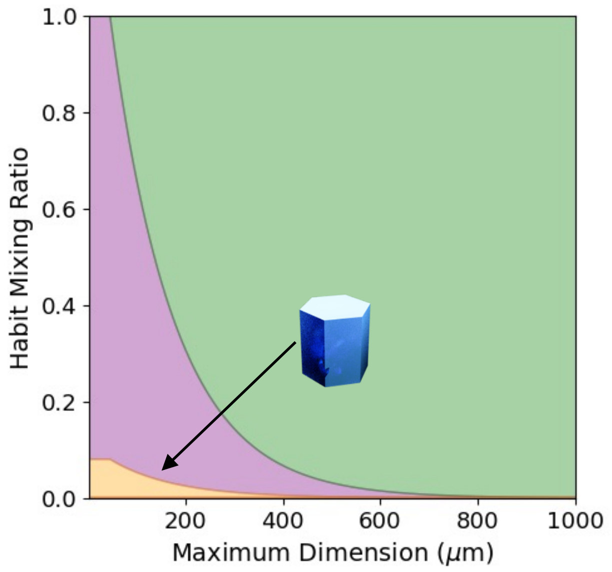


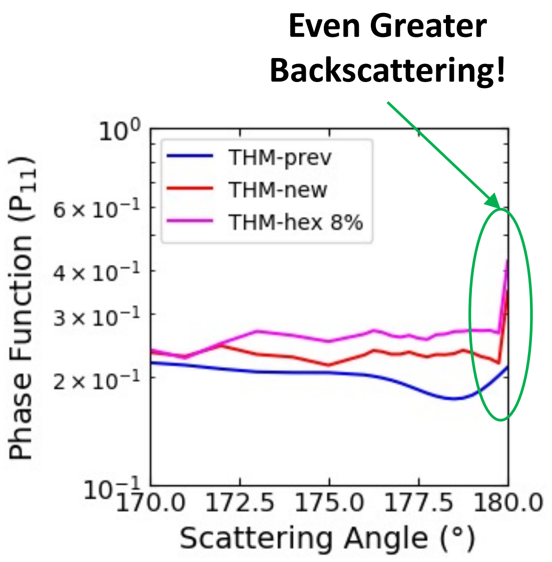
$$S = \frac{4\pi}{\omega_{bulk} P_{11,bulk}(180°)}$$

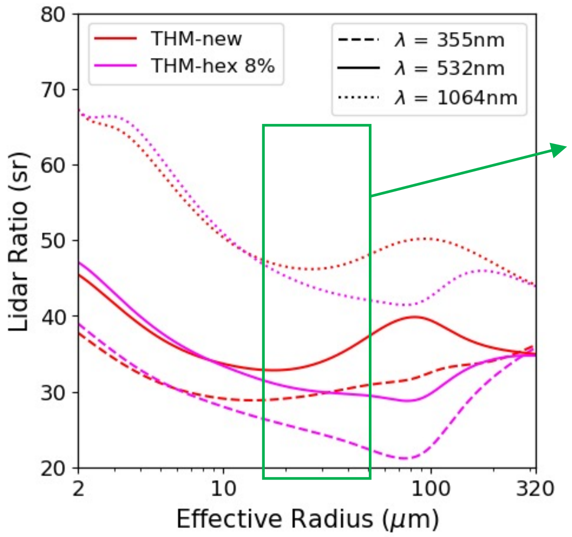


Further Optimizing THM-new with Smooth Hexagonal Columns

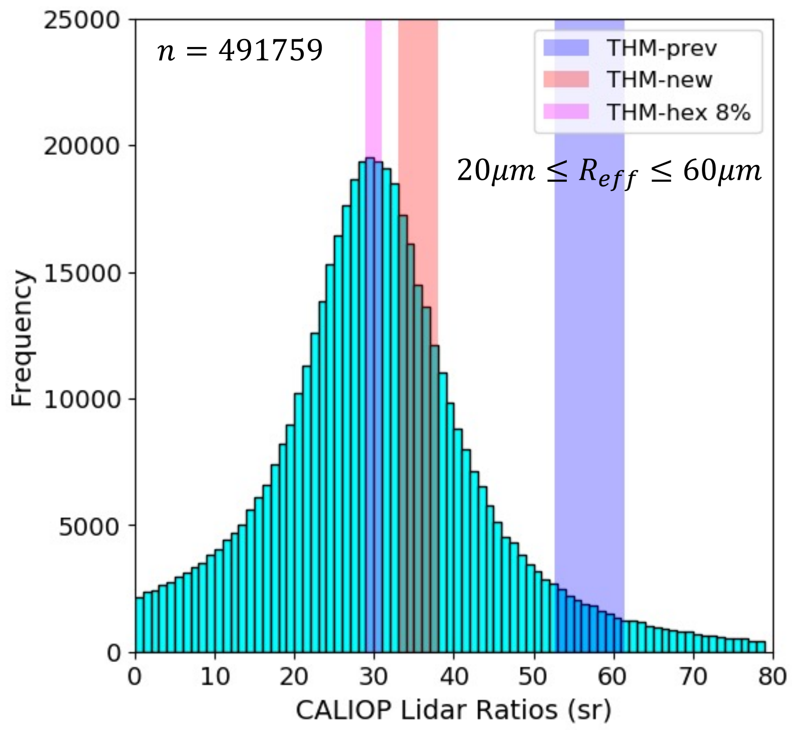
- THM-new 532nm lidar ratios still inconsistent with mode of CALIOP lidar ratios.
- Including small habit fraction of smooth hexagonal column further improves consistency (THM-hex).
  - Plan to find optimal hexagonal column habit fraction to include in THM-new based on latitudinal trends in lidar ratio and IAB-ICOT relationship.
  - Separate collocated cases into 10° or 5° latitude bins.







Collocated 532nm CALIOP Lidar Ratio Frequency Distribution



Spherical harmonic expansion of cloud properties

$$C_{l,m} = \int_0^{2\pi}\int_0^{\pi} \tau(\theta,\varphi) Y^*_{l,m}(\theta,\varphi)\sin\theta d\theta d\varphi$$

$$\tau_L(\theta,\varphi) \approx \sum_{l=0}^{L}\sum_{m=-l}^{m=l} C_{l,m}Y_{l,m}(\theta,\varphi)$$

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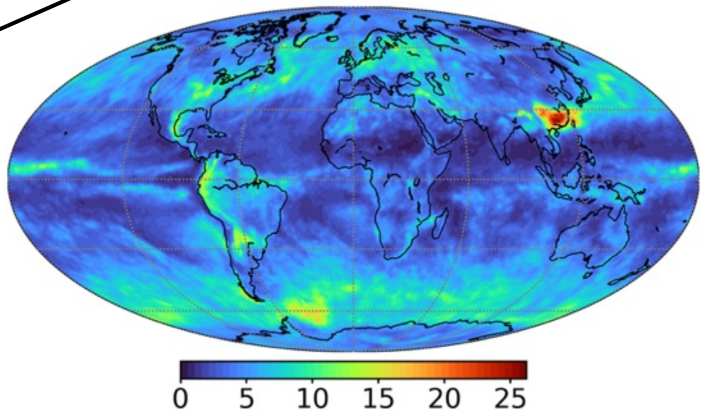
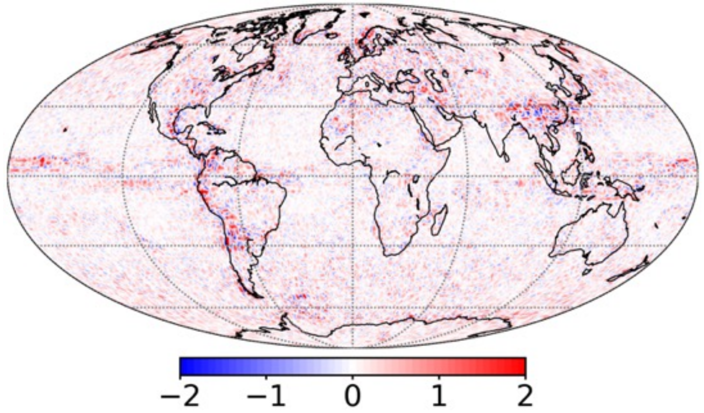
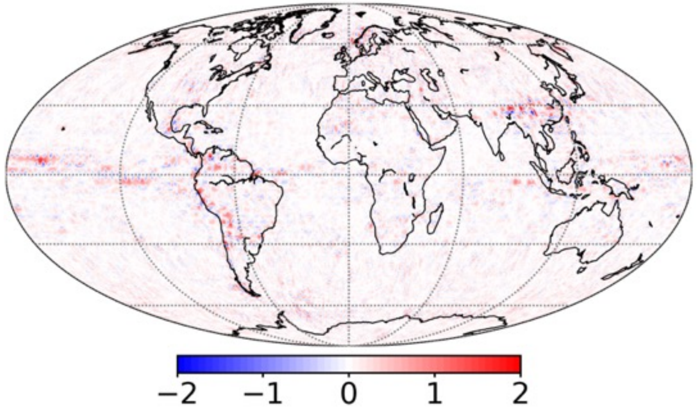
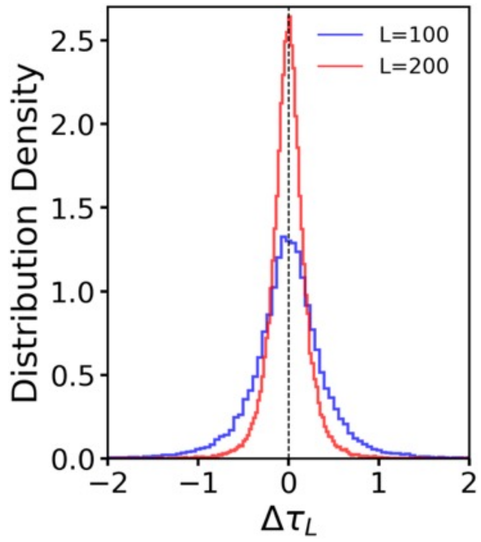


$\Delta\tau_L$, $L = 100$

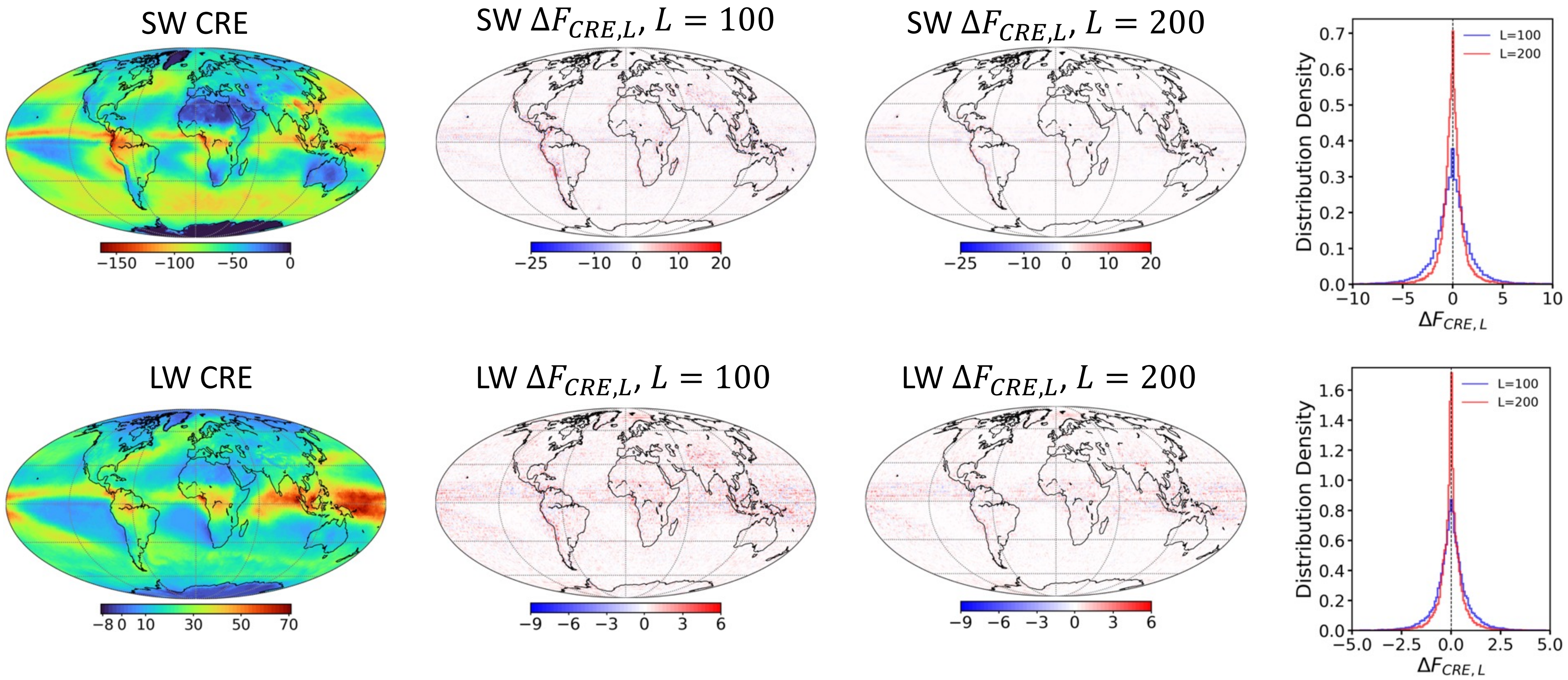


$\Delta\tau_L$, $L = 200$





RRTMG computation with reconstructed cloud properties

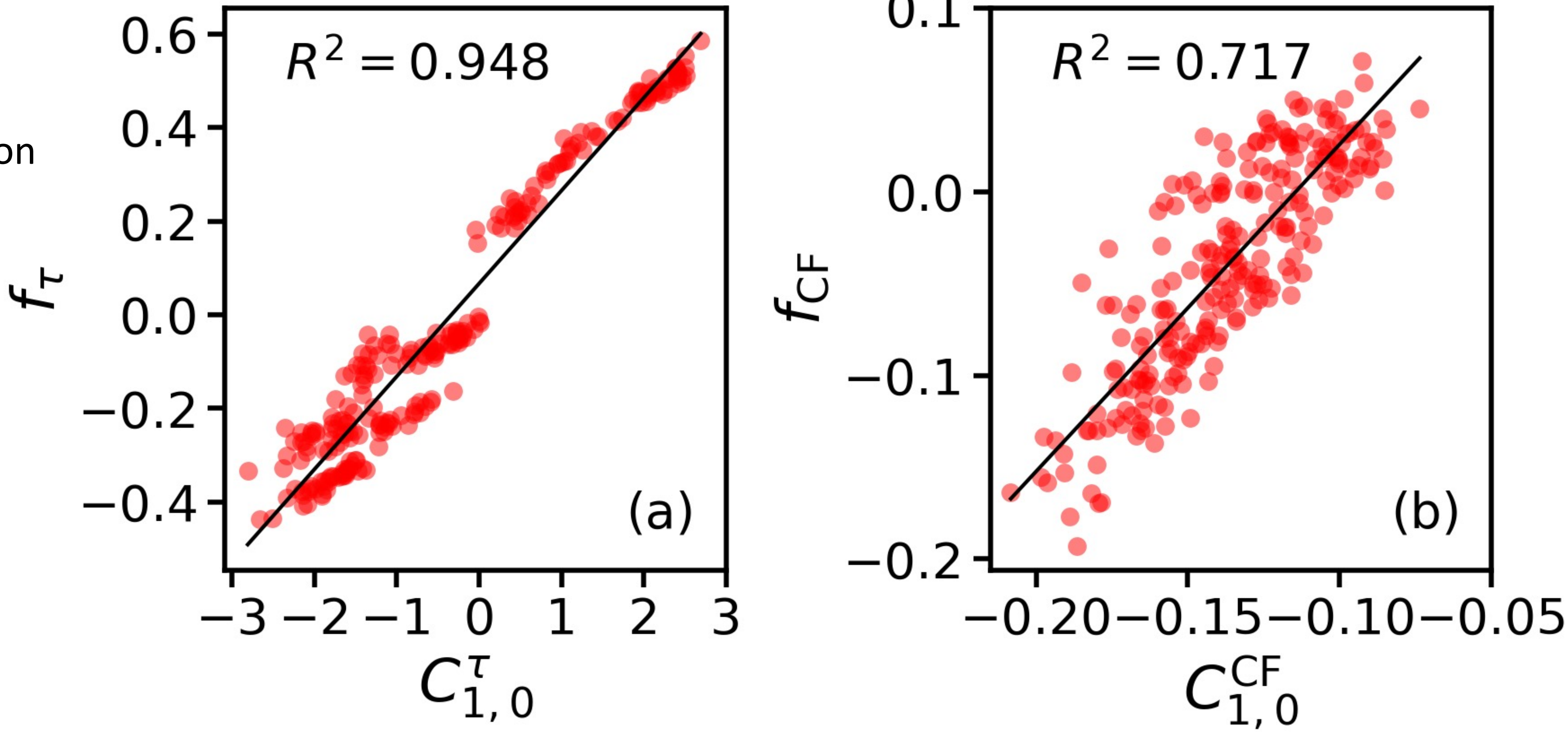


Spherical harmonic expansion coefficients

Asymmetry of cloud hemispheric distribution

$$f_\tau = \frac{\bar{\tau}_\mathrm{N} - \bar{\tau}_\mathrm{S}}{\bar{\tau}_\mathrm{globe}}$$

$$f_\mathrm{CF} = \frac{\overline{\mathrm{CF}}_\mathrm{N} - \overline{\mathrm{CF}}_\mathrm{S}}{\overline{\mathrm{CF}}_\mathrm{globe}}$$



Summary and Future Work

- **Full resolution database of new Two-Habit Model (THM-new) finalized and delivered.**
  - Added PGOM backscattering calculations to 94 shortwave wavelengths.
  - Improved consistency in the IAB-ICOT relationship to lidar observational data.
    - 1st draft of JGRL manuscript written and currently being revised.
  - Plans to modify THM-new to include small habit fractions of smooth hexagonal columns for lidar applications.
    - Optimize consistency to lidar observational data by latitudinal location of ice clouds.

- **Expansion of spherical harmonic function can accurately represent cloud properties on a global scale.**
  - Can even represent hemispheric asymmetry of cloud properties.
  - Explore cloud spatial distribution patterns using spherical harmonic expansion technique.