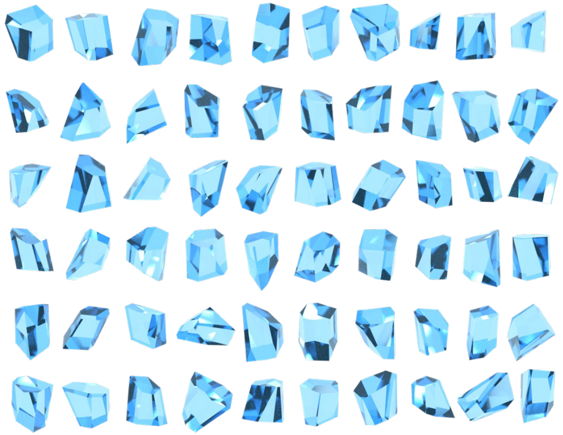
Testing the Active-Passive Ice Cloud Property Retrieval Consistency of the new THM and a new Temperature-Dependent Database

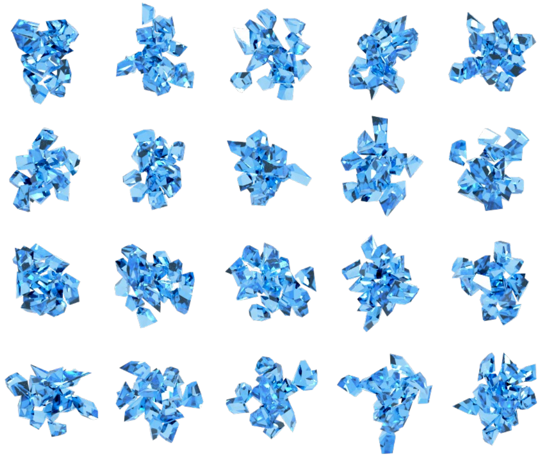
James Coy (Presenting Author), Dongchen Li, Ping Yang

Texas A&M University, Department of Atmospheric Sciences

CERES Science Team Meeting, Hampton, VA

May 14-16, 2024





NASA Optical Property Calculations Continuation Project

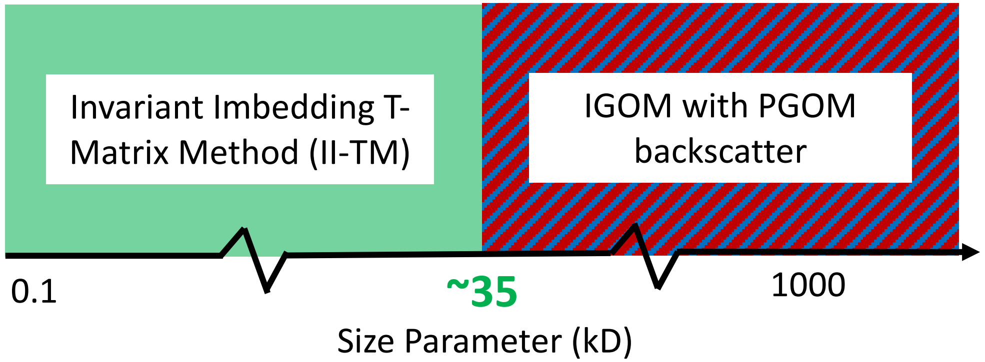
- Based on the suggestion that the same ice optical model should be used in a broadband radiation computation and retrieving the cloud description input to the broadband radiation model (Loeb et. al. 2018).
  - New Two-Habit Model (THMv2) optical property database developed and undergone preliminary testing for active-passive sensor ice cloud property retrieval consistency.
- New goal is to continue assessing the performance of THMv2 through extensive testing of spectral consistency and active-passive sensor consistency using observational data of various remote sensing instruments.
  - GOES-16/17, MODIS and VIIRS spectral consistency.
  - CALIPSO's CALIOP and IIR active/passive retrieval consistency.
- Another new goal is to develop a temperature-dependent THMv2 database for far-infrared (FIR) bands for the broadband radiative transfer model used by CERES Team.

New Broadband Two Habit Model Database (THMv2)

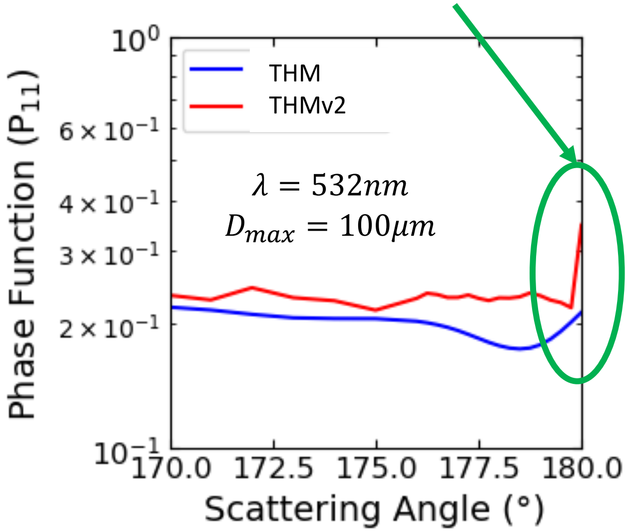
- 60-particle distorted single column and 20-particle distorted aggregate ensembles.
- Builds on the concept of the previously developed THM (Loeb et al. 2018).
- More accurate phase matrix backscattering calculations from Physical Geometric Optics Method (PGOM).
  - Uses ray-tracing technique to analytically obtain electromagnetic near field and subsequently maps it to far field (physical optics).
  - Replaces existing Improved Geometric Optics Method (IGOM) backscattering calculations.

	THM2
Wavelength	470 bins **(0.2 – 200µm)** 3 Lidar bins: **355, 532, 1064nm**
Size (D_{max})	189 bins **(2.206 – 11031.337µm)**

THMv2 Computation Methods

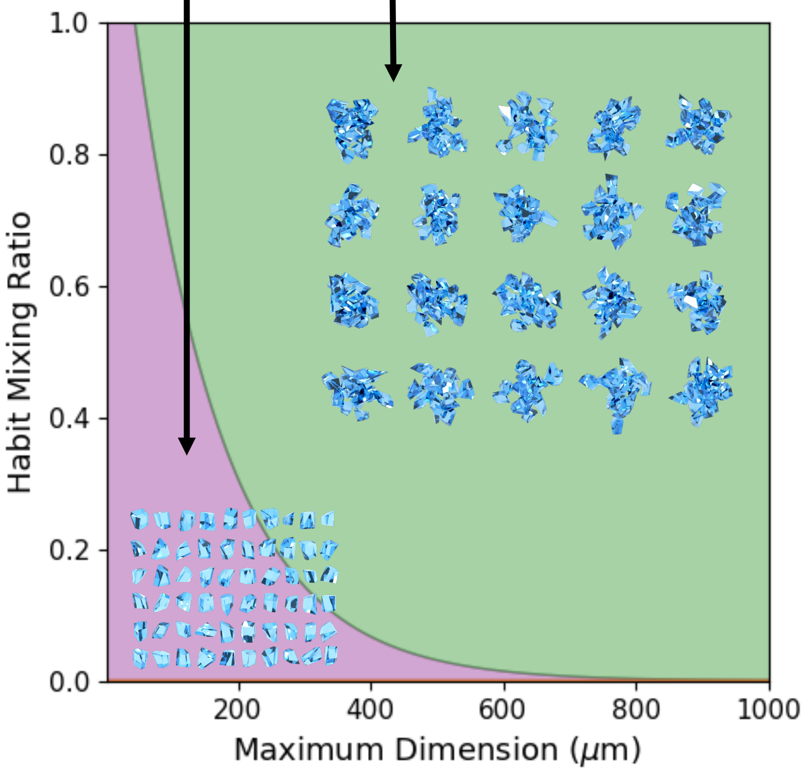


Greater Backscattering!



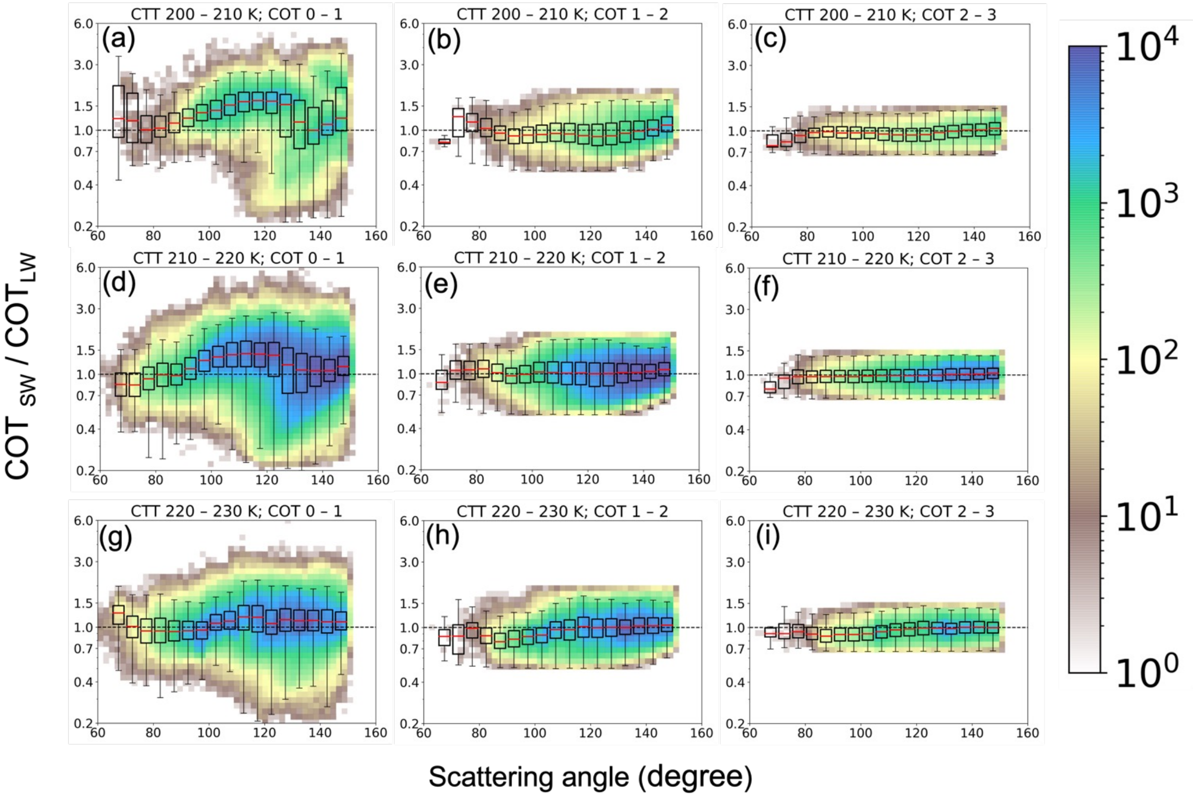
$$f_{single} = \begin{cases} e^{-0.0076(D_{max}-45)}, & D_{max} \geq 45\mu m \\ 1, & D_{max} < 45\mu m \end{cases}$$

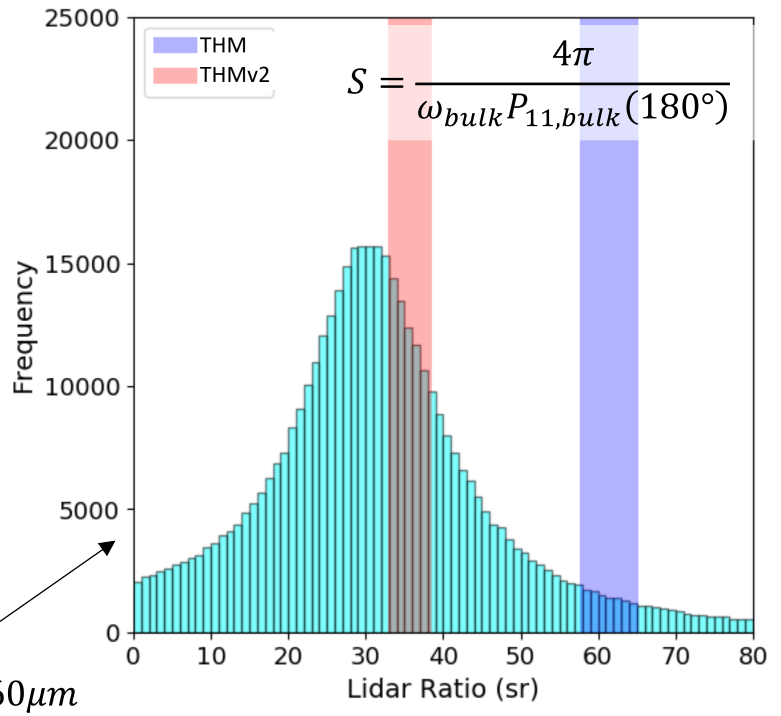
$$f_{aggregate} = 1.0 - f_{single}$$



Recap: THMv2 Rigorous Testing

- **Analytical results indicate THMv2 provided improved 532nm backscattering results in lidar ratio and integrated attenuated backscatter consistency with CALIOP observations.**
  - Active sensor consistency significantly improved.
- **THMv2 achieves optimal spectral consistency using GOES-17 data compared to simplistic ice particle models but biases exist for certain ranges of ice cloud optical thicknesses (COTs) and solar zenith angles (SZA).**
  - Determined the presence of mixed-phase clouds likely the cause of negative spectral consistency ratios for optically thin clouds and small SZA.
  - Causes of positive spectral consistency ratios biases for large SZA thought to be from longwave retrieval errors (cloud top temperature) but remain unexplained.

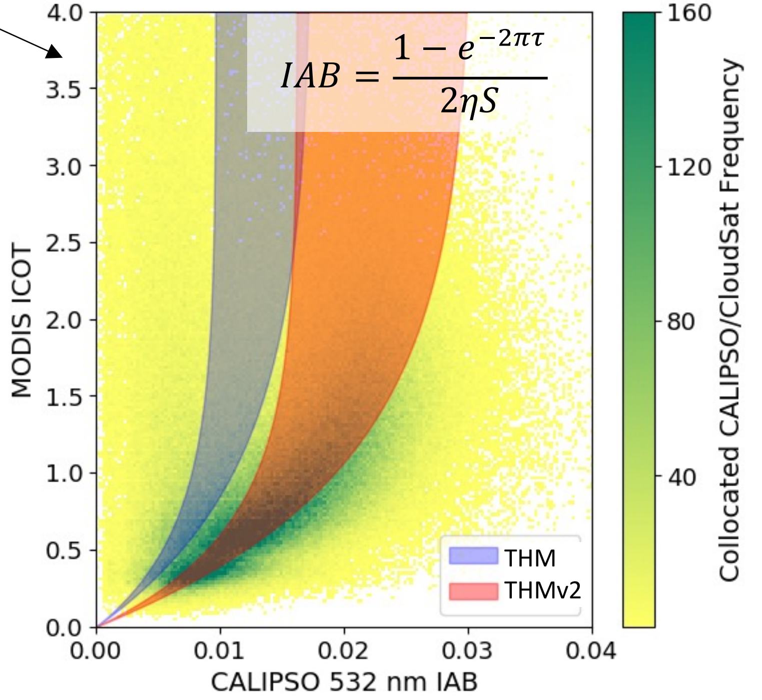




$$S = \frac{4\pi}{\omega_{bulk} P_{11,bulk}(180°)}$$

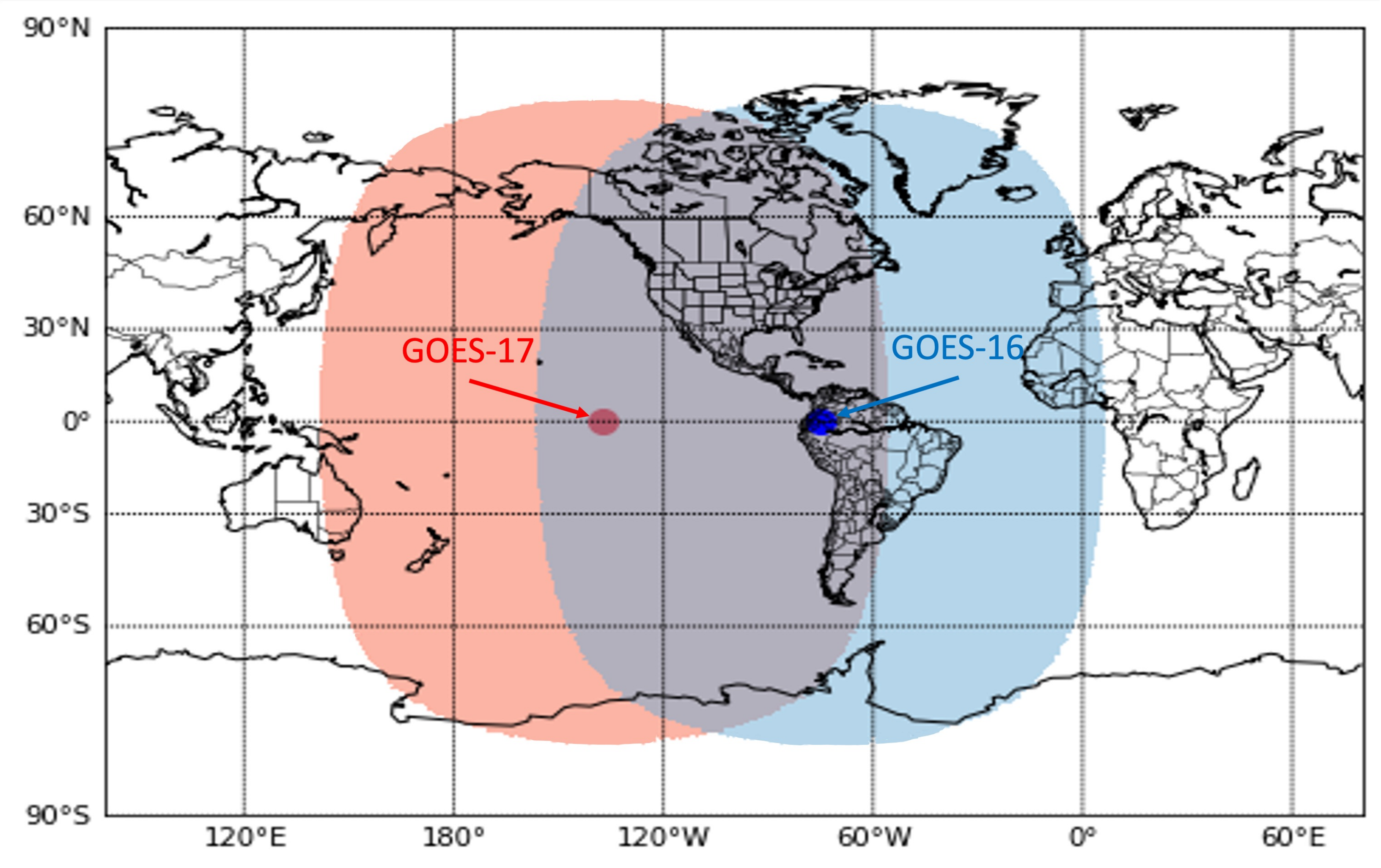
$n = 491759$

$20\mu m \leq R_{eff} \leq 60\mu m$



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

GOES-16 (East)/17 (West) Collocation and its Affect on COT Retrievals



Parallax Correction Algorithm

Geocentric angle

$$\beta = \frac{180}{\pi}\cos^{-1}(\cos(\varphi - \varphi_0)\cos(\lambda - \lambda_0))$$

Viewing azimuth angle

$$\eta_s = \frac{180}{\pi} cos^{-1}\frac{\sin\varphi_0 - \sin\varphi\cos\beta}{\cos\varphi\sin\beta}$$

where φ_0 and λ_0 are satellite subpoint latitude and longitude on Earth ,φ and λ are the latitude and longitude of the observation point on Earth.

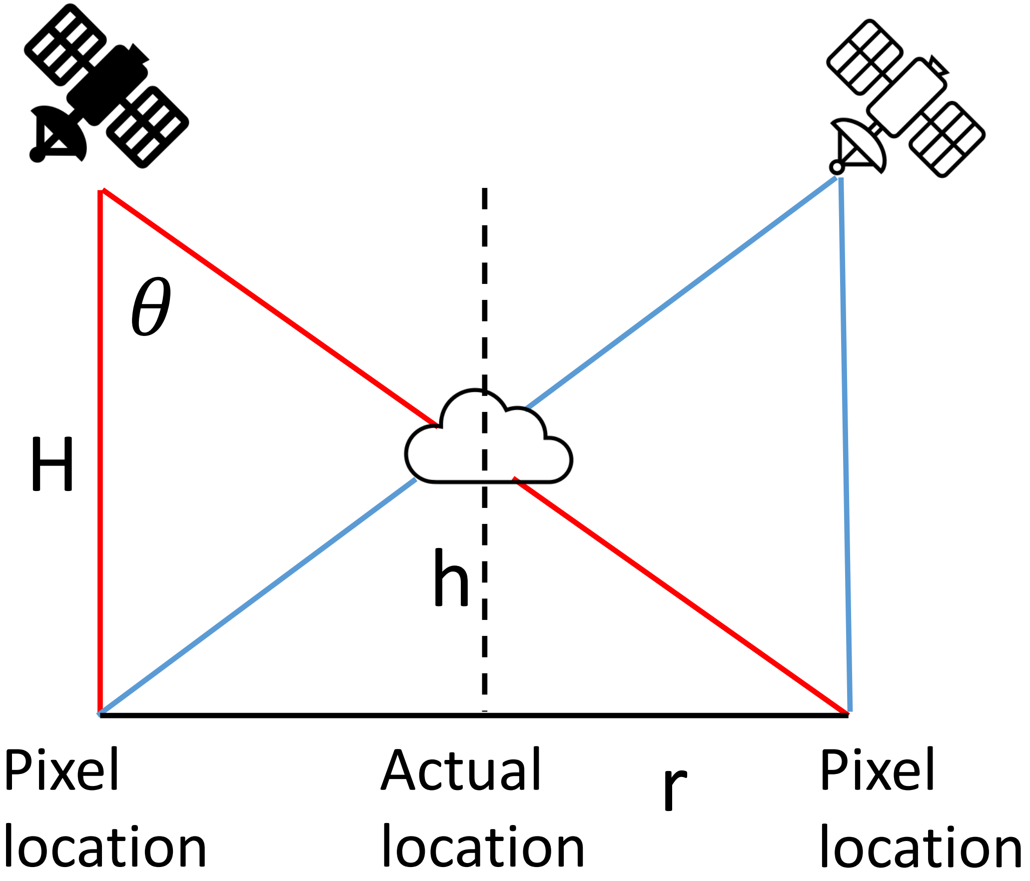
$$r = Hhtan(\frac{VZA}{H - h})$$

Where H is the operational altitude of GOES-R, h is the cloud top height and VZA is the viewing zenith angle of the pixel in radian.

$$\varphi_a = \varphi + \frac{r}{R_e} cos\ \eta_s$$

$$\lambda_a = \lambda + \frac{rsin\ \eta_s}{R_e * cos\varphi}$$

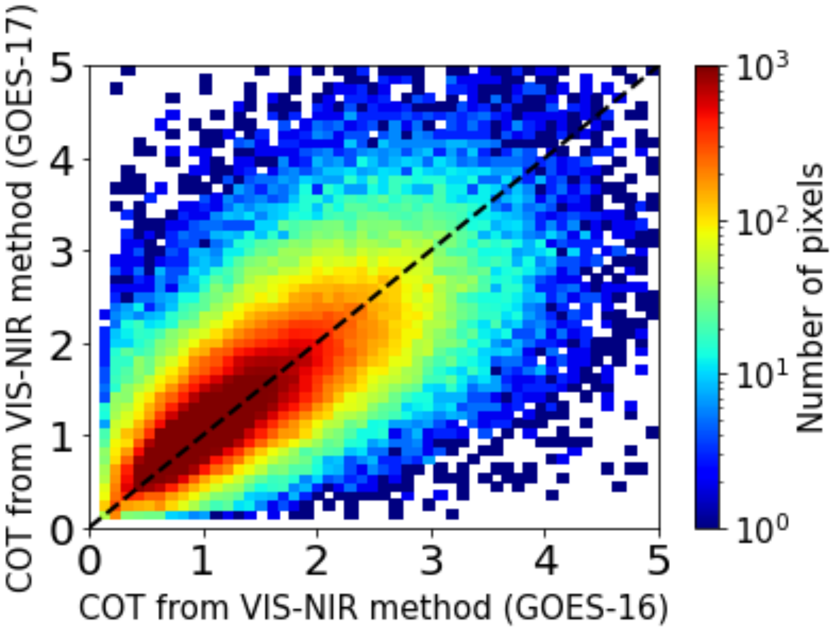
Where φ_a and λ_a are the actual latitude and longitude of the observed cloud, and R_e is the radius of earth.

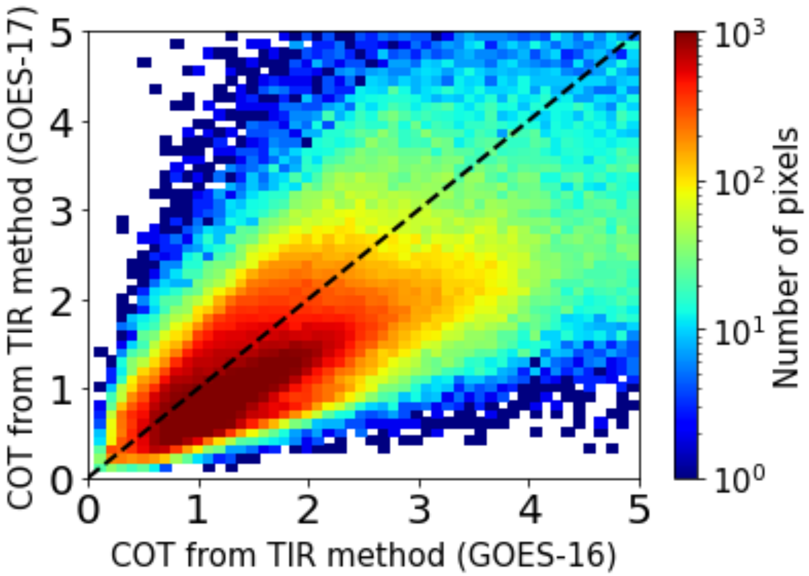


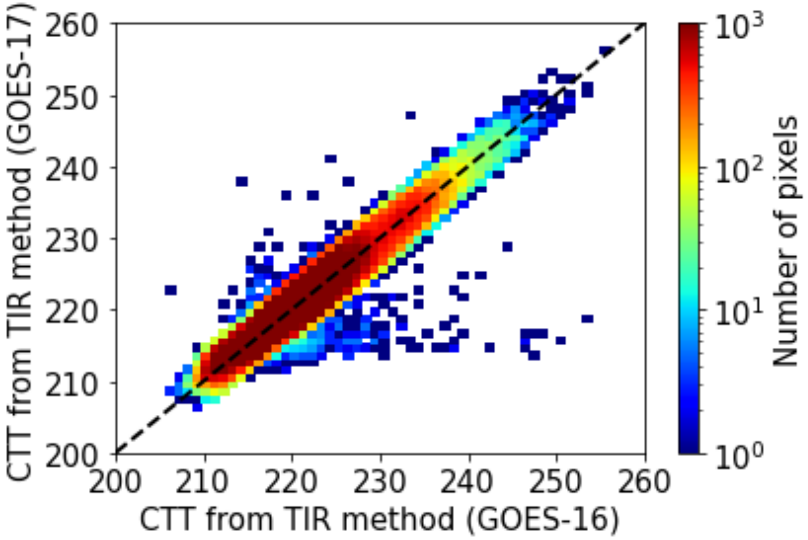
Collocation Process

- Interpolate MERRA-2 temperature profile and height data onto GOES-16/17 images.
- Based on the retrieved cloud top temperature (CTT), the cloud top height is obtained by the interpolation of the MERRA-2 temperature profile
- Apply the parallax correction algorithm to derive the actual geolocation of the clouds.
- Collocate GOES-16/17 pixels by identifying the nearest ones.

Comparison of retrieval results from VIS-NIR and TIR methods between GOES-16 and GOES-17 based on two days data collocation results (2019-09-24, 2020-03-20)

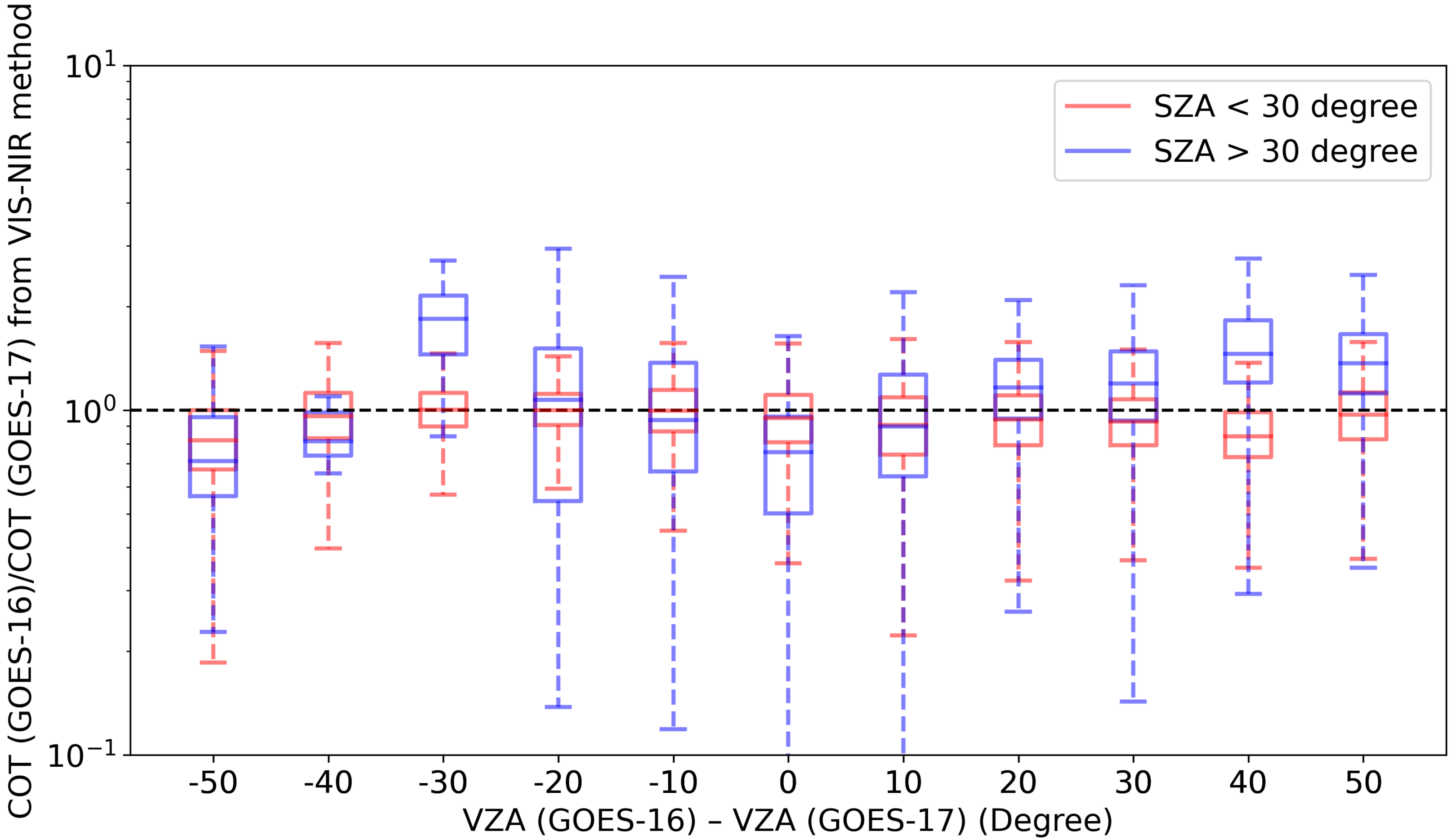






To reduce the uncertainty caused by the collocation process, we only select collocated pixels that have cloud top height difference ($|CTH_{GOES16}-CTH_{GOES17}|$) less than 0.5 km.

Retrieval Results from VIS-NIR Method

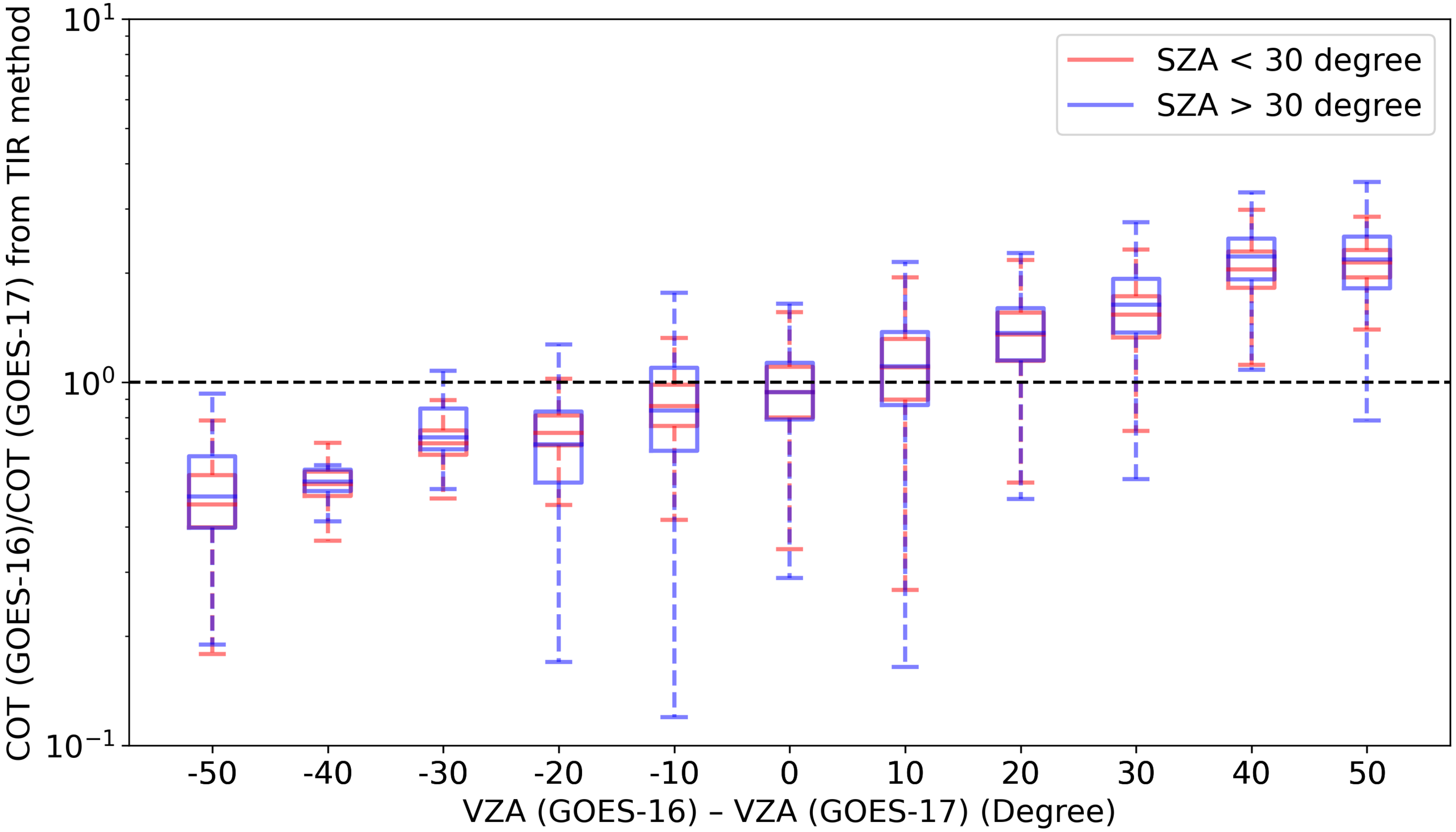


- GOES-16/17 COT Ratio:
  - < 1: greater GOES-17 COT
  - > 1: greater GOES-16 COT

- COT retrieval results have relatively small variation along with VZA when SZA is less than 30 degree.

- COT retrievals become more variant and exhibit higher uncertainty when the SZA exceeds 30 degrees, in contrast to cases where SZA is less than 30 degrees.

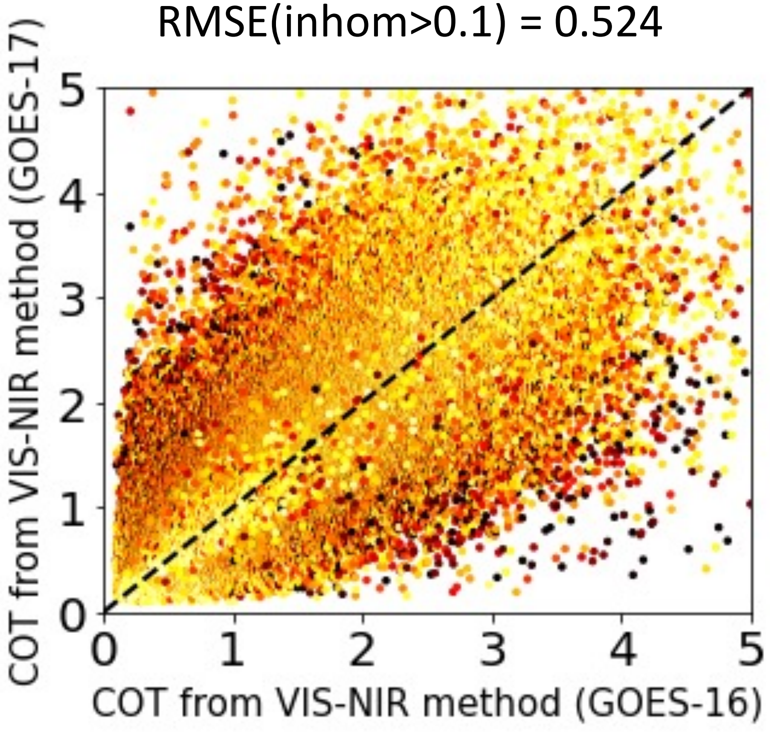
Retrieval Results from TIR Method



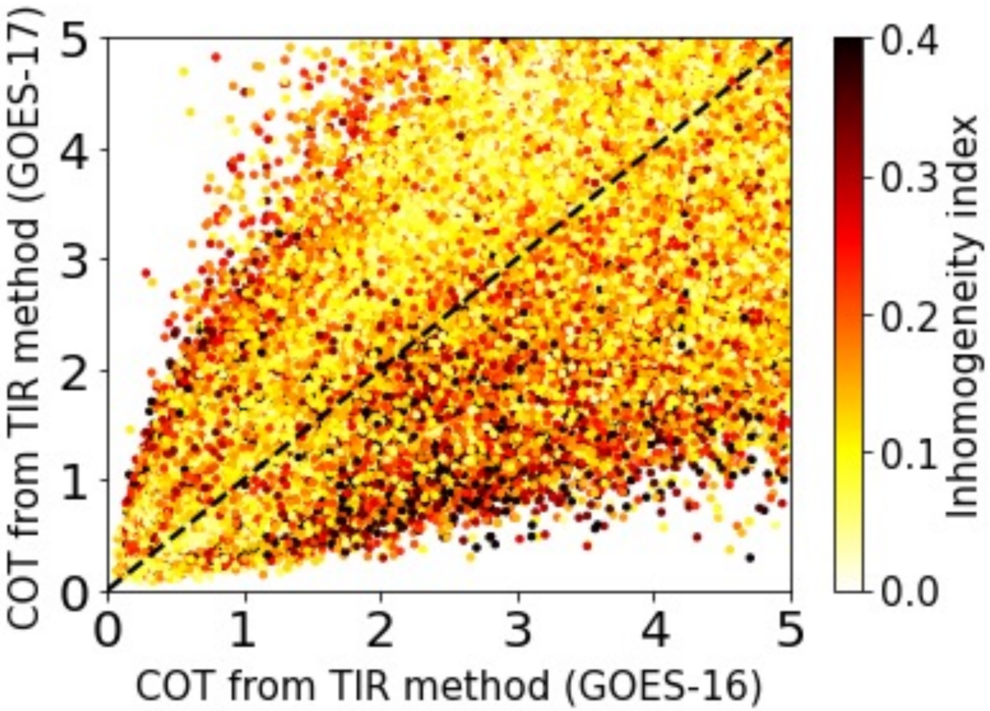
- COT retrieval results have strong dependence on VZA. Larger VZA leads to a larger COT retrieval results.

- COT retrievals show less dependence on SZA, while exhibiting slightly higher uncertainty when SZA is greater than 30 degree

RMSE(inhom<0.1) = 0.330
RMSE(inhom>0.1) = 0.524



RMSE(inhom<0.1) = 0.674
RMSE(inhom>0.1) = 0.714



Inhomogeneity index =

$$\frac{stdev[R(0.64\mu m, 500m)]}{mean[R(0.64\mu m, 500m)]}$$

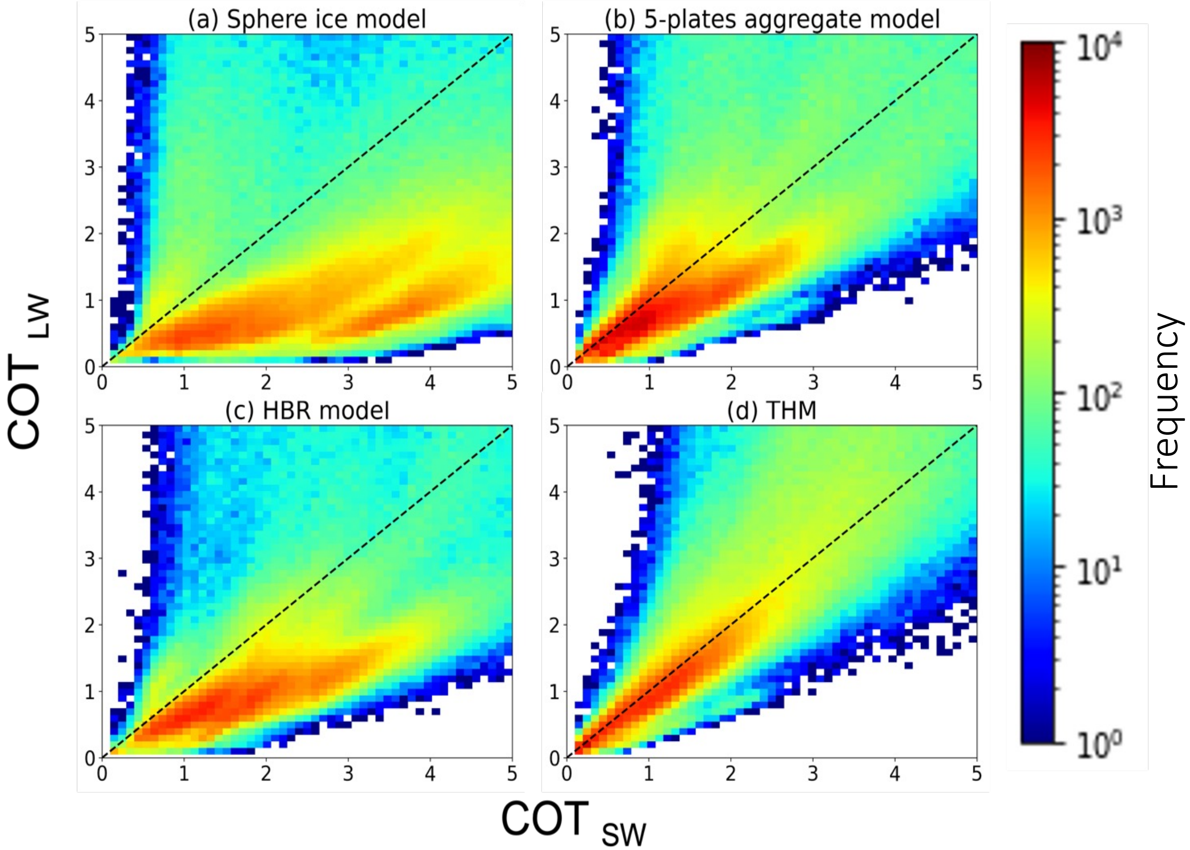
- For the VIS-NIR method, COT retrievals from GOES-16 and GOES-17 demonstrate good consistency when cloud inhomogeneity is low. However, as cloud inhomogeneity increases, this consistency diminishes.

- For the TIR method, COT retrievals have less dependence on cloud inhomogeneity.

THMv2 Spectral Consistency Tests for MODIS Bands

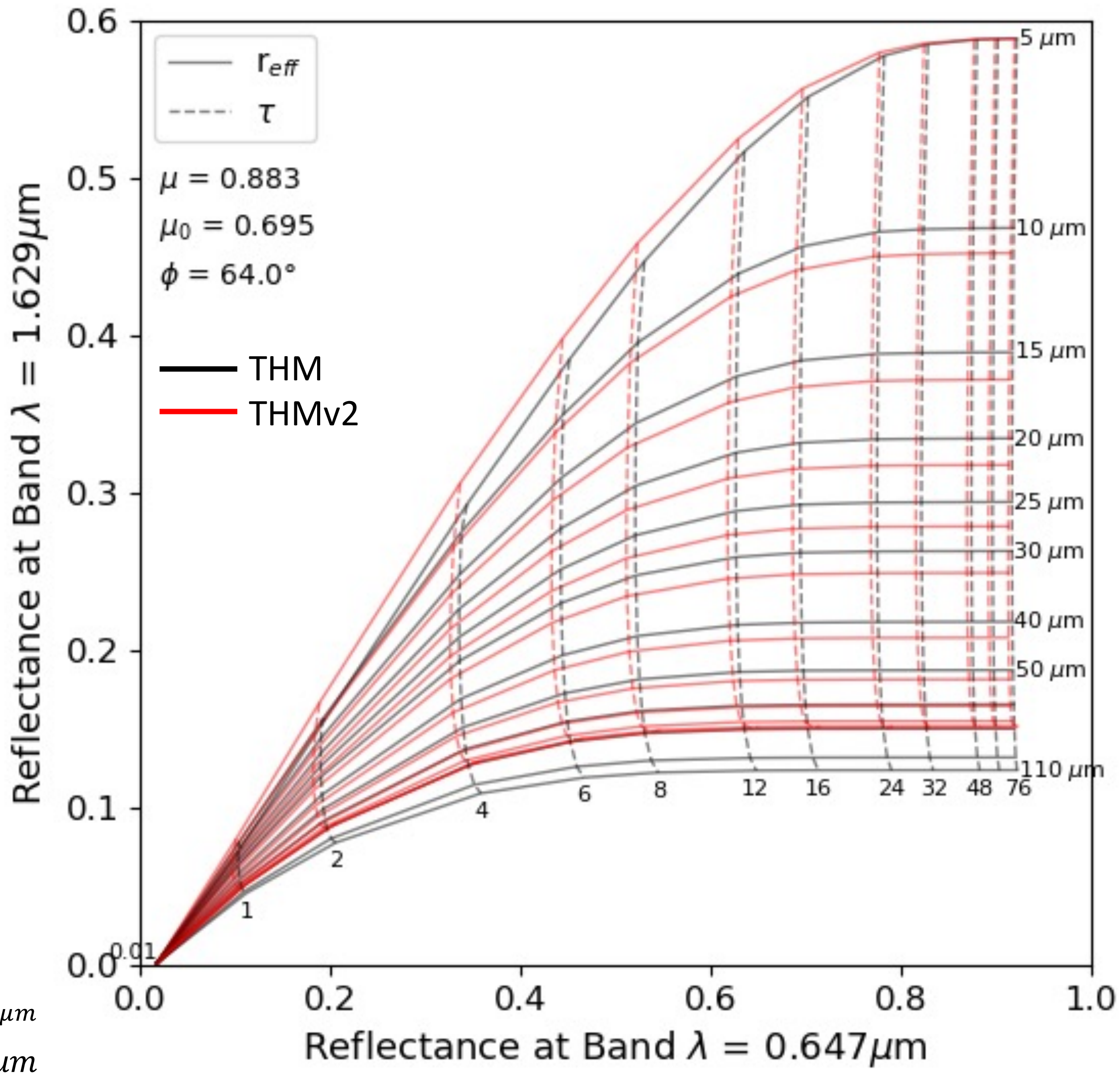
- Spectral consistency analyses for THMv2 database only performed using GOES-17 shortwave (SW), near-infrared (NIR), and thermal infrared (TIR) bands.
- Spectral consistency tests using MODIS bands currently being conducted.
  - Analyses of the Nakajima-King and Split Window look-up table (LUT) differences between the THMv2 and previous version THM have been performed.
  - Retrievals of ice cloud effective radius and COT will be conducted soon.

COT 2-dimensional frequency distribution created using 1 hour GOES-17 observations from 20:00 – 20:50 UTC on Sept. 23, 2019.



Nakajima-King LUT: MODIS Band 1 ($0.647\mu m$) vs. Band 6 ($1.629\mu m$)

- Shortwave (Band 1) reflectances mostly unchanged between THM and THMv2.
- Significant changes in NIR (Band 6) reflectances between databases.
    - Retrievals likely to be more accurate for THMv2 for ice clouds containing small effective radii ice particles.
    - Significantly more compressed large effective radii isolines for THMv2 leading to worse retrievals than THM.
- Likely caused by different habit fraction equations being used to develop THM and THMv2.
    - Can noticeably affect the single-scattering properties.



THMv2

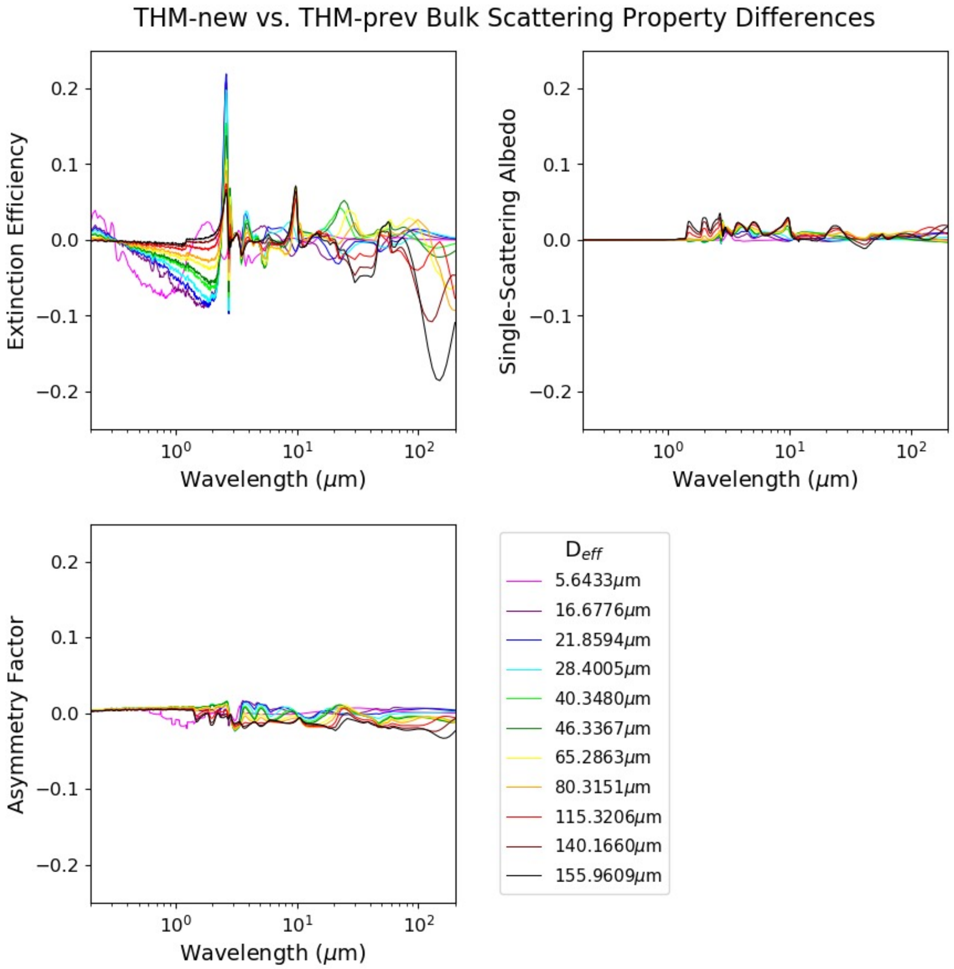
$$f_{single} = \begin{cases} e^{-0.0076(D_{max}-45)}, & D_{max} \geq 45\mu m \\ 1, & D_{max} < 45\mu m \end{cases}$$

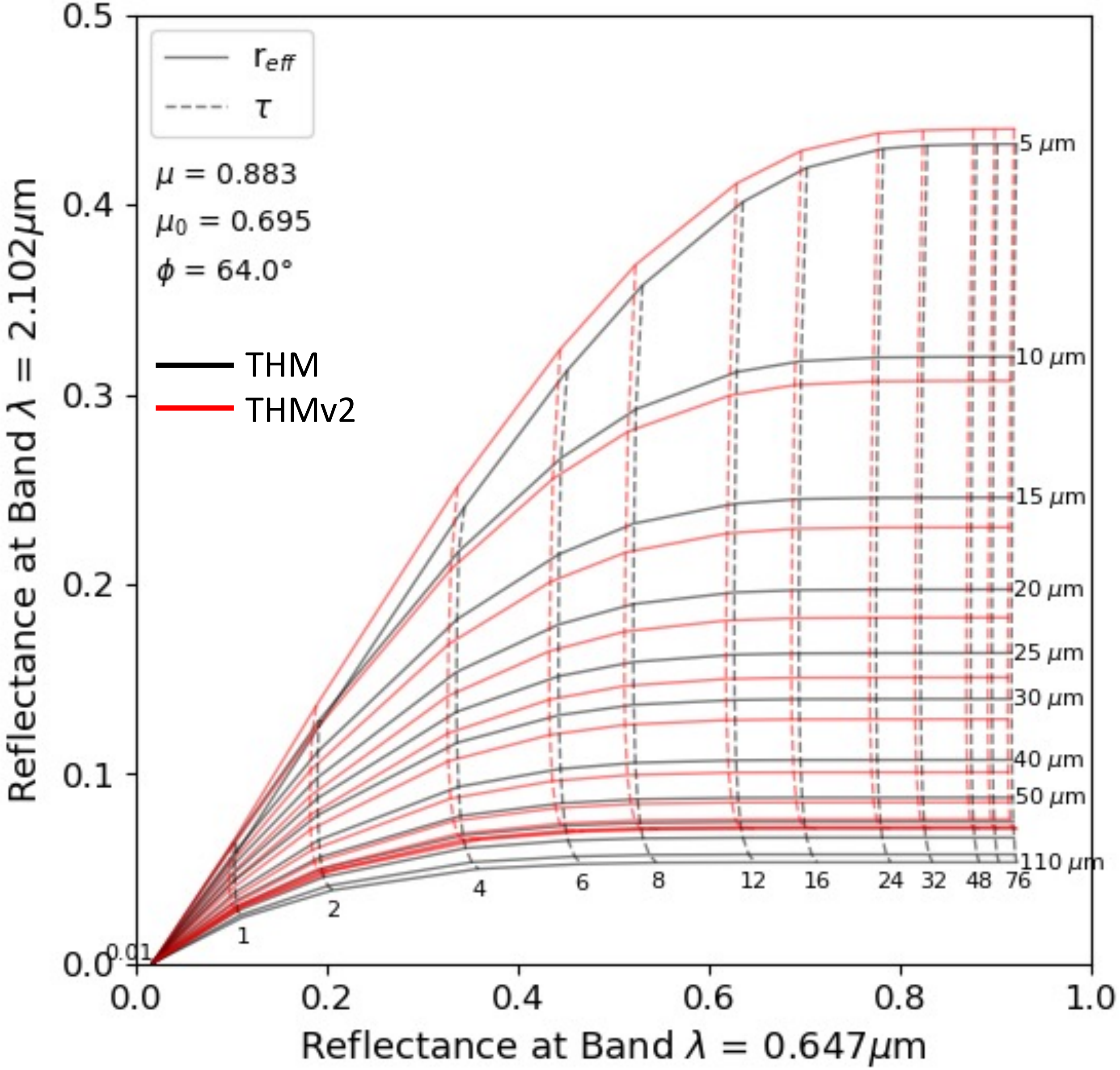
THM

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

Nakajima-King LUT: MODIS Band 1 ($0.64\mu m$) vs. Band 7 ($2.10\mu m$)

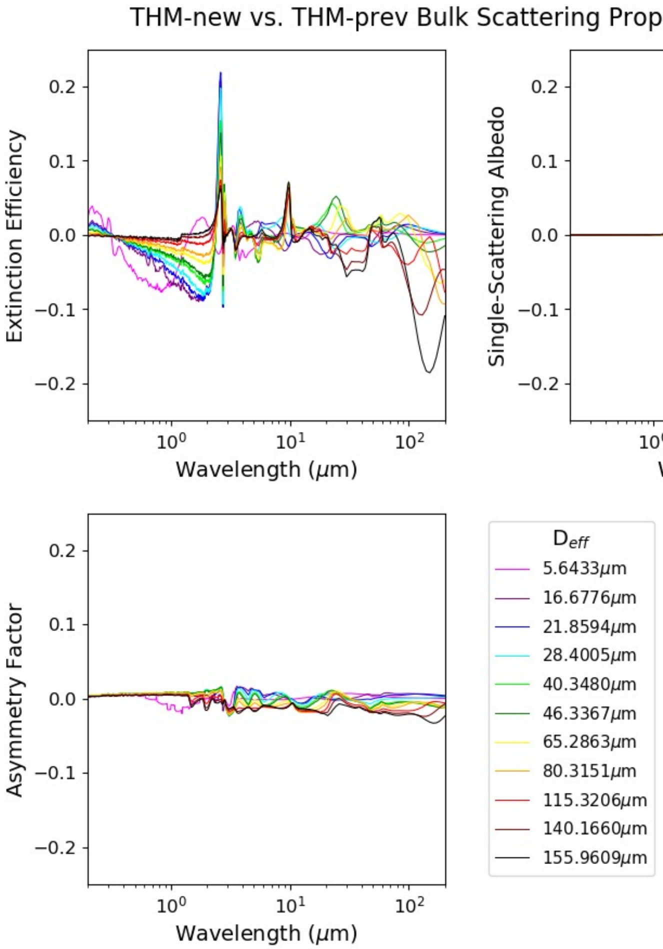
- Similar results as Band 1 vs. Band 6.
- THMv2 reflectance isolines compress for large effective radii.
- Bulk scattering properties shown to noticeably vary for NIR spectral region.


THM-new vs. THM-prev Bulk Scattering Property Differences



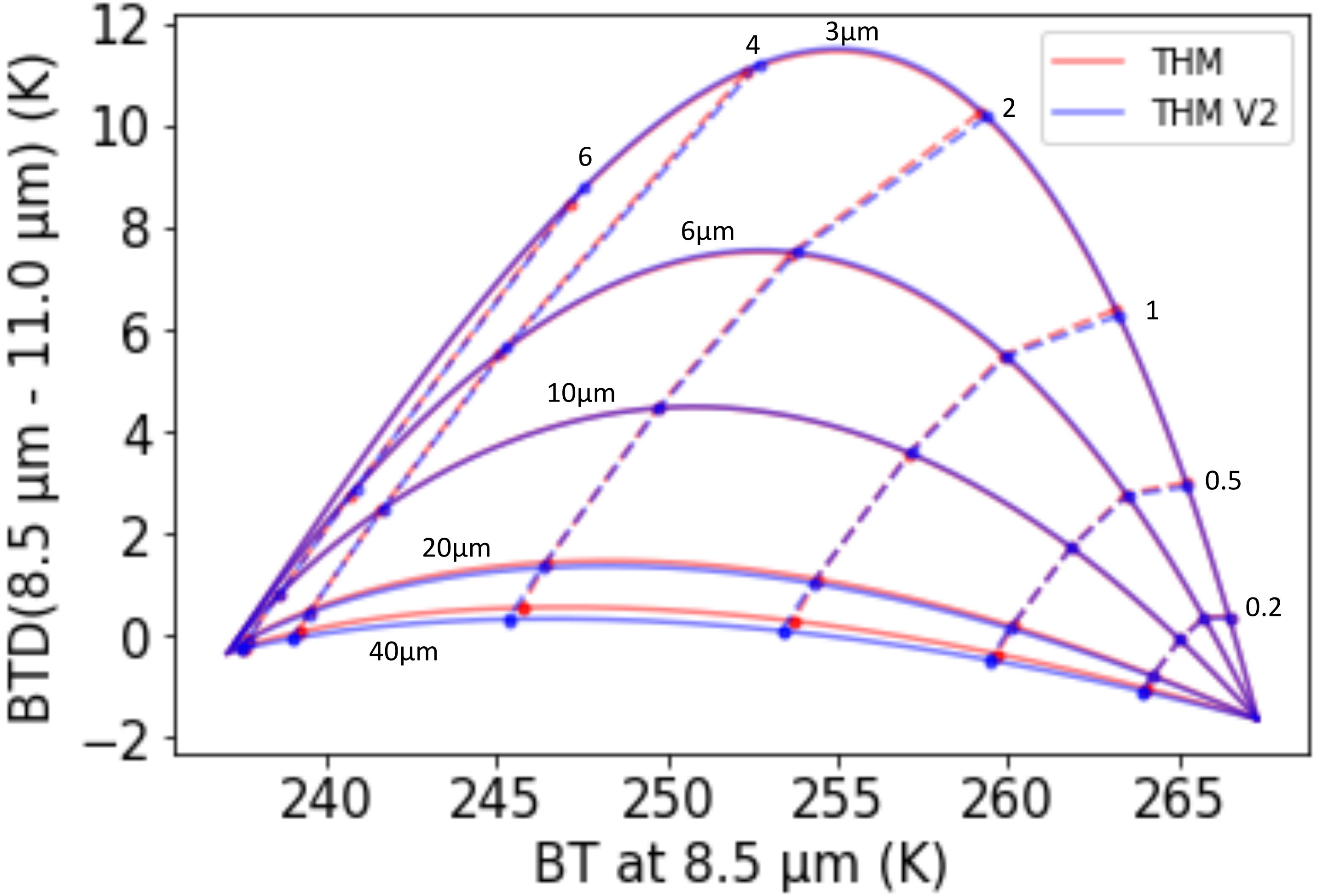
Split Window: MODIS Band 29 (8.5µm) vs. 31 (11µm)

- No significant difference in Split-Window look-up table.
- Differences in single-scattering properties, especially extinction efficiency, are minimal for these TIR bands.



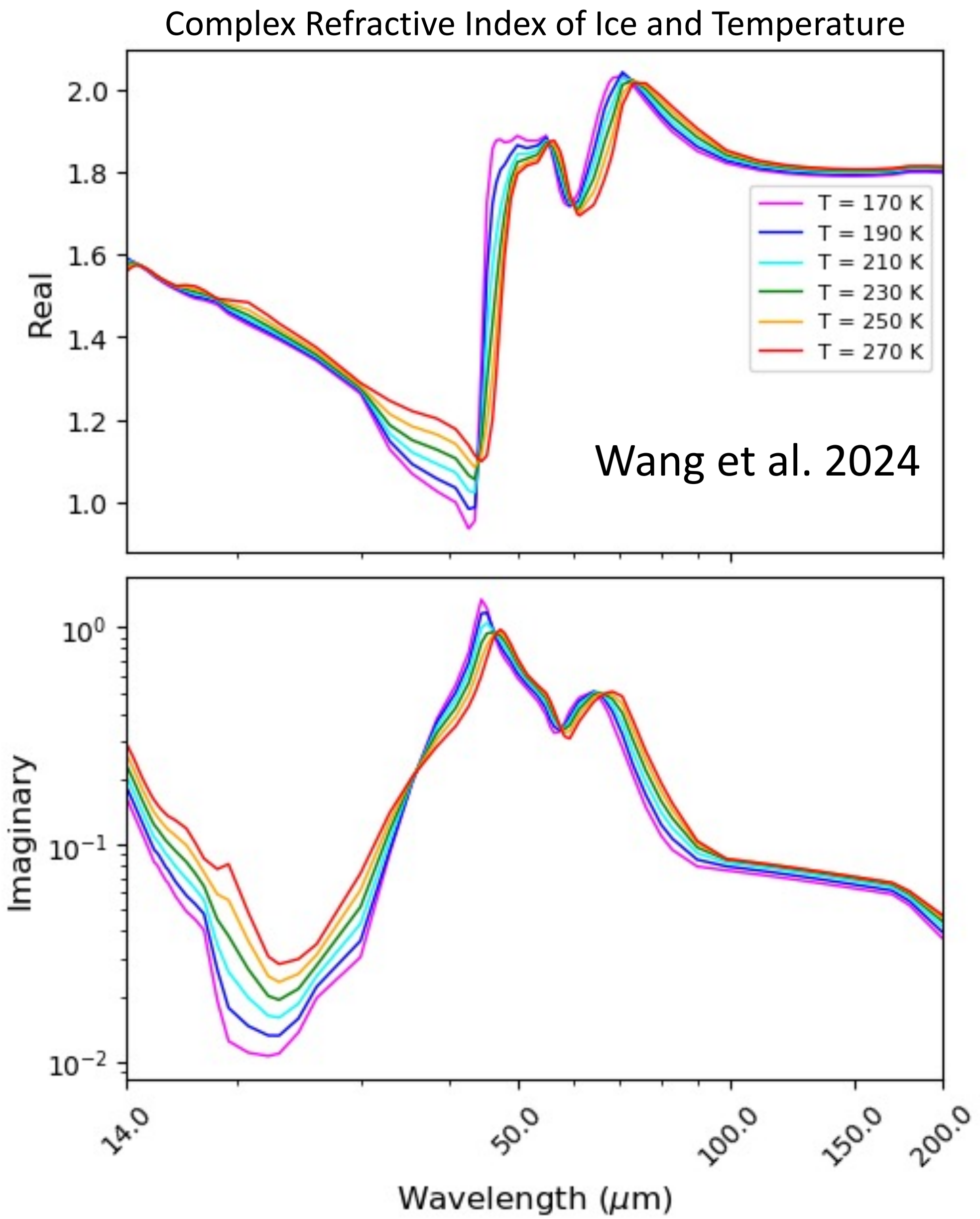
THM-new vs. THM-prev Bulk Scattering Property Differences

$\mu = 0.6$
Precipitable Water = 17.8 mm
Surface Emissivity = 0.99
Surface temperature = 297K
Cloud Top Temperature = 240K



Far-Infrared Temperature Dependence of Ice

- Current ice cloud property parametrizations used in broadband radiative transfer models have pronounced shortcomings in assuming ice refractive index for a single ice particle temperature.
  - Such assumptions could lead to systematic biases in broadband radiative transfer simulations in far-infrared (FIR) bands.
- The complex refractive index of ice significantly varies for a large range of FIR wavelengths.
  - These significant variations can have a noticeable impact on the single-scattering properties of ice particles and therefore radiative transfer simulation results.
- Two upcoming satellite missions:
  - **NASA:** Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) (5 – 45µm)
  - **ESA:** Far-infrared-Outgoing-Radiation Understanding and Monitoring (FORUM) (6.25 – 100µm)


Complex Refractive Index of Ice and Temperature

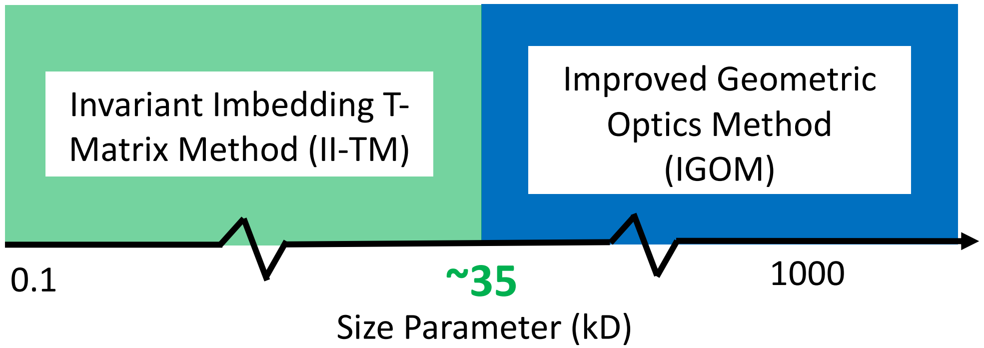
Wang et al. 2024

THMv2-TEMP: Development of a Temperature Dependent THMv2 Database

- THMv2 will be expanded to include temperature-dependent single-scattering properties for FIR wavelengths (14 – 200μm).
- 6 temperatures will be considered ranging from 170 – 270K.
- Since only FIR wavelengths is primary focus, no Physical Geometric Optics Method (PGOM) calculations will be performed due to lack of backscattering.
- Temperature-dependent complex refractive index data to be used for development from Wang et al. 2020.

	THMv2-TEMP
Temperature	6 bins **(170 – 270K; 20K increments)**
Wavelength	80 bins **(14.0 – 200μm)**
Size (D_{max})	189 bins **(2.206 – 11031.337μm)**

THMv2-TEMP Computation Methods



Invariant Imbedding T-Matrix Method (II-TM)

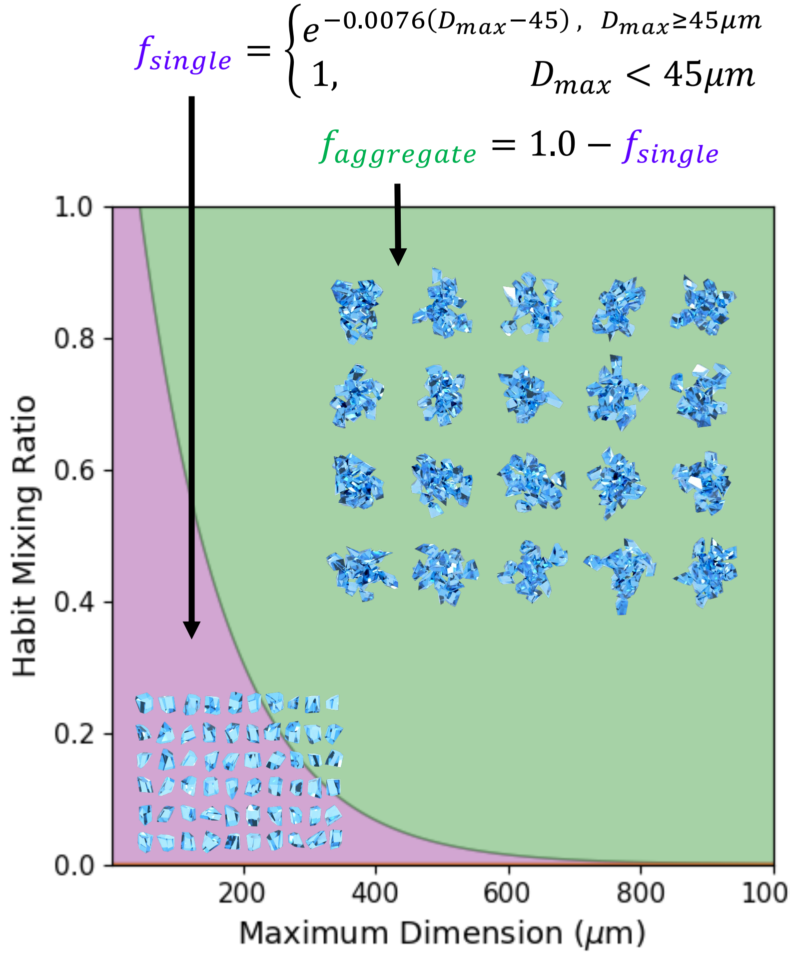
Improved Geometric Optics Method (IGOM)

0.1

~35

1000

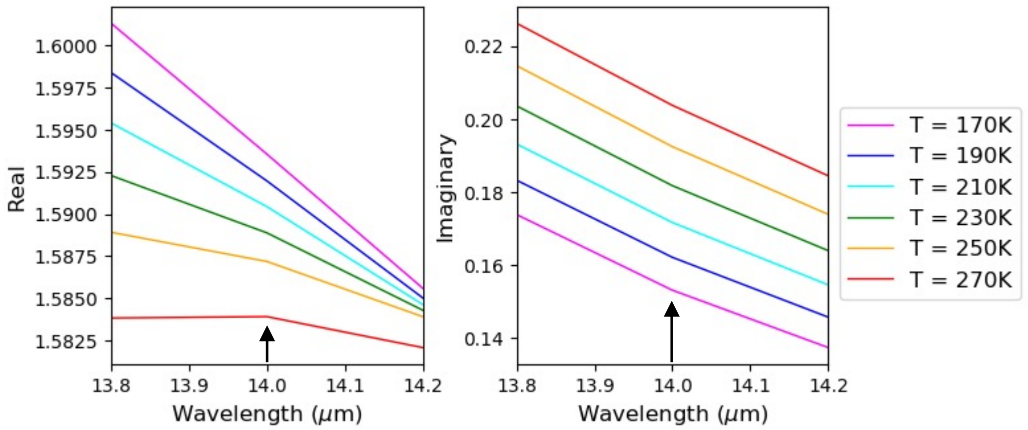
Size Parameter (kD)

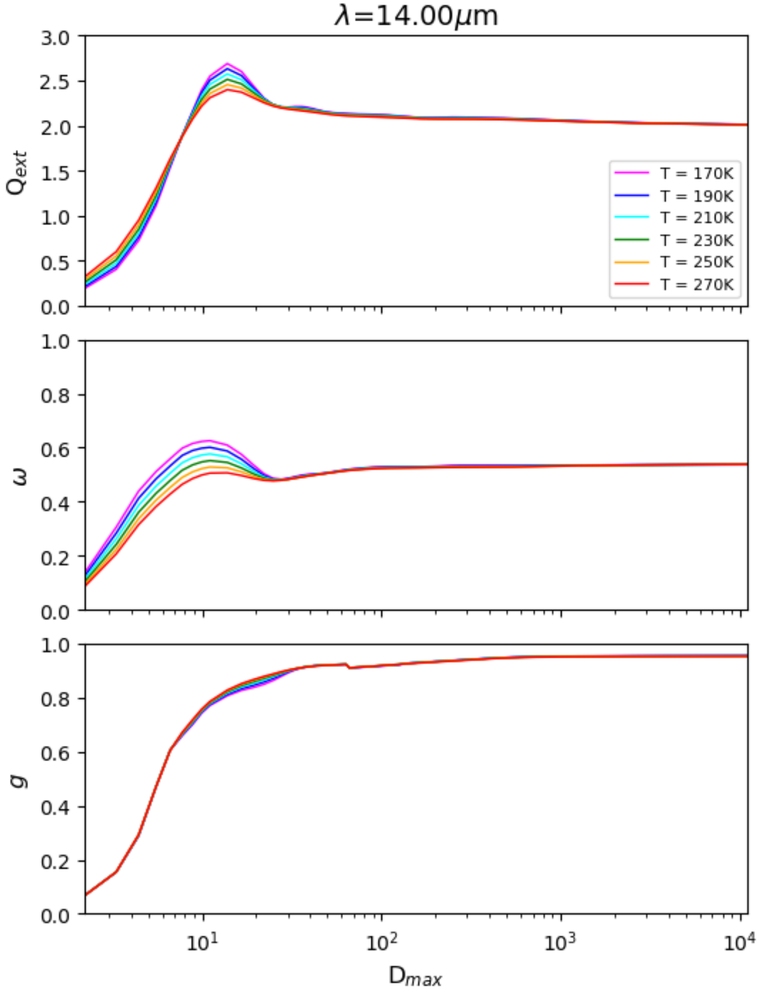


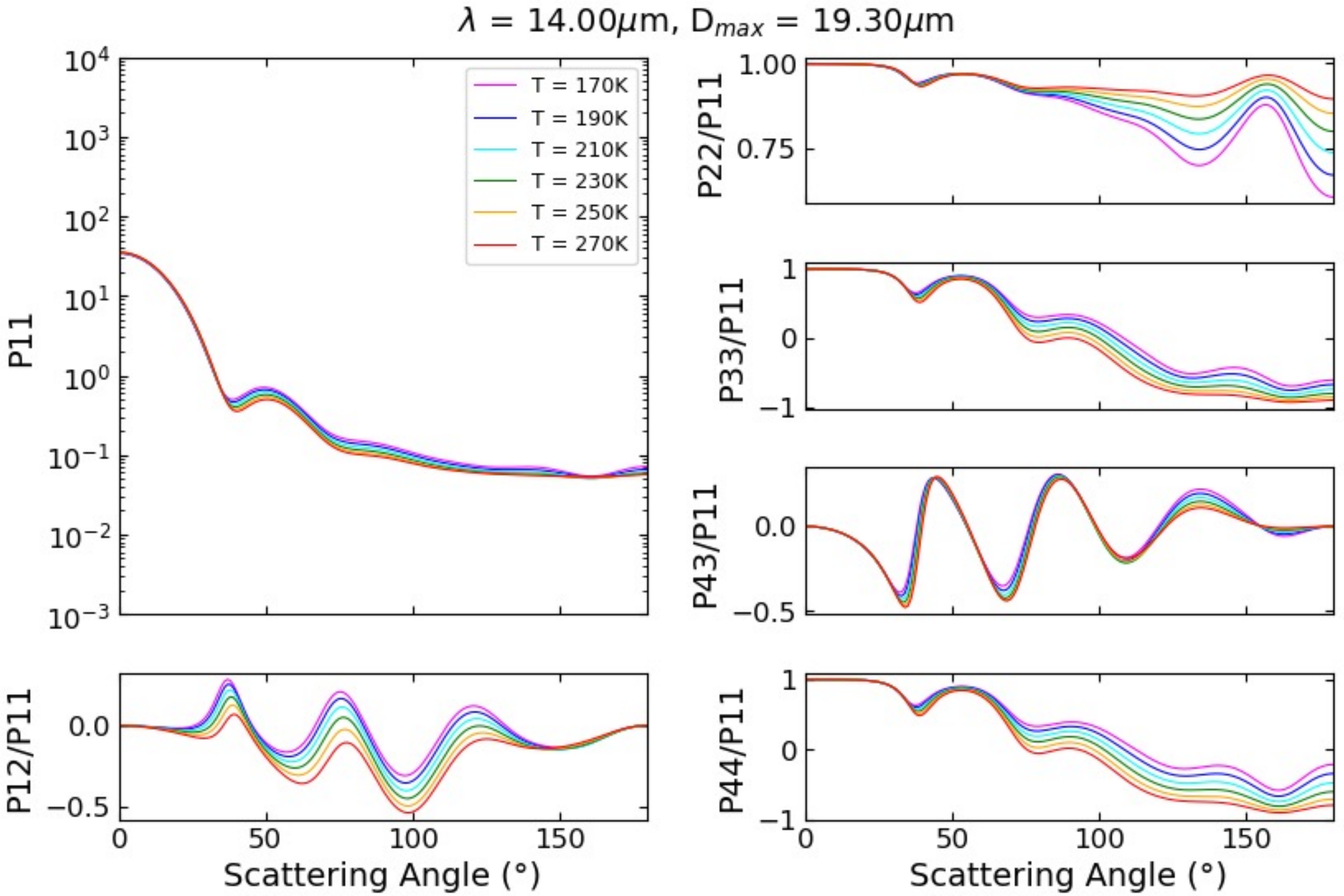
$$f_{single} = \begin{cases} e^{-0.0076(D_{max}-45)}, & D_{max} \geq 45\mu m \\ 1, & D_{max} < 45\mu m \end{cases}$$

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

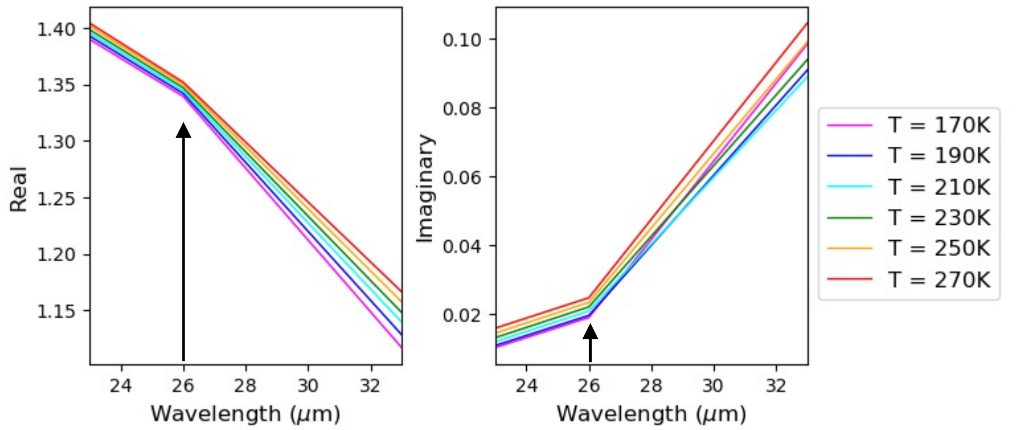
Preliminary Single-Scattering Property Comparisons: 14.00μm

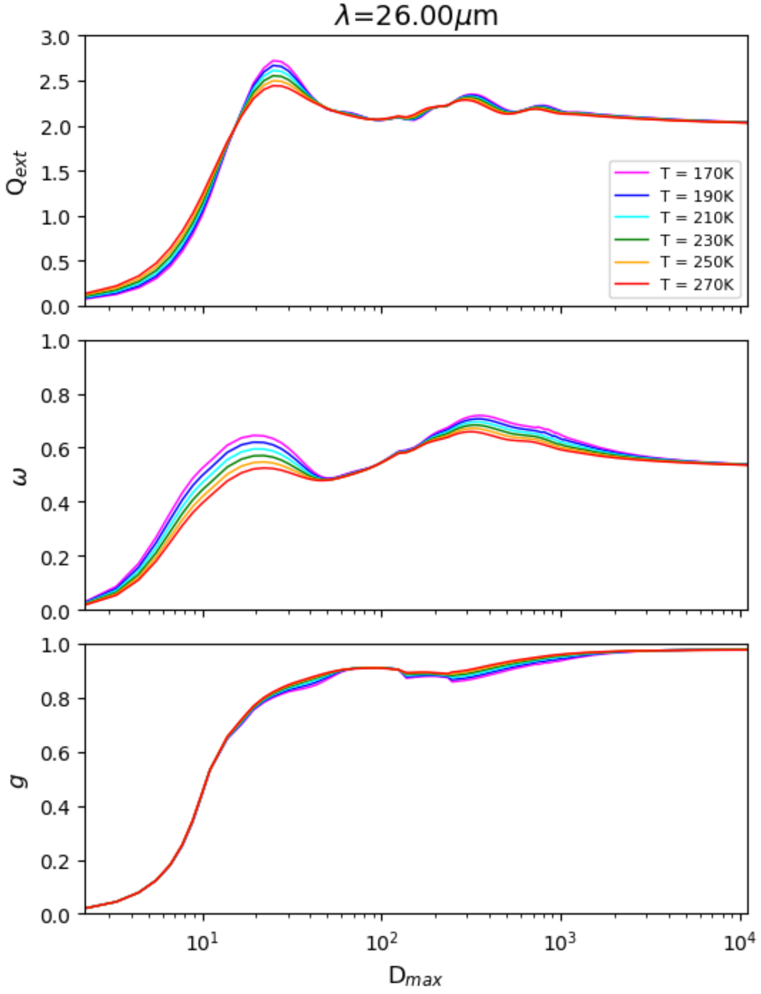


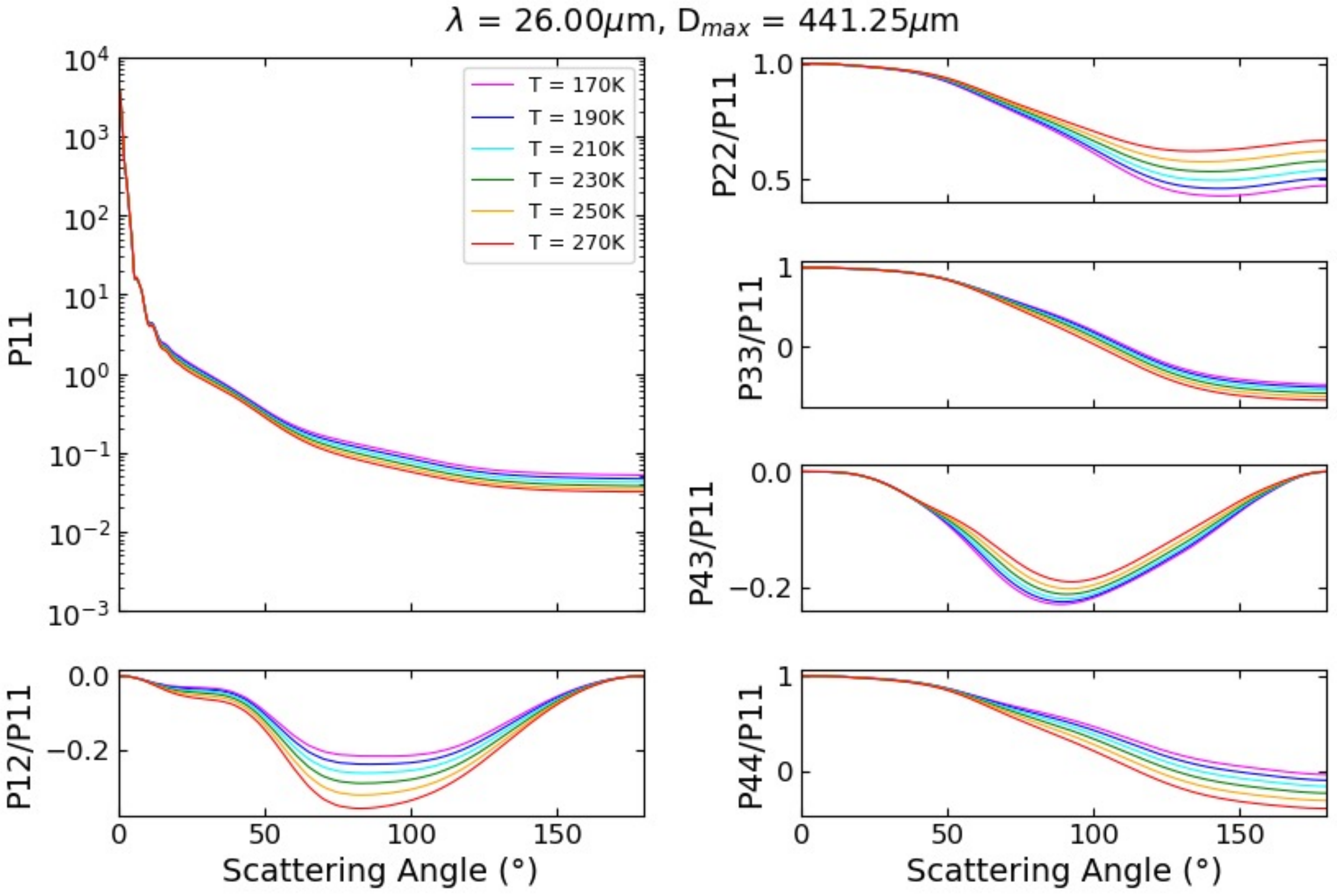




Preliminary Single-Scattering Property Comparisons: 26.00μm







Summary and Future Work

- For GOES-16/17 retrieval analyses:
  - VIS-NIR Method: SZA affects COT retrieval certainty (larger SZA = larger uncertainty).
  - TIR Method: VZA affects COT retrieval magnitude (larger VZA = larger COT retrievals).
  - Cloud inhomogeneity from averaging VIS reflectance pixels decrease GOES-16 and -17 COT retrieval consistency.
- MODIS Nakajima-King retrieval LUTs
  - THMv3 effective radius isolines compress for smaller effective radii than THMv2.
  - Difference could be due to using difference habit fraction mixture/distorted particle shapes.
- Minimal difference in TIR split-window LUT due to scattering becoming less important.
- Preliminary THMv2-TEMP single-scattering property calculations show noticeable difference across the 170-270K temperature range.

- Spectral consistency tests will soon be performed for MODIS and VIIRS instruments.
  - CALIOP and IIR active-passive consistency will also be performed.
  - THMv2 habit fraction mixing ratios will probably be altered to further improve spectral consistency if needed.
- Plans to compare broadband flux RTM calculations utilizing THM, THMv2, and other conventional ice particle single-scattering databases against CERES observations.
- Development of the complete THMv2-TEMP database likely will be complete by end of year.
  - IGOM calculations already complete but need to be reviewed.

References

Loeb, N. G., Yang, P., Rose, F. G., et al. (2018). Impact of ice cloud microphysics on satellite cloud retrievals and broadband flux radiative transfer model calculations. *Journal of Climate*. **31,** 1851-1864.

Wang, S., Ren, T., Yang, P., et al. (2024). Improved temperature-dependent ice refractive index compilation in the far-infrared spectrum. *Geophysical Research Letters*. *(Forthcoming)*

Contacts

lidc@tamu.edu (Dongchen Li)

jcoy93@tamu.edu (James Coy)