Improved Ice Cloud Modeling Capabilities of the Community Radiative Transfer Model

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Introduction – the CRTM

- The Community Radiative Transfer Model (CRTM) developed by the U.S Joint Center for Satellite Data Assimilation (JCSDA).
- CRTM is a powerful and accurate tool to perform radiance (and Jacobian) simulations at the top of the atmosphere (TOA) for a versatile of satellite instruments including visible, infrared and microwave sensors.
- CRTM is designed to accommodate various clear-sky and all-sky conditions.
- Accurate cloud optical property look-up table is the prerequisite of accurate radiance simulation under cloudy sky.

http://www.star.nesdis.noaa.gov/smcd/spb/CRTM/

Examples of satellite sensors supported by CRTM

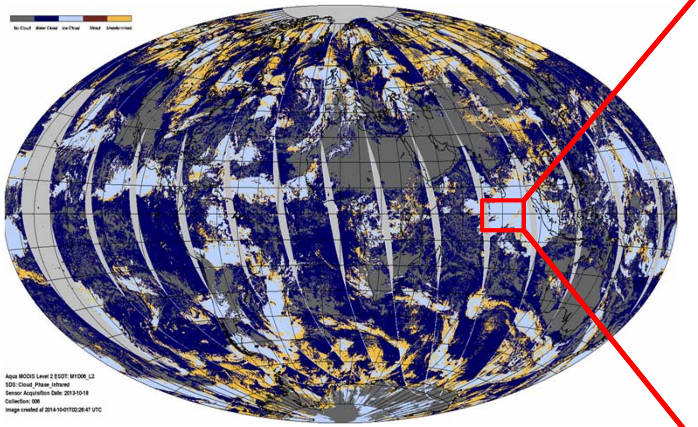
- Aqua AIRS, AMSR-E, MODIS
- NOAA AVHRR, AMSU, HIRS, MHS, MSU, SSU
- NPP CrIS, VIIRS; MetOp-A/B IASI
- GOES; Meteosat; GOES-R ABI
- Fengyun-3a/b IRAS, MERSI, MWHS
- Fengyun-4a, Himawari-8
- Visible + IR + Microwave
- And many more …

Features of CRTM

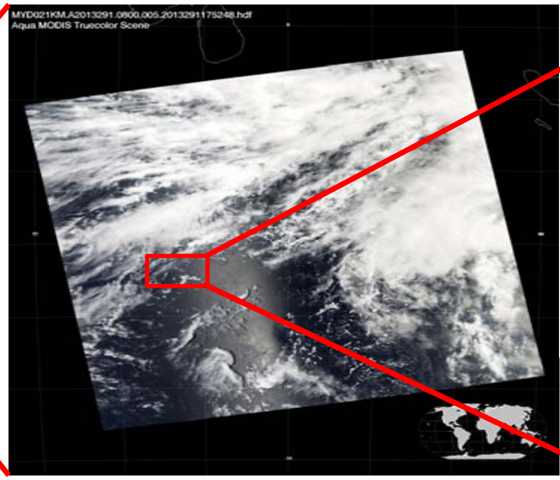
- Four major modules of CRTM
  - Atmospheric transmittance module
    - The Optical Path TRANsmittance (OPTRAN) model
  - Surface emissivity/reflectivity module
    - Contains ocean, land, snow and ice surface components
  - Cloud/aerosol optical property module
    - Contains six cloud and eight aerosol types
  - Radiative transfer module
    - Advanced fast adding-doubling method
- We update specially ***the ice cloud optical property look-up table*** for the ***visible, IR, and microwave*** spectral range. To be replaced by CHYM!

Complexity of ice cloud

From the global perspective:

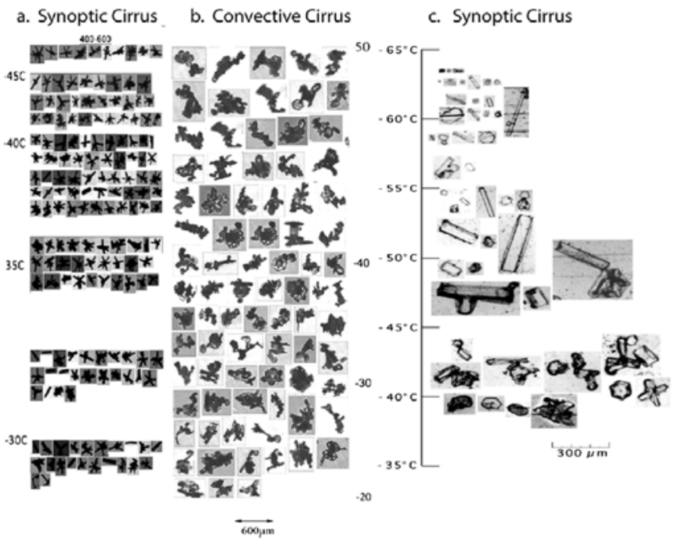


From the satellite view:

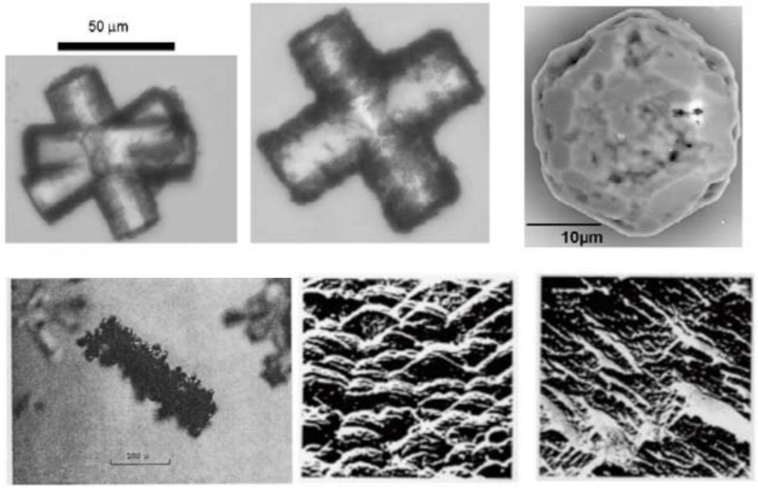


From the ground level:

From the field campaign air-borne observations:

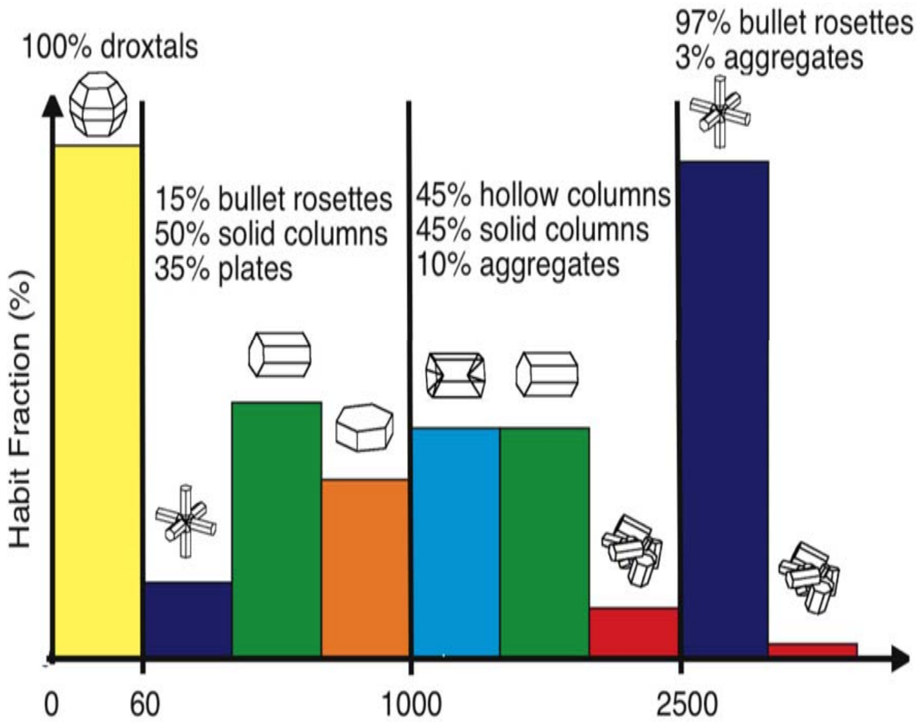


From the laboratory instruments:



The old ice cloud model

MODIS Collection 5 ice cloud model

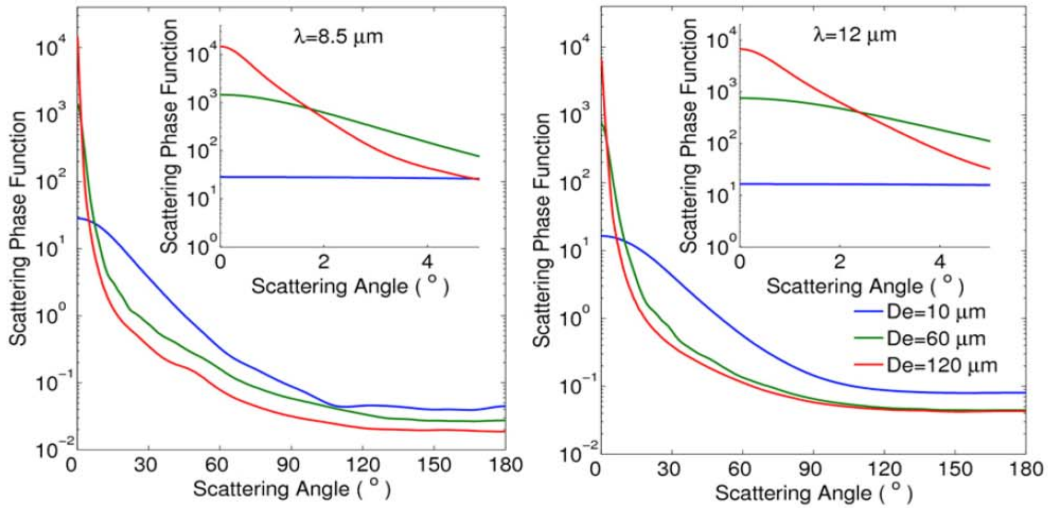


Known problems

- **Scattering properties from observations**: Featureless phase functions are frequently observed;
- **Scattering properties for climate modeling**: Relatively small asymmetry factors (approximately g=0.75 at visible bands) are required for models;
- **Spectral inconsistency for satellite retrievals**: Cloud optical depths retrieved from the VIS/NIR bands are larger than those from IR retrievals based on existing ice cloud models;

MODIS collection 5 ice cloud optical properties

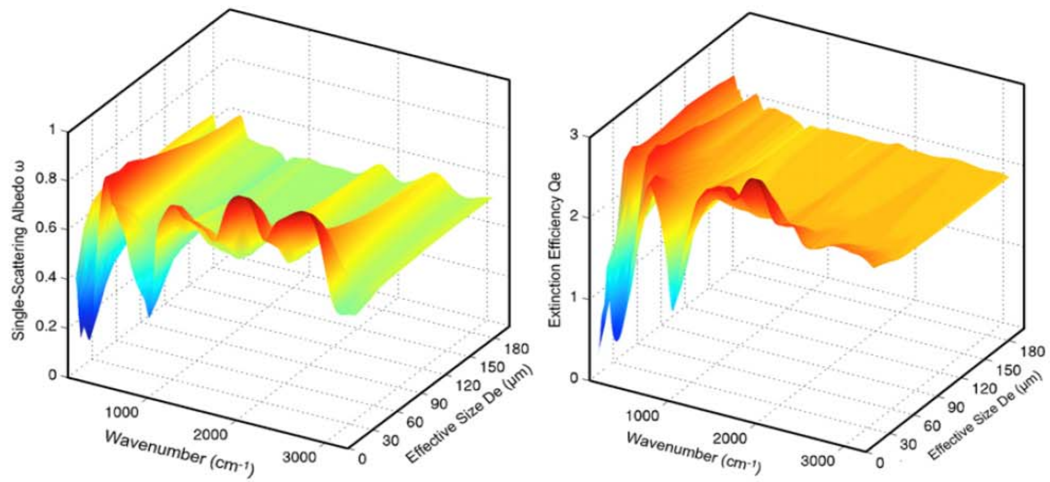
Phase function



Larger size, stronger forward peak, g -> 1

Fig. 1. Scattering phase functions of ice clouds with various effective particle sizes at wavelengths of 8.5 and 12.0 µm.

Single scattering albedo



Extinction efficiency

Fig. 2. Variation of ice cloud single-scattering albedo (left), and extinction efficiency (right) with wavenumber and effective particle size.

Ding et al., 2011, JQSRT

The new ice cloud model

MODIS Collection 6 ice cloud particle model:

- ***Severely Roughened hexagonal column aggregate***

Particle Size Distribution:

- Modified Gamma size distribution

$$n(r) = n_0 r^{(1-3b)/b} e^{-r/(ab)},$$

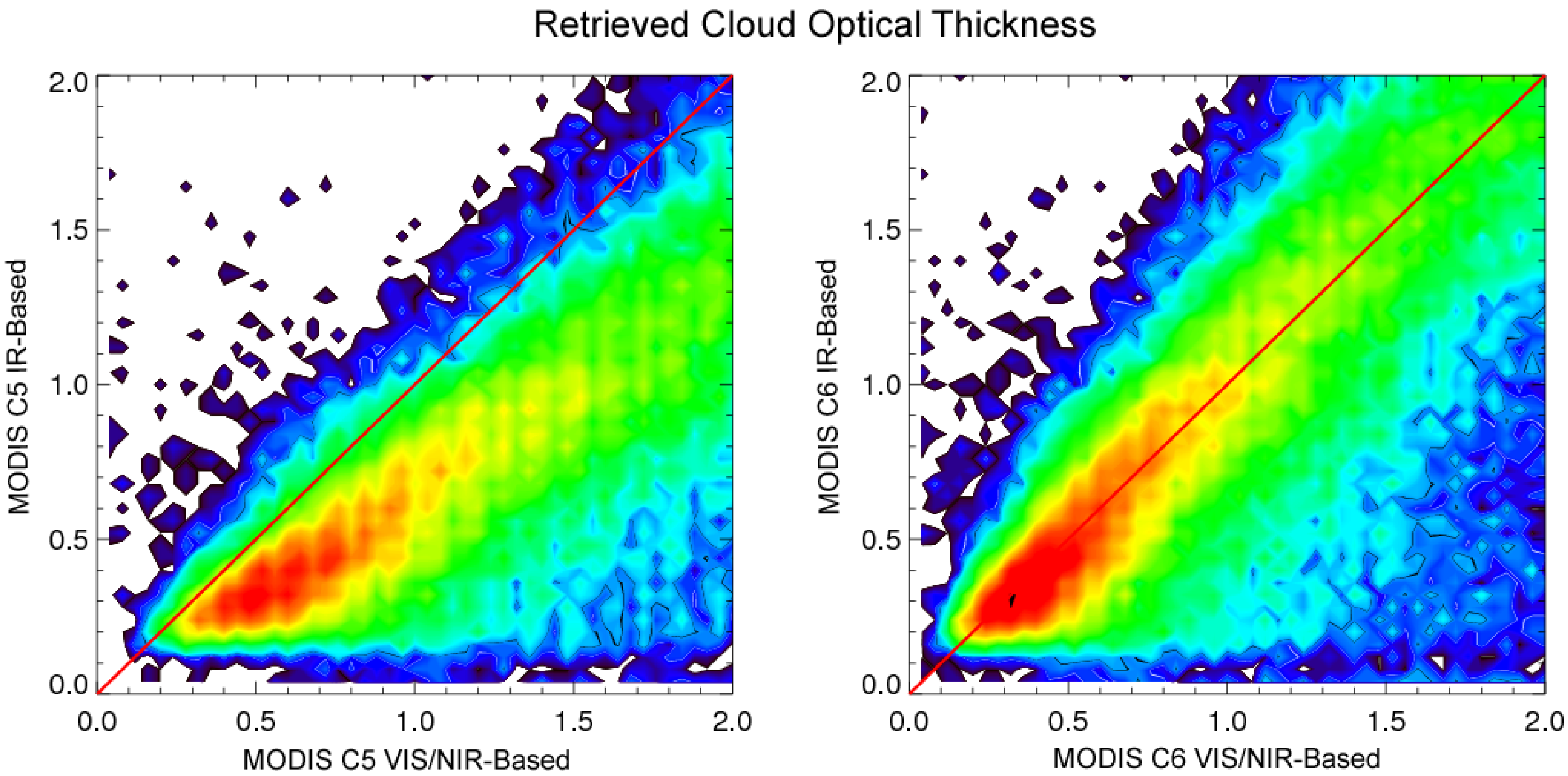
where n_0 is a constant,

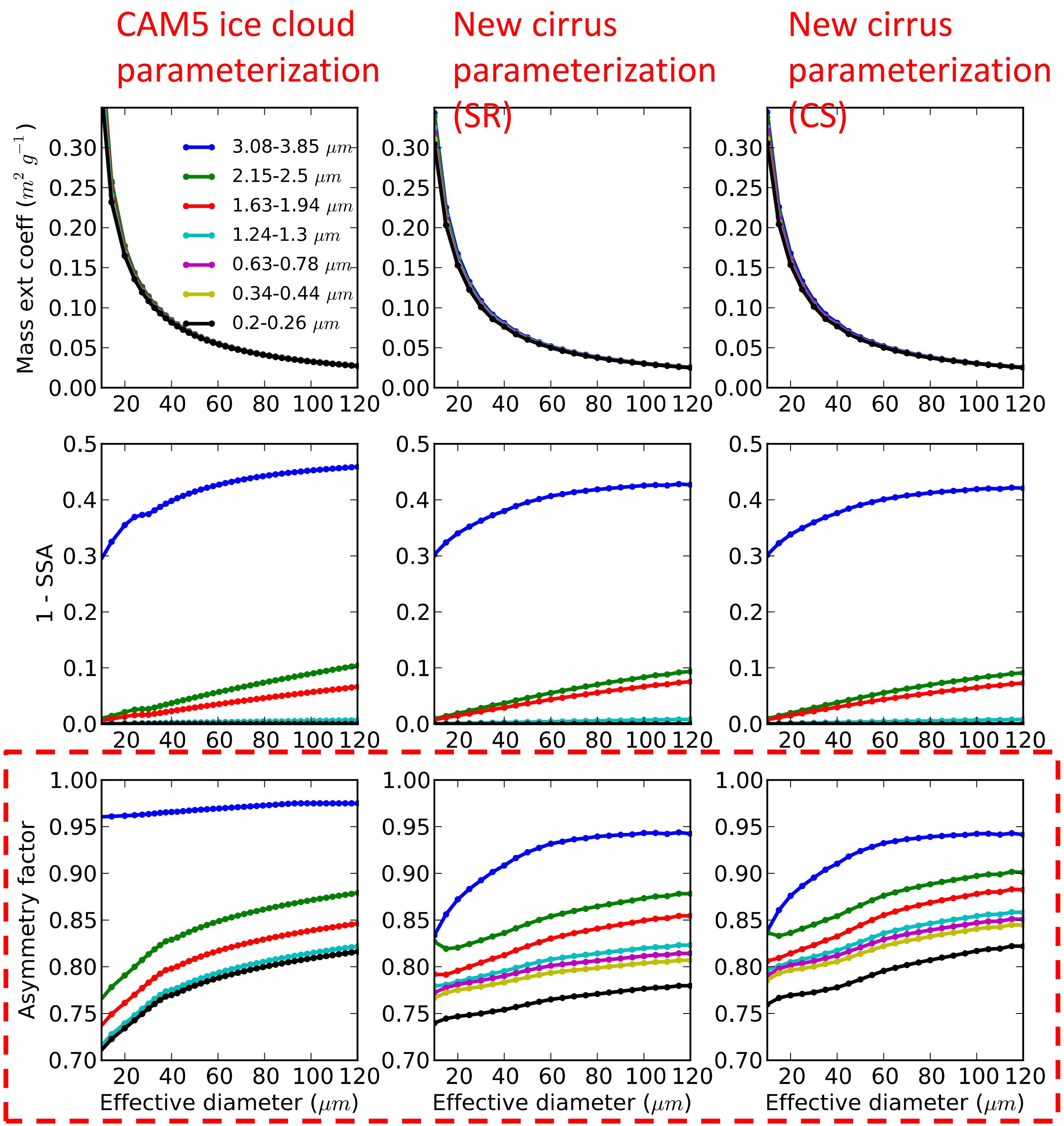
a is the effective radius R_{eff}

b is the mean effective variance

• Previous results (i.e., Cole et al. 2013) supports the use of **severely roughened** ice particle model by comparing simulations with satellite observed polarized reflection data.

Spectral Consistency: MODIS C5 versus MODIS C6

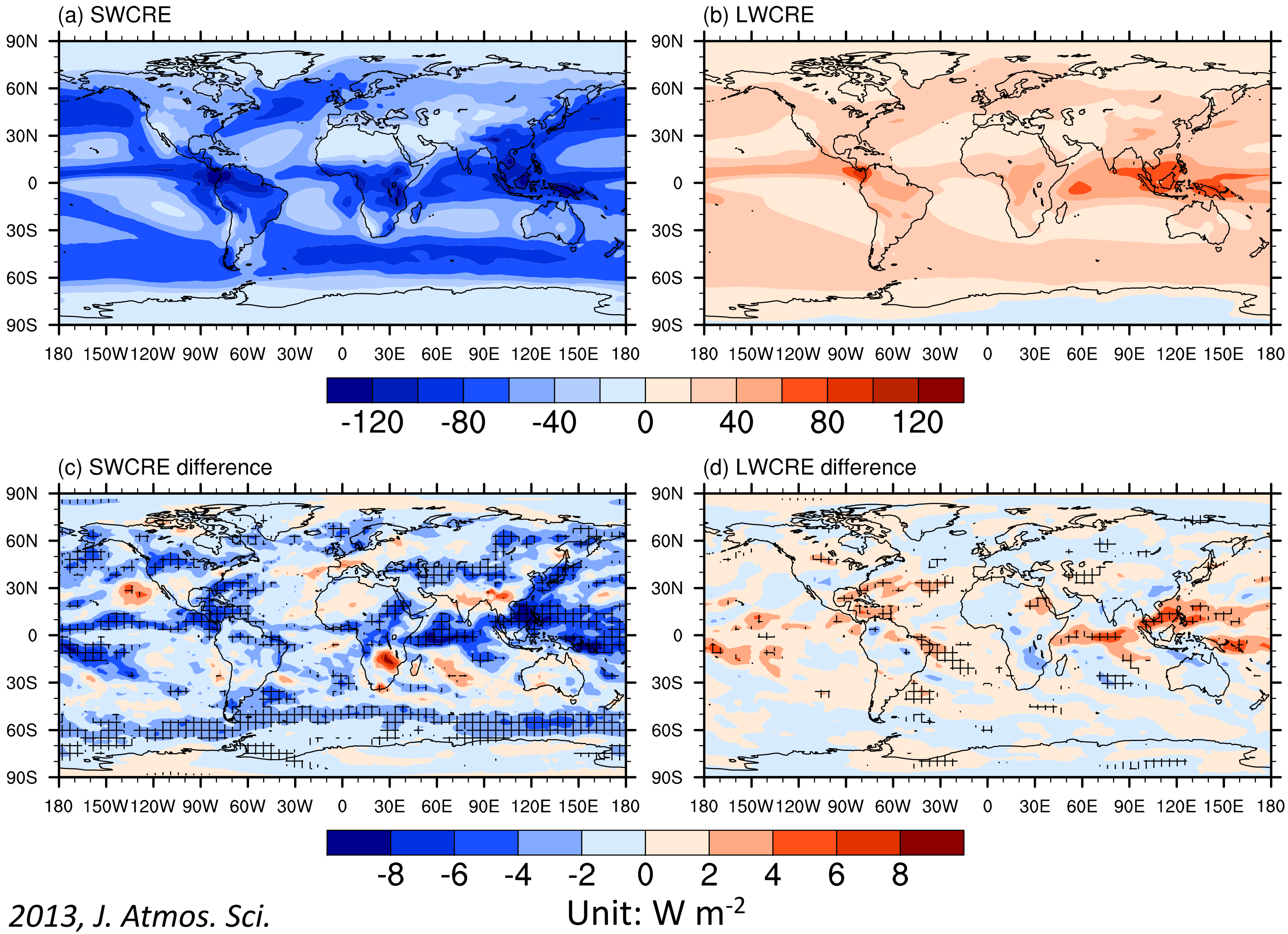




• Ice cloud optical property parameterization for selected bands of RRTMG

Yi et al., 2013, J. Atmos. Sci.

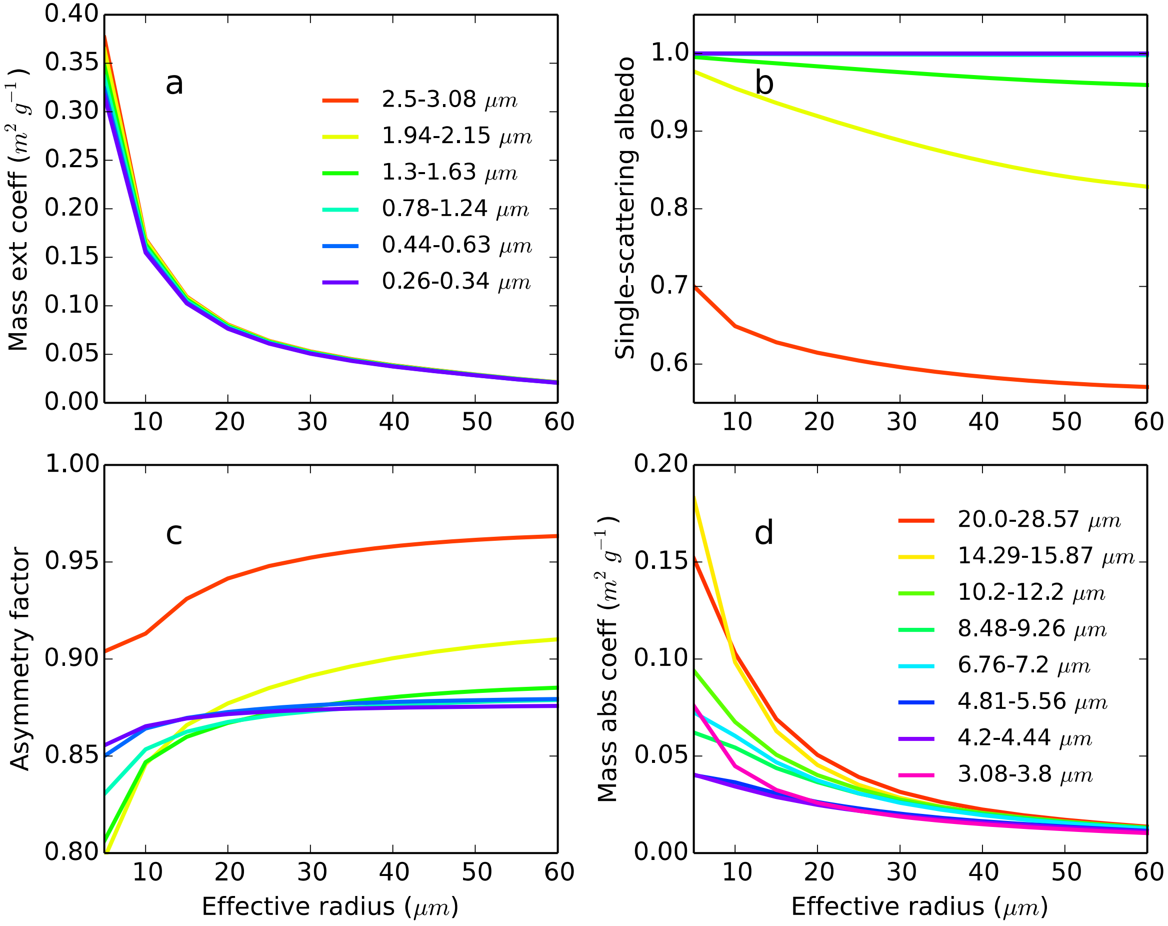
Ten-year mean annual total cloud radiative effect and the roughening effects from AGCM



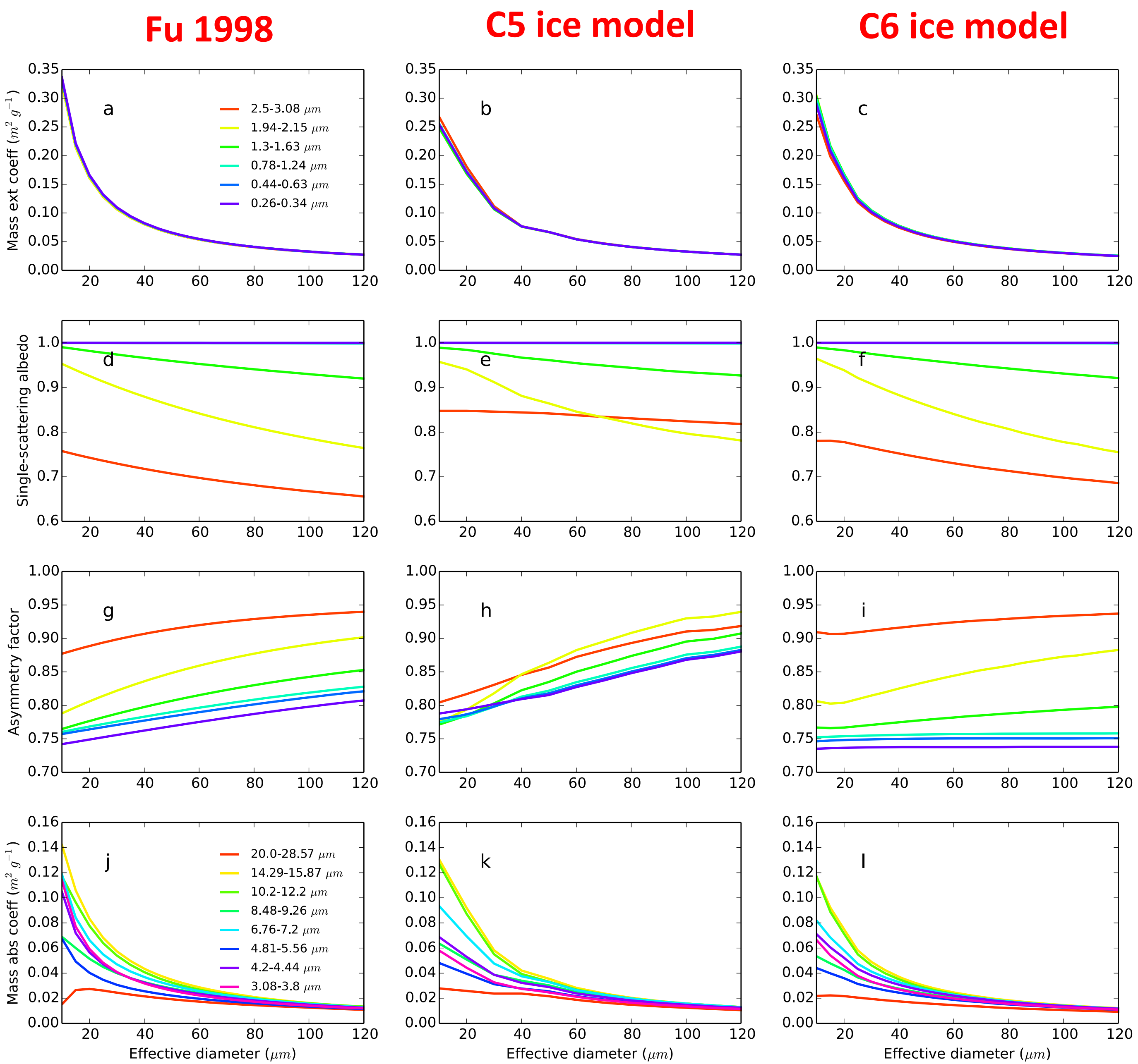
Yi et al., 2013, J. Atmos. Sci.

Liquid water cloud optical properties parameterizations

- Liquid water cloud optical properties for selected bands of RRTMG;
- Assume spherical cloud particle shape;



Ice cloud bulk scattering properties in selected RRTMG bands



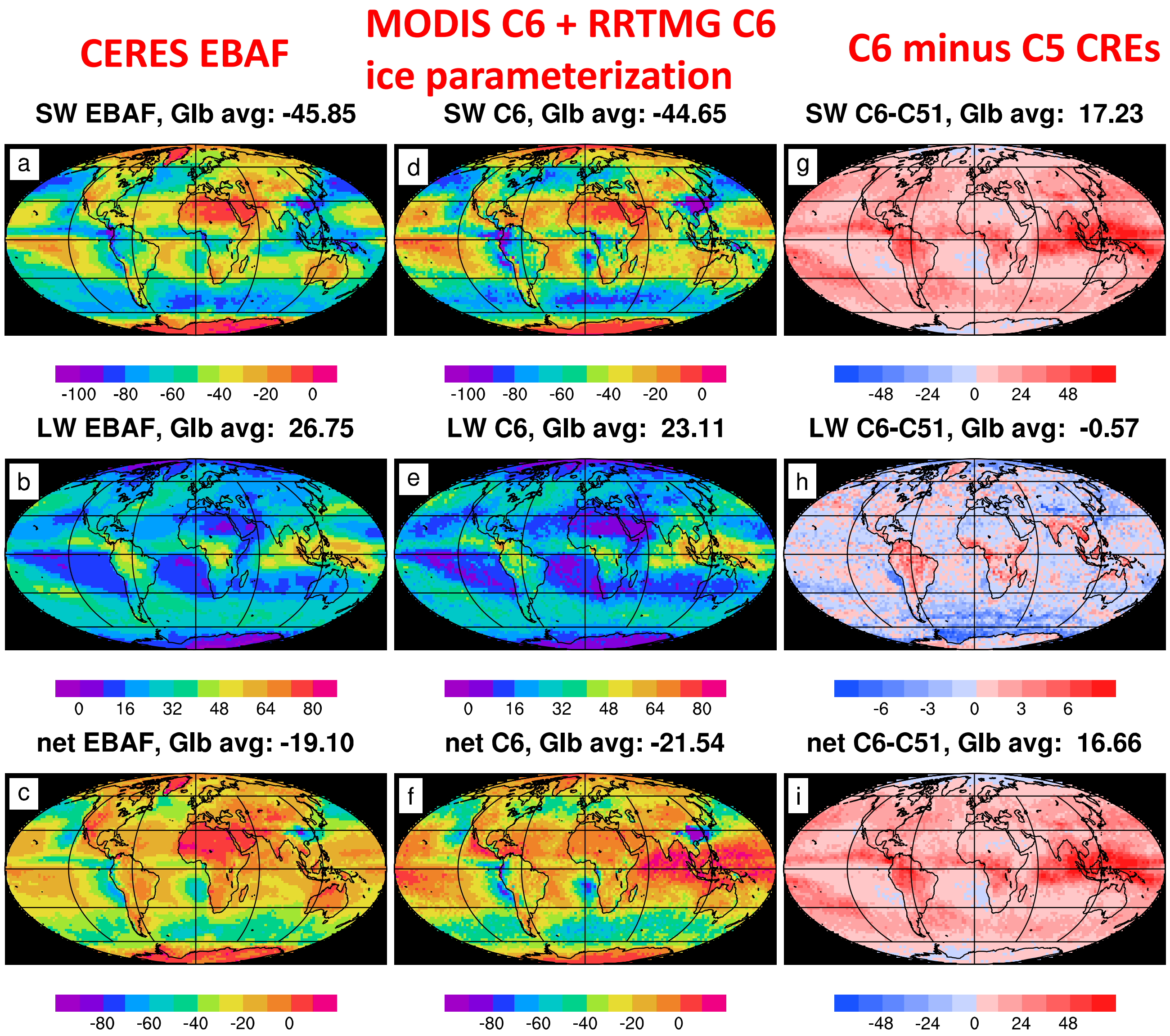
Mass extinction coefficient

Single-Scattering albedo

Asymmetry factor

Mass absorption coefficient

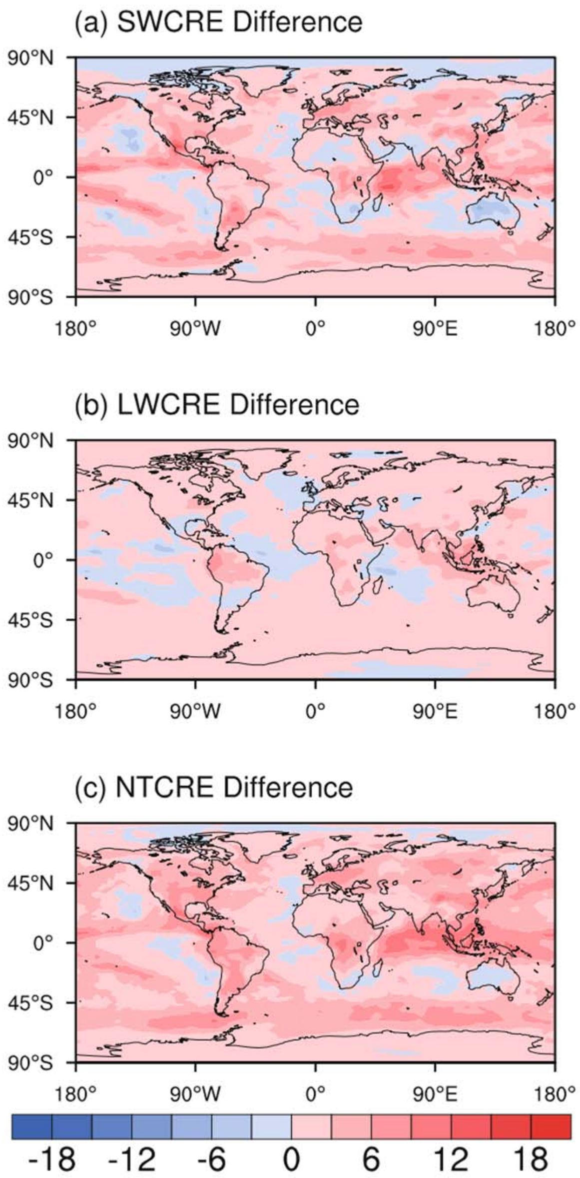
Comparison between observed and simulated cloud radiative effects (CREs) at the TOA

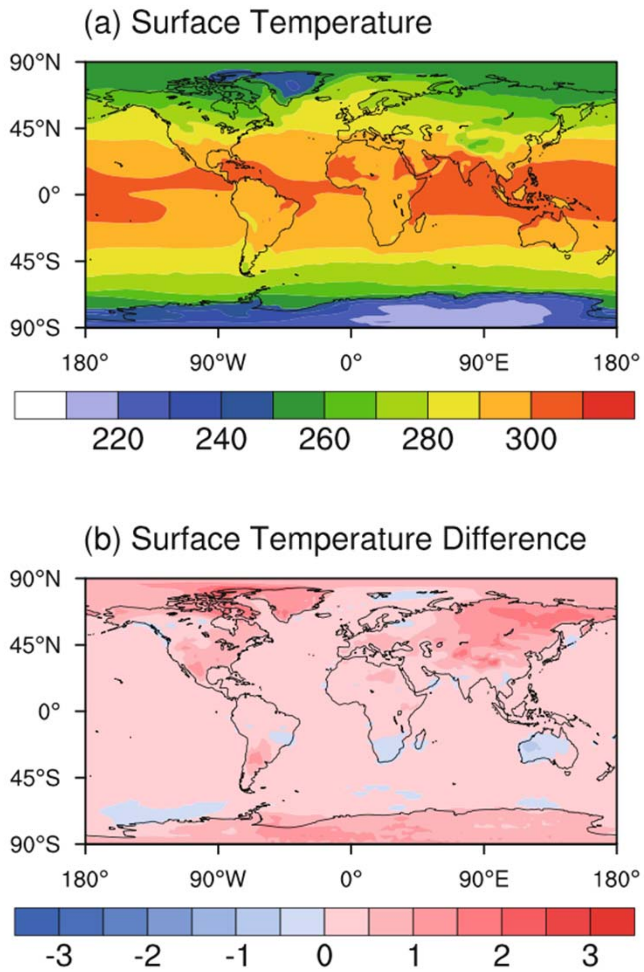


Yi et al., 2017 a, b, J. Geophy. Res. Atmos.

Unit: W m^{-2}

Non-spherical effects of Ice clouds





- **The Lorenz–Mie theory case simulates a warmer climate**

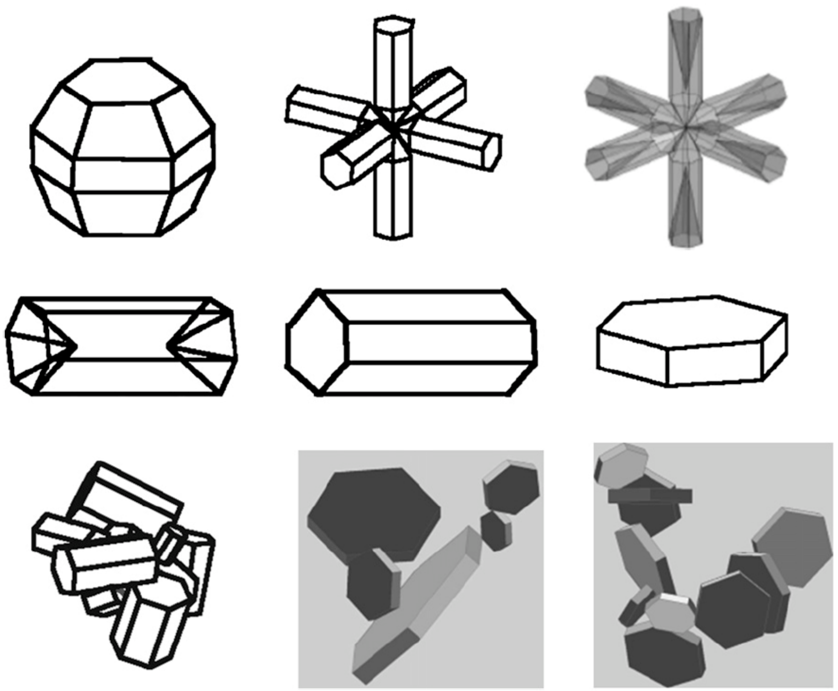
Yang et al., 2015, Adv. Atmos. Sci

The ice optical property library

Ice particle single-scattering property database

Spectrally Consistent Scattering, Absorption, and Polarization Properties of Atmospheric Ice Crystals at Wavelengths from 0.2 to 100 μm

PING YANG,* LEI BI,* BRYAN A. BAUM,+ KUO-NAN LIOU,# GEORGE W. KATTAWAR,@ MICHAEL I. MISHCHENKO,& AND BENJAMIN COLE*



Yang et al., 2013, JAS

Advantages:

- Developed with the most accurate and state-of-the-art light scattering computation methods (T-Matrix *[Bi et al., 2014]* and IGOM *[Yang et al., 1996]*);
- Wide coverage of the spectrum from 0.2 to 100 um;
- Wide particle size range (maximum dimension) from 2~10^4 um;
- Complete scattering phase matrix with polarization
- Three degrees of ice surface roughness: Completely Smooth, Moderately Rough, Severely Rough;
- Extended to the microwave spectrum; temperature dependence considered; (new in 2016 version)
- Publicly available upon request.

Spectral bulk scattering properties of ice clouds

$$r_{eff} = \frac{3}{2}\frac{\int_{r_{min}}^{r_{max}} V(r)n(r)dr}{\int_{r_{min}}^{r_{max}} A(r)n(r)dr},$$

Ice bulk optical properties as functions of effective radius R_{eff}

$$\overline{Q_{ext}} = \frac{\int_{r_{min}}^{r_{max}}[Q_{ext}(r)A(r)n(r)]dr}{\int_{r_{min}}^{r_{max}}[A(r)n(r)]dr},$$

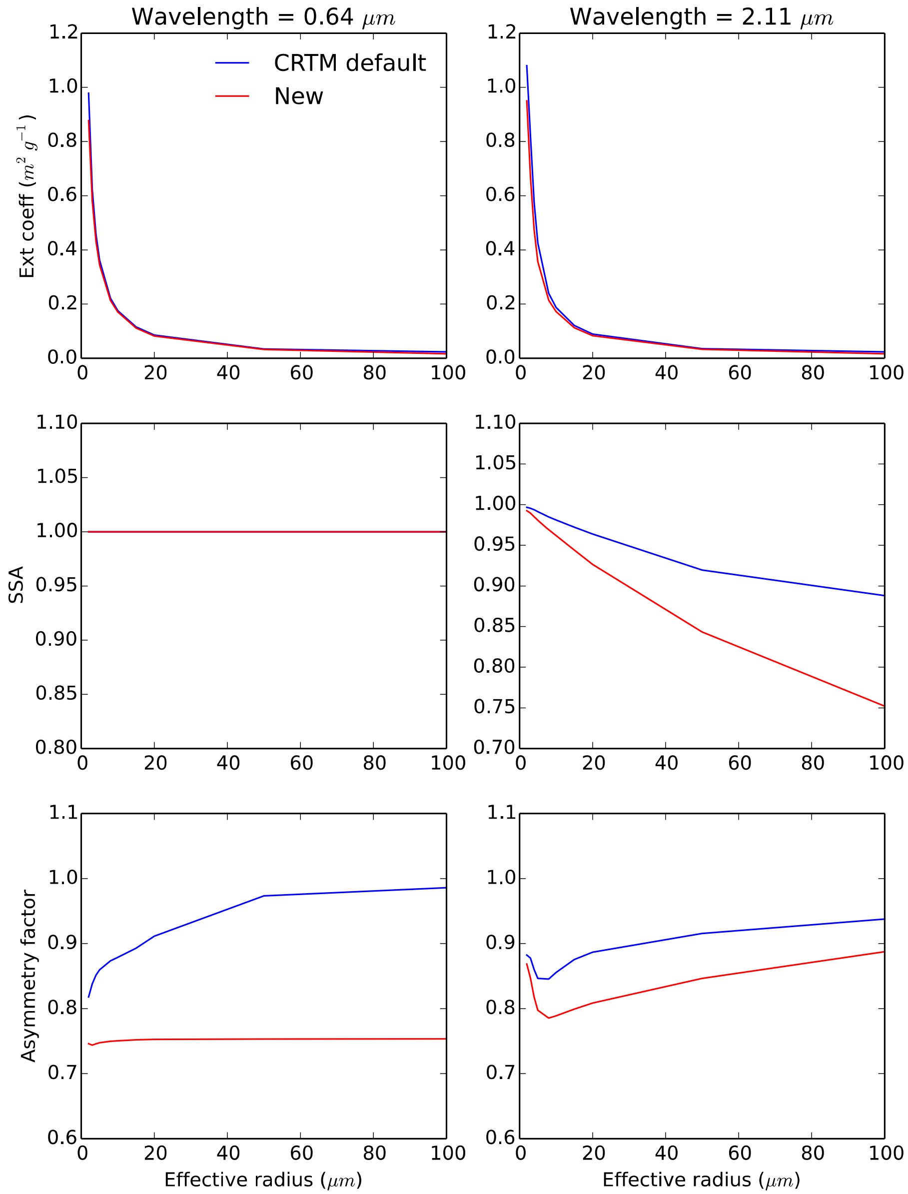
$$\overline{Q_{sca}} = \frac{\int_{r_{min}}^{r_{max}}[Q_{sca}(r)A(r)n(r)]dr}{\int_{r_{min}}^{r_{max}}[A(r)n(r)]dr},$$

$$\overline{\omega} = \frac{\overline{Q_{sca}}}{\overline{Q_{ext}}},$$

$$\overline{g} = \frac{\int_{r_{min}}^{r_{max}}[g(r)A(r)Q_{sca}(r)n(r)]dr}{\int_{r_{min}}^{r_{max}}[Q_{sca}(r)A(r)n(r)]dr},$$

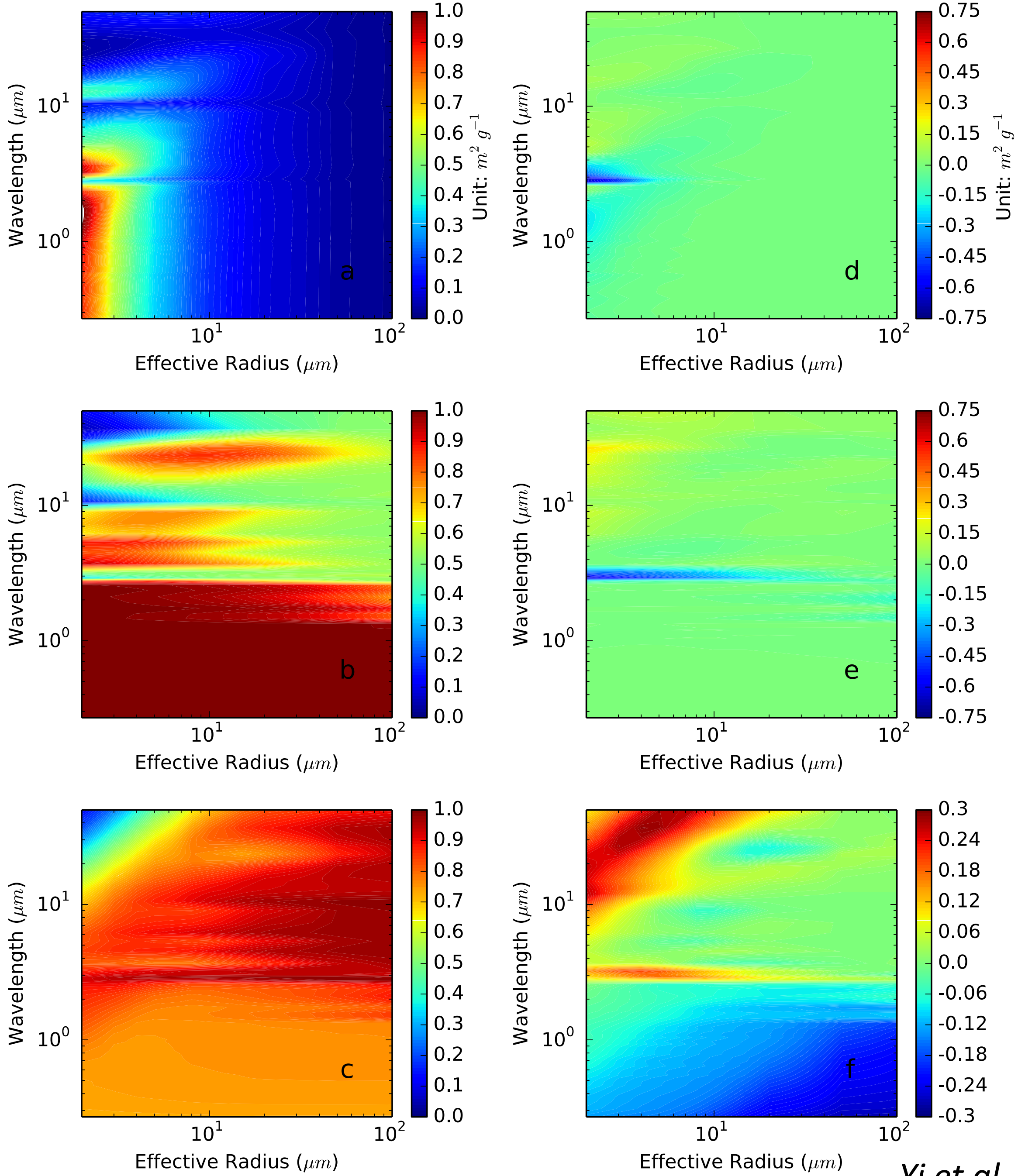
$$\overline{P(\theta)} = \frac{\int_{r_{min}}^{r_{max}}[P(\theta,r)Q_{sca}(r)A(r)n(r)]dr}{\int_{r_{min}}^{r_{max}}[Q_{sca}(r)A(r)n(r)]dr},$$

- Mass extinction coefficient
- Single-scattering albedo
- Asymmetry parameter
- Phase function Legendre expansion coefficient



CRTM ice cloud optical properties: 2.1.3 version VS this study

- Ice mass extinction coefficients:
  - Little difference
- The single-scattering albedo:
  - ~1 (0.64 μm wavelength)
  - Decreases with the increase of effective radius (2.11 μm wavelength)
- The asymmetry factor:
  - Shortwave (0.64 μm) ice cloud is almost independent to the effective size and remains constant around 0.75.
  - Conversely, the CRTM default ice cloud asymmetry factor has increasingly larger value with an increase in the effective radius.

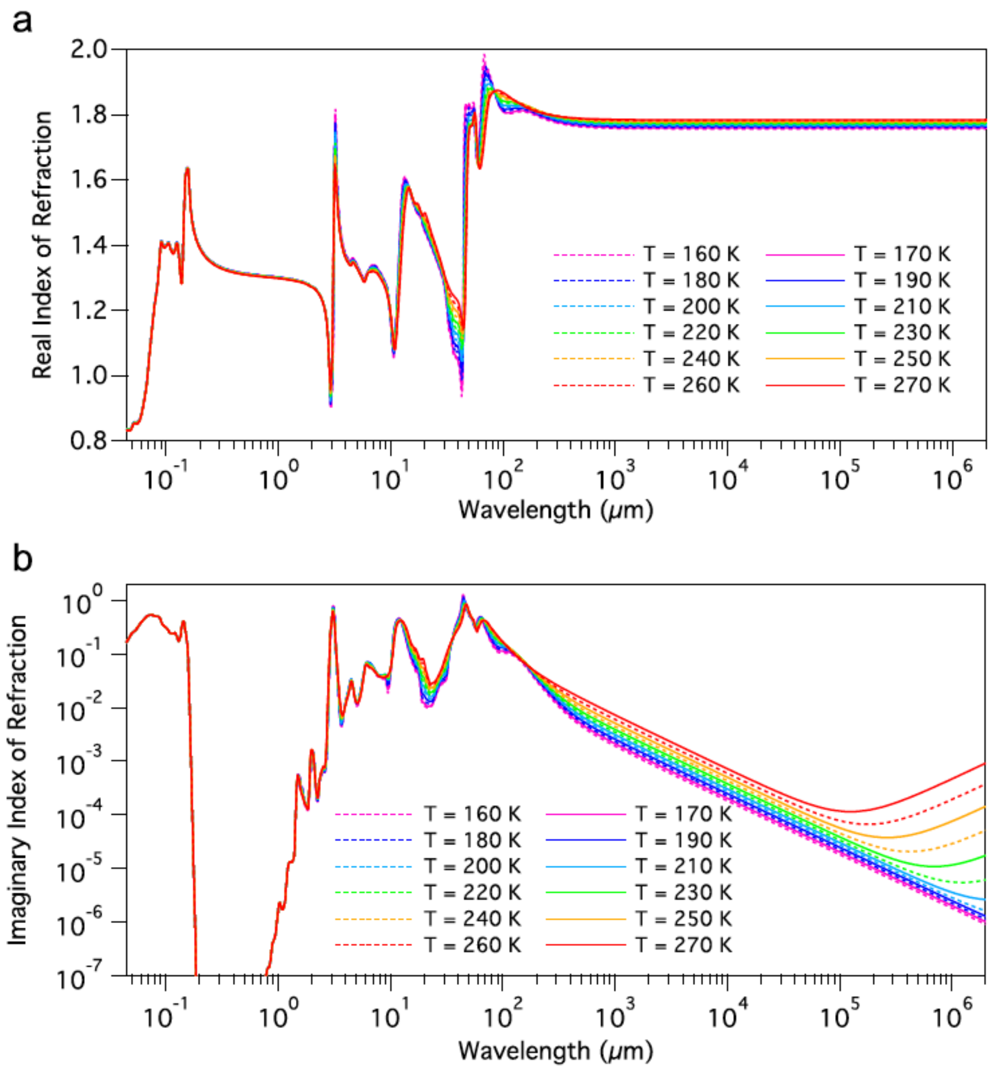


CRTM ice cloud optical properties:
2.1.3 version VS this study –
visible + infrared

- Ice mass extinction coefficients
- The single-scattering albedo
- The asymmetry factor

Yi et al., 2016, J. Geophy. Res. Atmos.

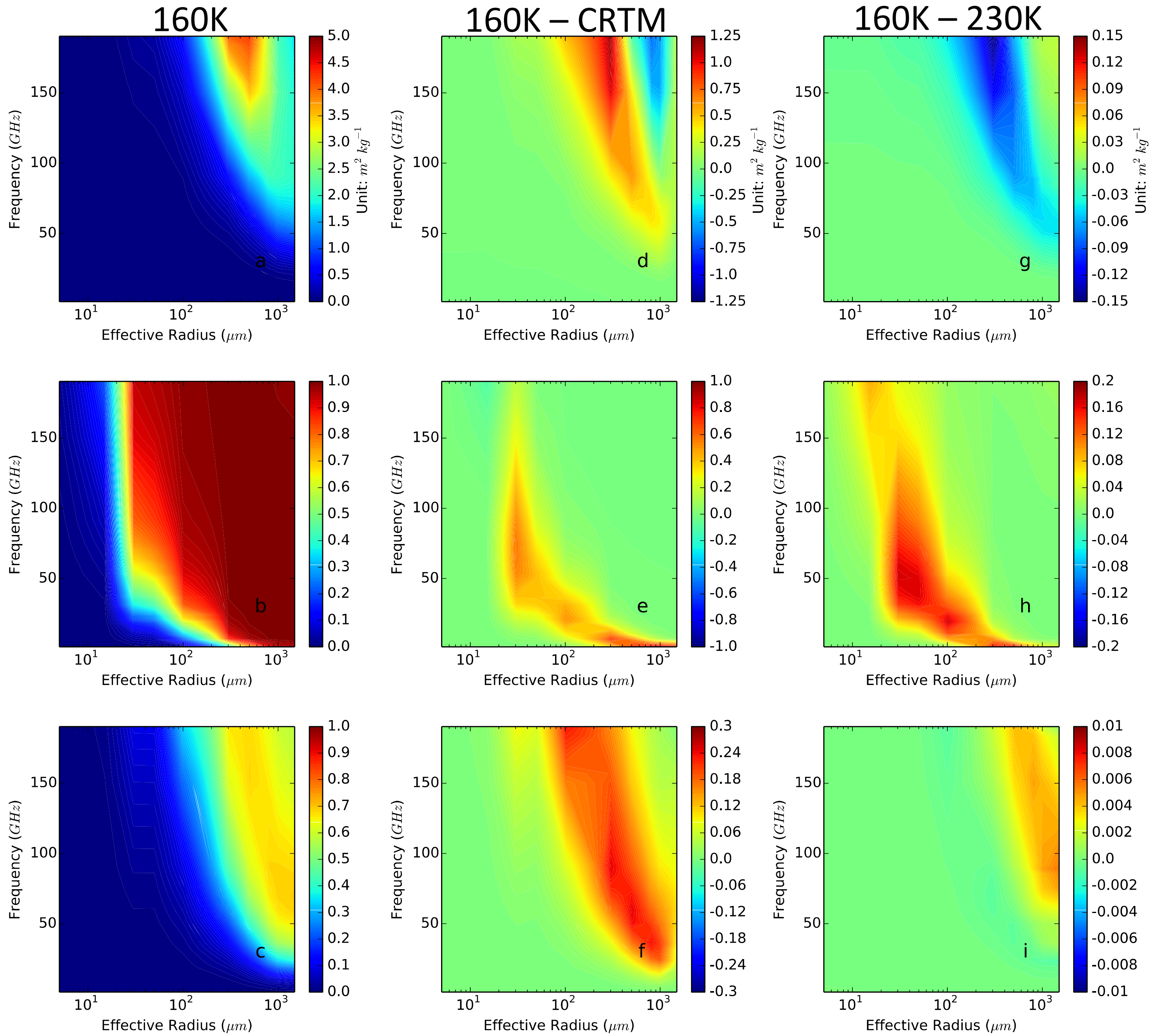
Refractive index in the microwave: Temperature dependence



Strong variation of imaginary part of ice refractive index with temperature

Iwabuchi and Yang, 2011

CRTM ice cloud optical properties: current version VS this study – microwave

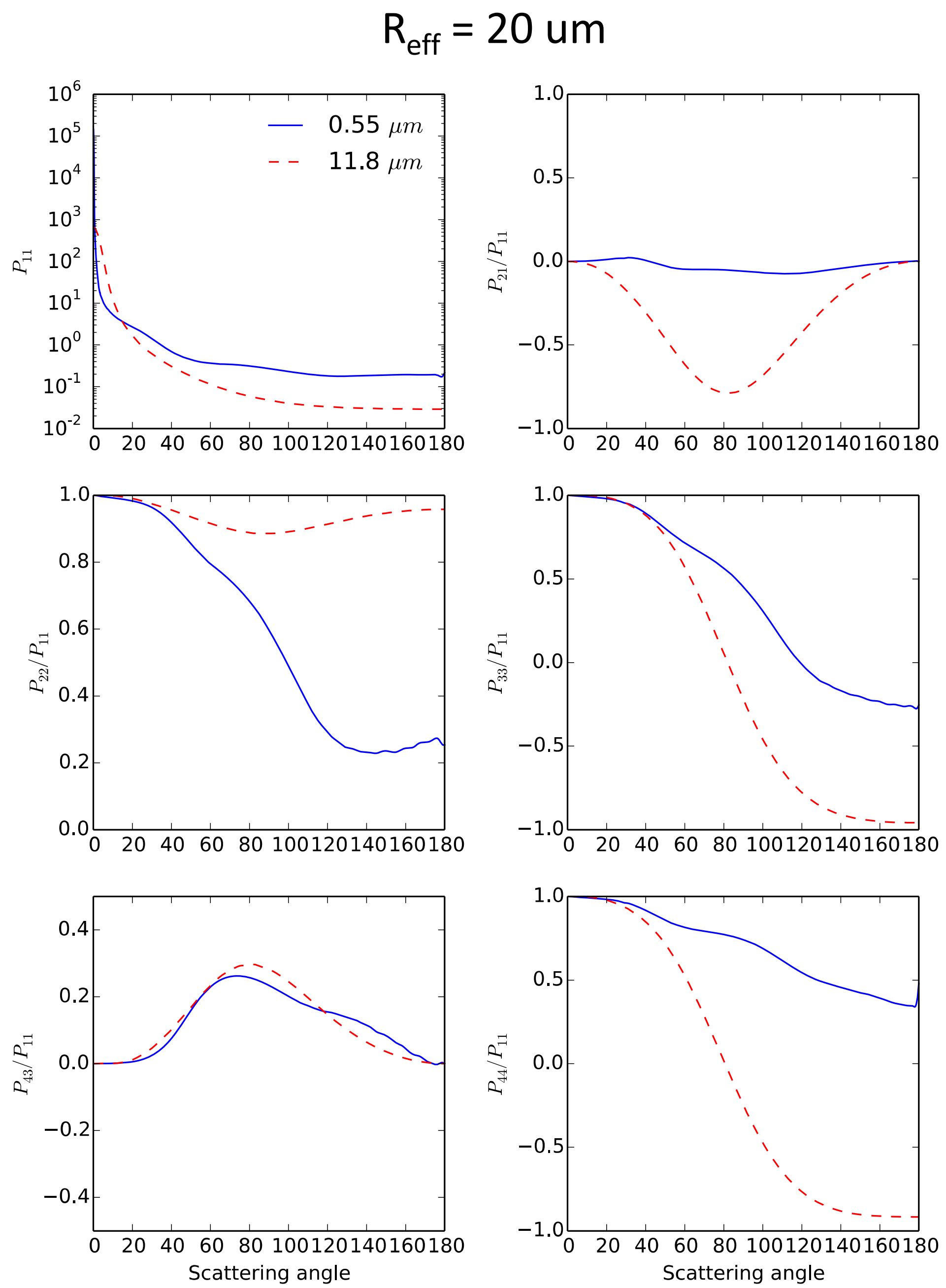


Full scattering phase matrix of ice clouds with polarization

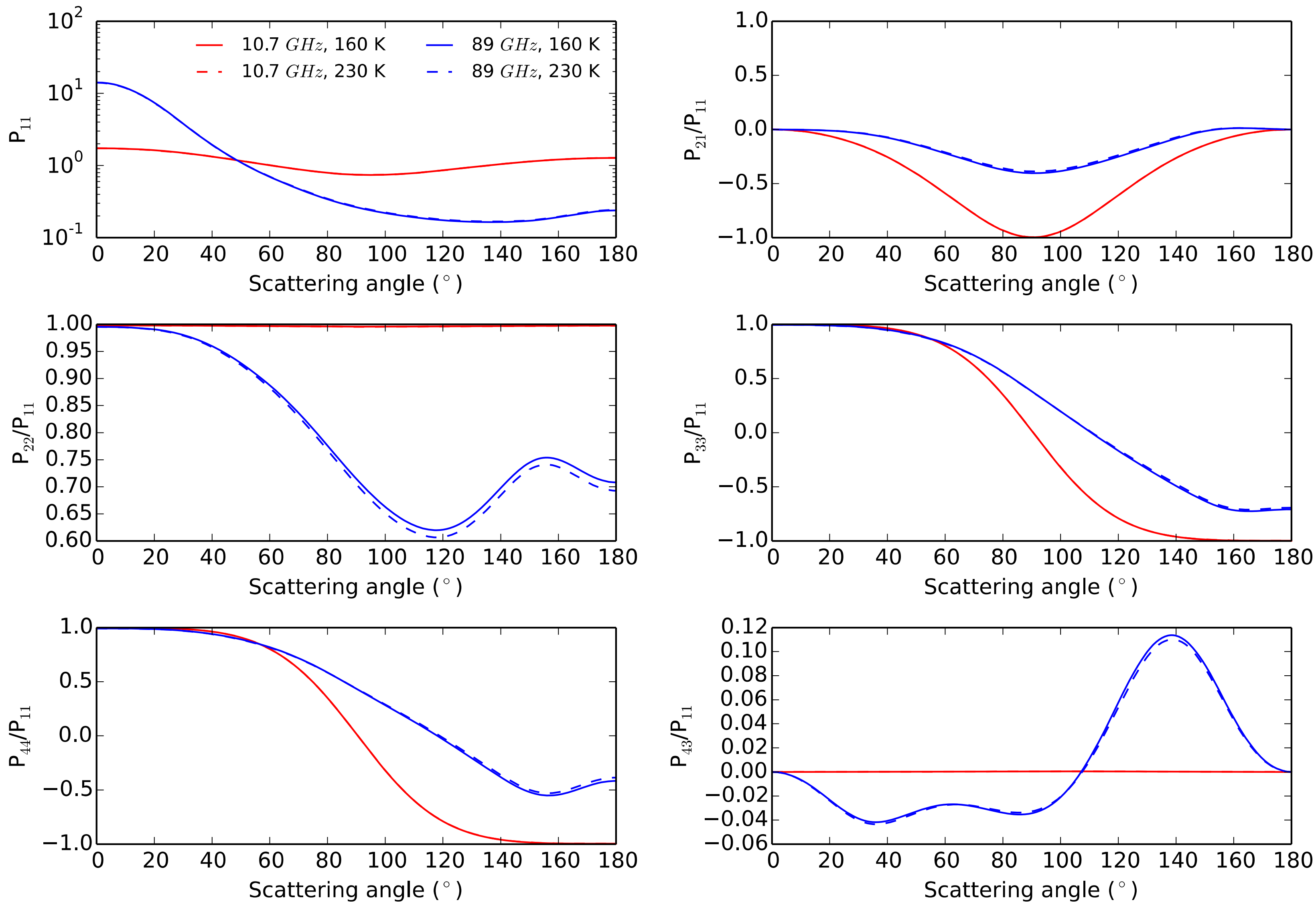
For randomly oriented particles:

$$\begin{bmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{bmatrix} = \frac{\sigma_s}{4\pi r^2} \begin{bmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{12} & P_{22} & 0 & 0 \\ 0 & 0 & P_{33} & P_{34} \\ 0 & 0 & -P_{34} & P_{44} \end{bmatrix} \begin{bmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{bmatrix}$$

Expand the capabilities of CRTM to account for ice cloud polarization



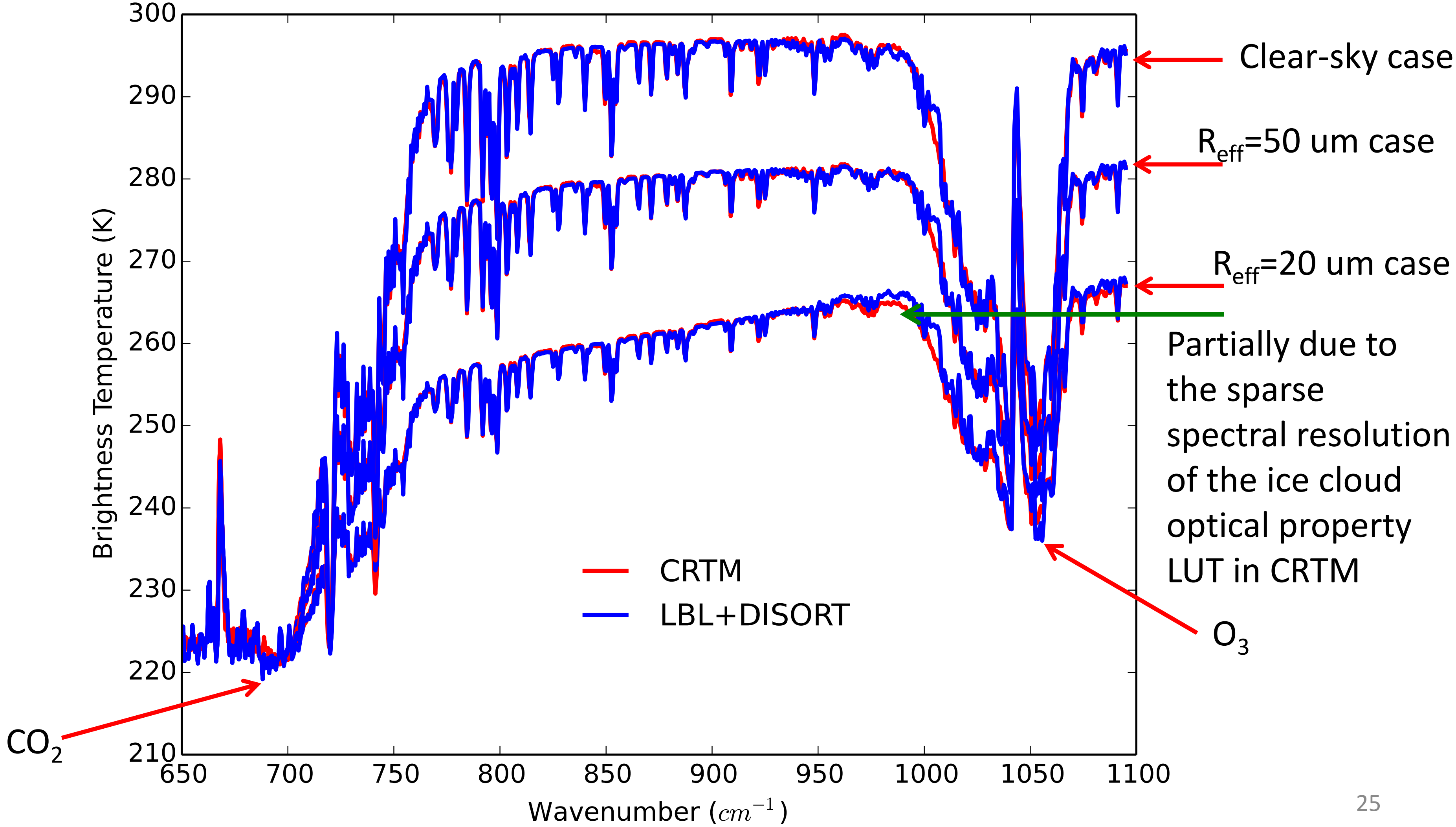
Microwave region, R_{eff} = 800 um



Model settings

- Benchmark
  - LBLRTM+DISORT
- In comparison with CRTM results
- US standard atmospheric profile 1976 is used
- One layer of ice cloud with IWP = 0.02 kg m^{-2} is set at around 300 hPa
- 16-stream calculation

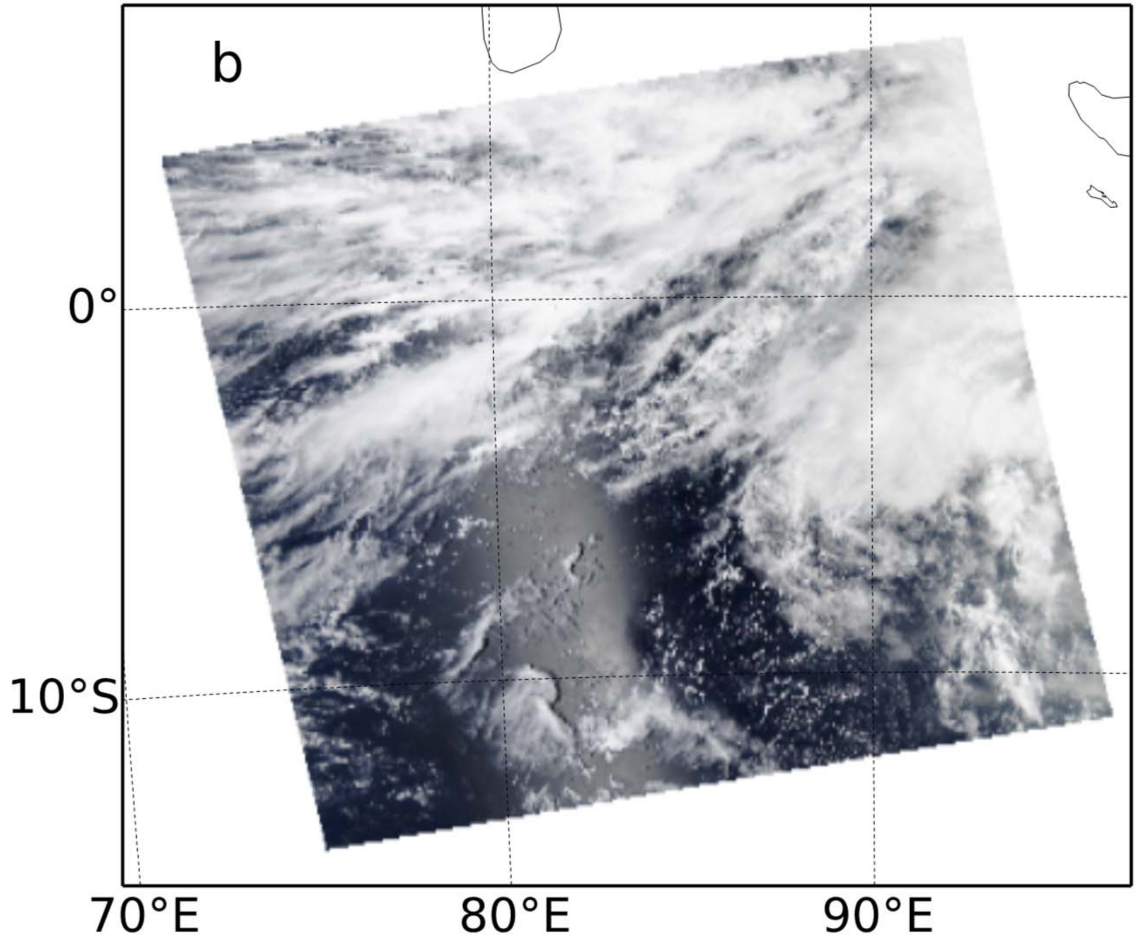
Comparison of hyper-spectral simulation of TOA brightness temperature over CrIS band



Simulation of MODIS LW band brightness temperature

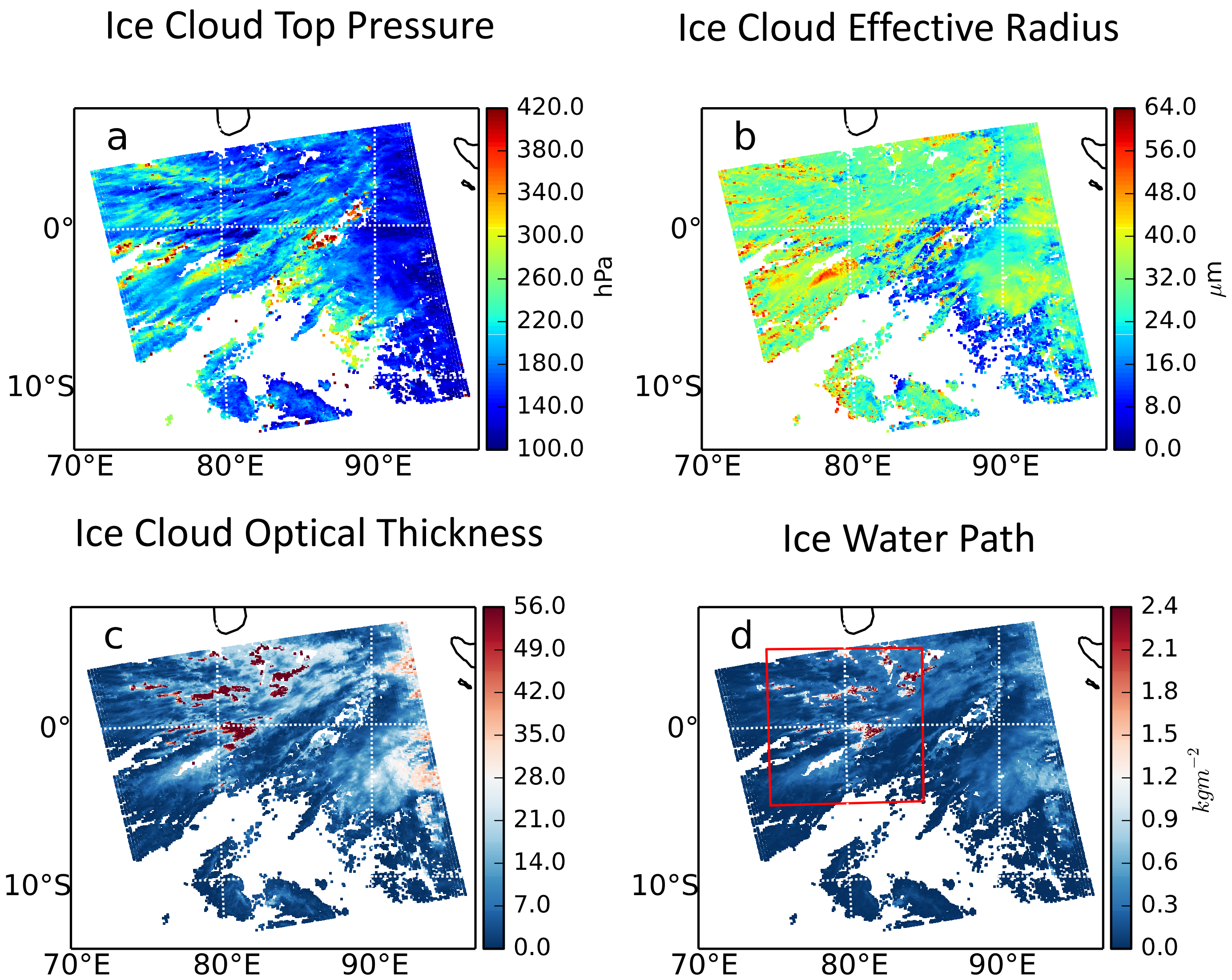
- Source-viewing geometries come from MODIS products
- MODIS ice cloud products are used:
  - Ice water path
  - Ice cloud effective radius
  - Cloud top pressure
- Merra reanalysis provides the vertical atmospheric profile
  - Meteorological fields: Pressure, temperature, etc.
  - Interpolate into 82 vertical layers
  - Temporal and horizontal collocations
  - Trace gases: H_2O, O_3 and CO_2

AQUA MODIS granule with ice clouds over Indian Ocean

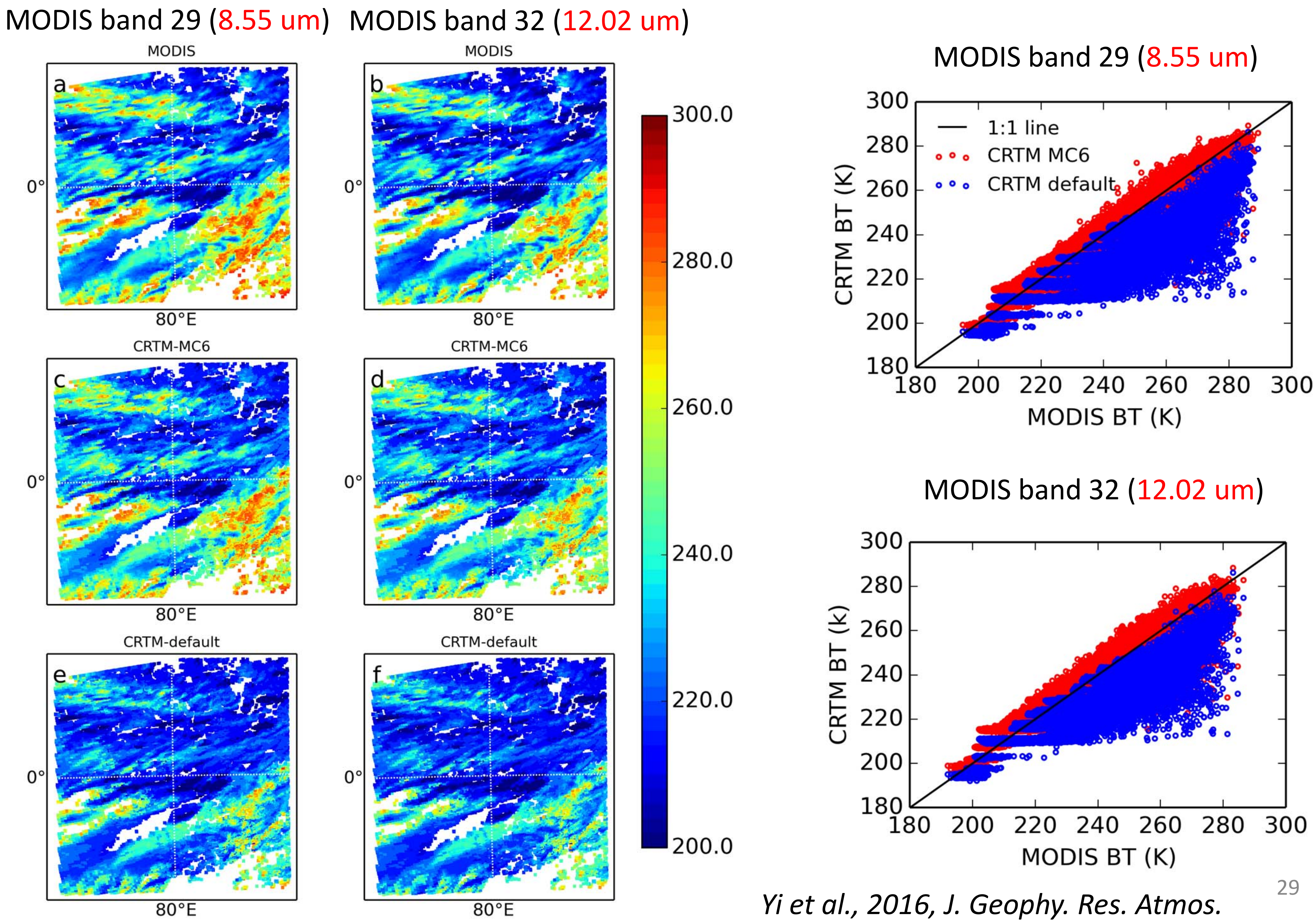


2013-10-18 08:00 UTC

MODIS ice cloud properties (MYD06)

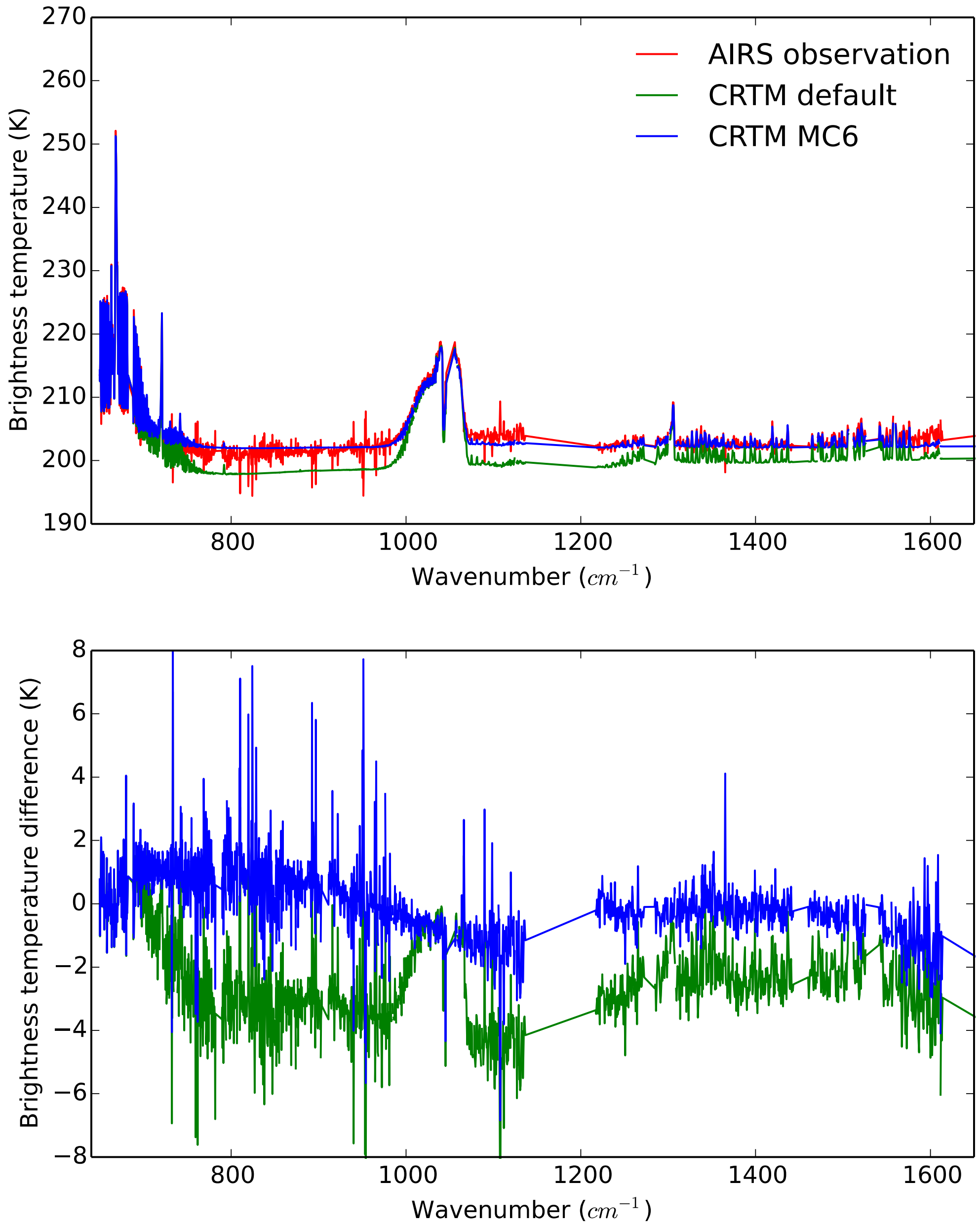


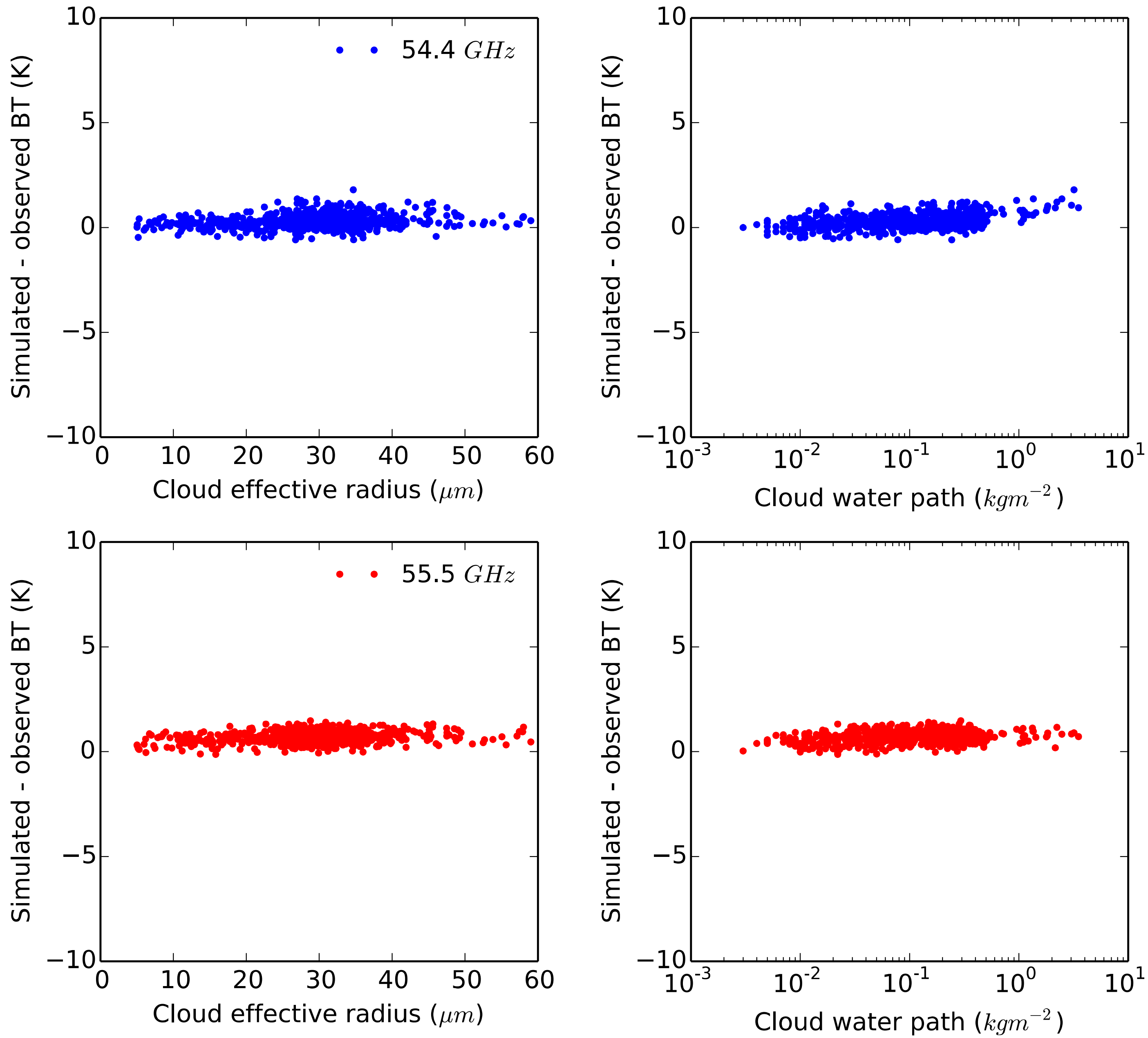
Simulated vs observed MODIS band brightness temperature



Yi et al., 2016, J. Geophy. Res. Atmos.

Simulat ature




54.4 GHz
55.5 GHz
Simulated - observed BT (K)
Cloud effective radius (μm)
Cloud water path (kgm^{-2})
10
5
0
−5
−10
0
10
20
30
40
50
60
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

Error analysis of CRTM simulation

- Possible errors
  - Uncertainties in *the height of cloud layer*
  - Uncertainties in *the cloud phase classification*
  - Uncertainties in *cloud properties: ice cloud effective radius, optical thickness, ice water path, etc.*

Stochastic model for density-dependent microwave Snow and Graupel scattering coefficients

Table 1
Solid hydrometeor categories and associated densities in the CRTM Release 2.1.3.

Category	Density (g/cm^3)
Cloud ice	0.900
Graupel and hail	0.400
Snow	0.100

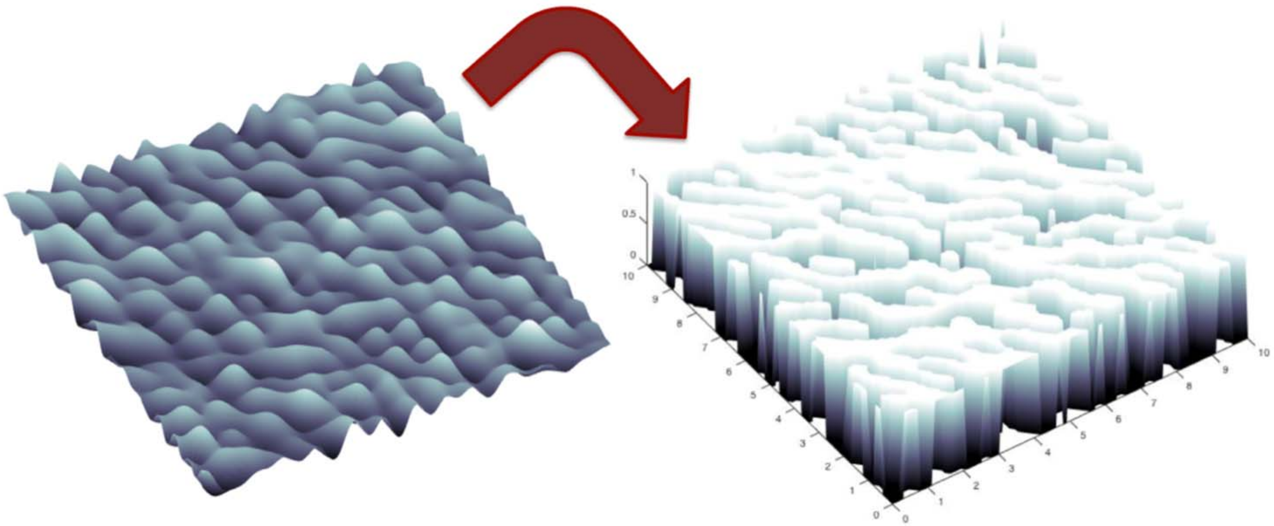


Fig. 1. Random superposition of cosine wave fields before (left) and after (right) the application of the ice–air threshold.

Stegmann et al., 2018

Graupel and Snowflake particle representation

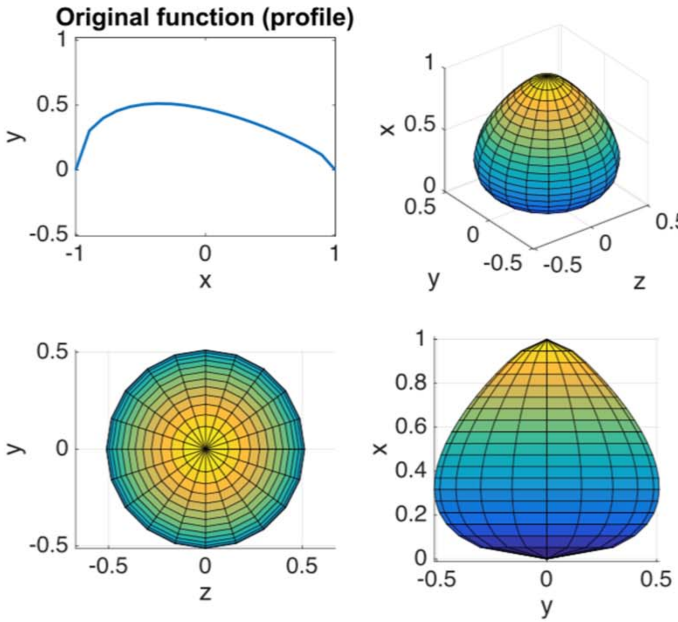


Fig. 2. A droplet-like body of revolution as a stand-in for a pristine graupel shape.

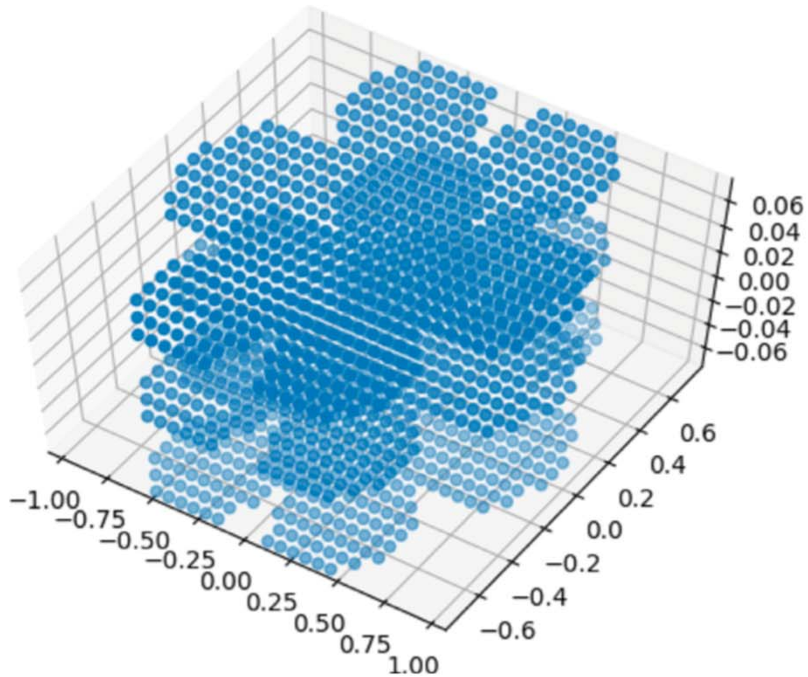


Fig. 4. Discrete representation of the snowflake geometry of Fig. 3 on a cubic lattice. On display is a low-resolution discretization for better visibility of the spatial structure. Each vertical layer is detached, so as to improve the visibility of the layer below.

Stegmann et al., 2018

Influence of particle density on the snow optical properties

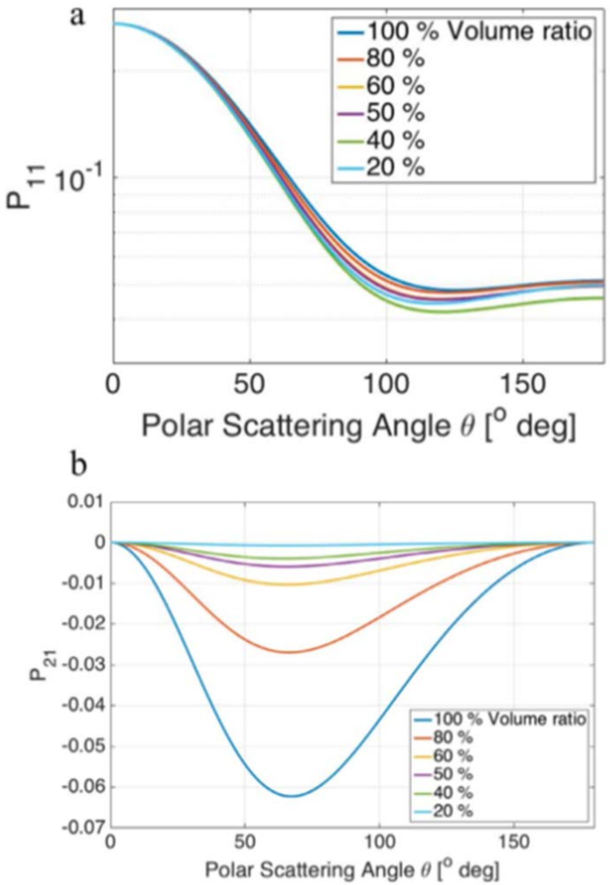


Fig. 10. (a) Influence of particle density on the phase function P_{11} for a snow particle with 1 mm size at 270 K and illuminated by 190 GHz microwave radiation. (b) Influence of particle density on the phase matrix element P_{21} for a snow particle with 1 mm size at 270 K and illuminated by 190 GHz microwave radiation.

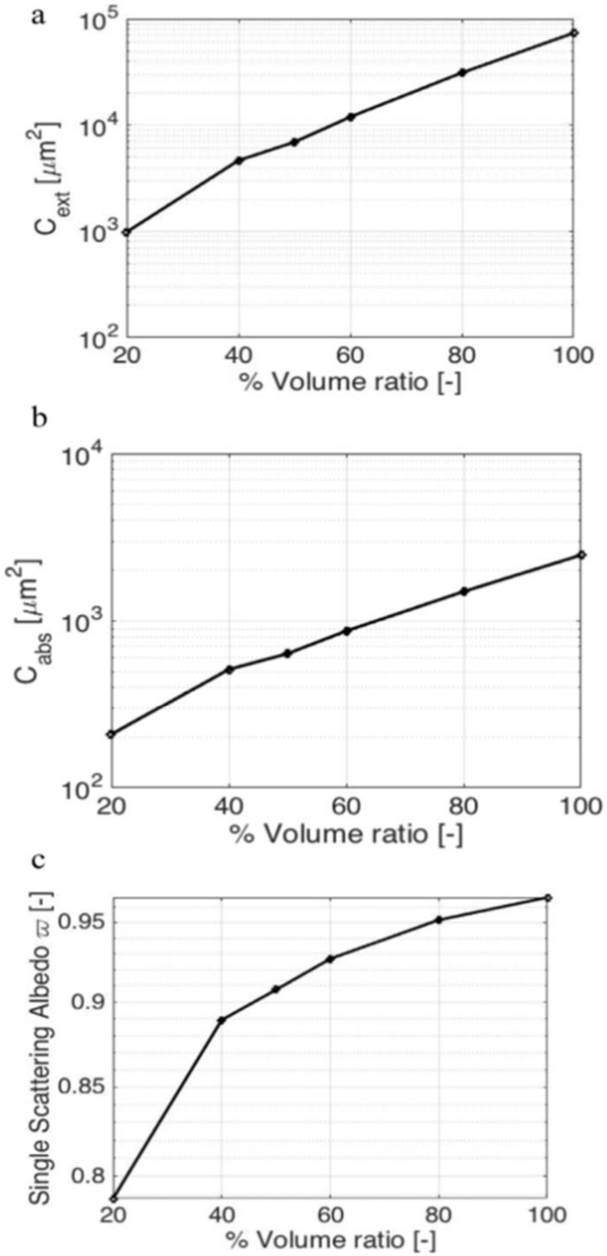


Fig. 11. (a) Influence of particle density on the extinction cross-section for a snow particle with 1 mm size at 270 K and illuminated by 190 GHz microwave radiation. (b) Influence of particle density on the absorption cross-section for a snow particle with 1 mm size at 270 K and illuminated by 190 GHz microwave radiation. (c) Influence of particle density on the single-scattering albedo for a snow particle with 1 mm size at 270 K and illuminated by 190 GHz microwave radiation.

Stegmann et al., 2018

Simulated AMSU-A BT: obs vs simulation

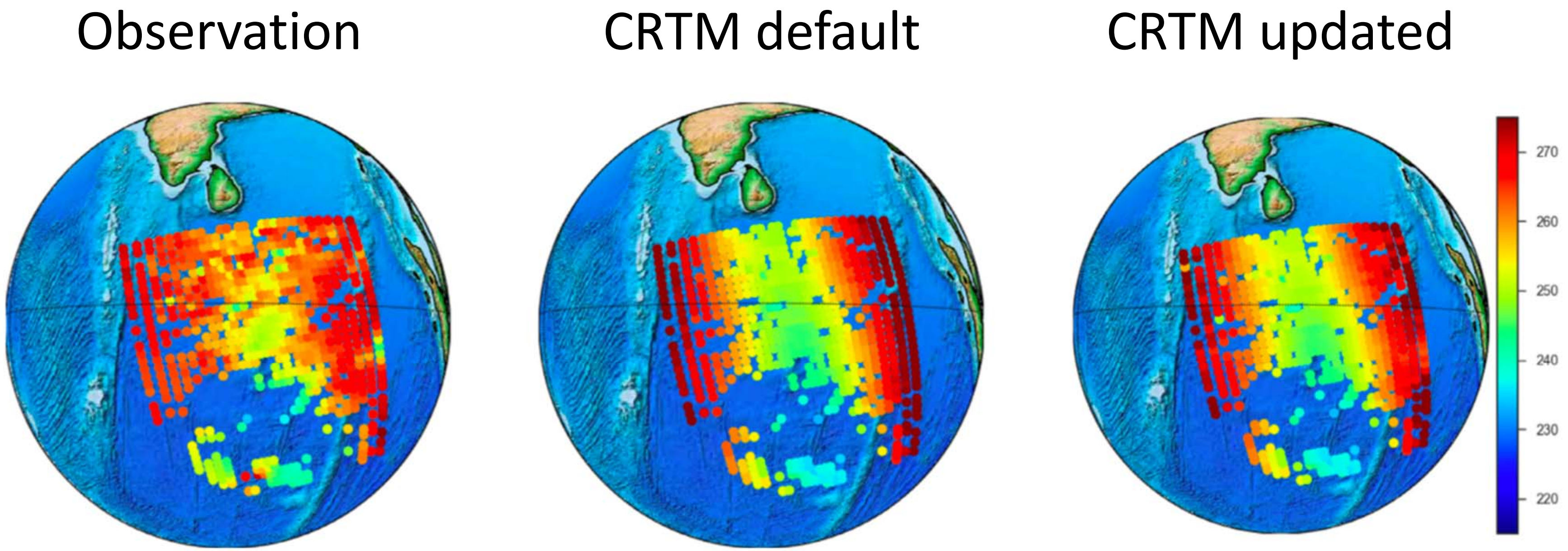


Fig. 19. Comparison of brightness temperature pixels in Kelvin of Channel 15 as observed by the AMSU-A instrument onboard the Aqua satellite (left), computed using the CRTM REL-2.1.3 default snow scattering coefficients (center), and computed using the BRM snow coefficients (right). Near-sided perspective projection at the 705 km altitude of the Aqua satellite orbit.

Stegmann et al., 2018

Simulated AMSU-A BT: obs vs simulation

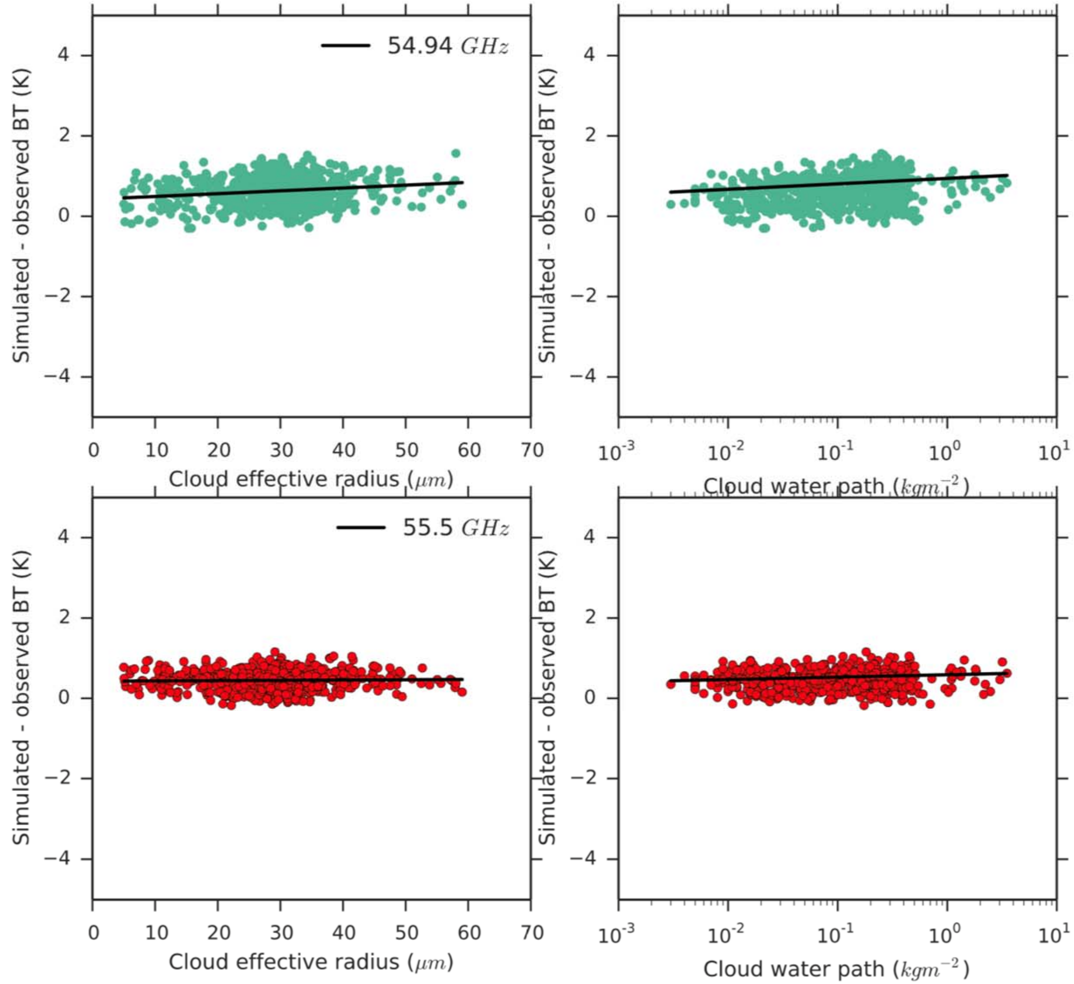


Fig. 21. Brightness temperature differences for AMSU-A channels 7 and 8 over cloud particle effective radius and cloud water path for the granule shown in Fig. 19. The linear regression of the sample pixels is shown in black.

Stegmann et al., 2018

Summary

- We updated the ice cloud optical property look-up table (visible and IR) used in the CRTM from MODIS collection 5 to collection 6 ice cloud model.
- High-spectral resolution simulation of brightness temperature under clear and ice cloudy sky with the new ice cloud optical properties matches well with rigorous calculation with LBL+DISORT.
- CRTM simulated brightness temperature for the MODIS IR band, AIRS, and AMSU-A show close agreement with the satellite observation.
- Errors in the simulated results are likely due to the uncertainties in the cloud layer height, as well as the cloud phase classification and insufficient spectral resolution of the ice cloud optical property look-up table.

RTTOV cloud optical properties

- RTTOV provides two methods of specifying the optical properties of the scattering particles.
- *Method 1 – use pre-defined optical properties:* specify abundance profiles for the pre-defined particle types.
- *Method 2 – provide optical properties explicitly:* supply profiles of the scattering optical properties for each instrument channel directly. This provides greater flexibility as you are not limited to the pre-defined particle types, but it is a slightly more complicated way of calling RTTOV.

Column 1:	Stratus Continental	STCO
Column 2:	Stratus Maritime	STMA
Column 3:	Cumulus Continental Clean	CUCC
Column 4:	Cumulus Continental Polluted	CUCP
Column 5:	Cumulus Maritime	CUMA
Column 6:	Ice cloud (all types despite the name "CIRR")	CIRR

Table 24. Cloud types available in RTTOV v12.

https://www.nwpsaf.eu/site/software/rttov/download/coefficients/coefficient-download/

RTTOV water cloud optical properties

- Two options for predefined cloud liquid water (CLW) optical properties
- **OPAC CLW scheme**
  - These optical properties were introduced in RTTOV v9
  - Based on five OPAC cloud types and vertical profiles of layer cloud concentrations
  - The optical properties are computed from Mie theory.
  - Each particle type has a fixed effective particle size: the particles differ in the assumed size distributions.
  - Therefore the CLW effective diameter is not used for these properties.
- **Deff CLW scheme**
  - These optical properties were introduced in RTTOV v12.2.
  - They are based on the Mie properties available with libRadtran: in this case there is just one particle type and the optical properties are stored in terms of particle effective diameter.

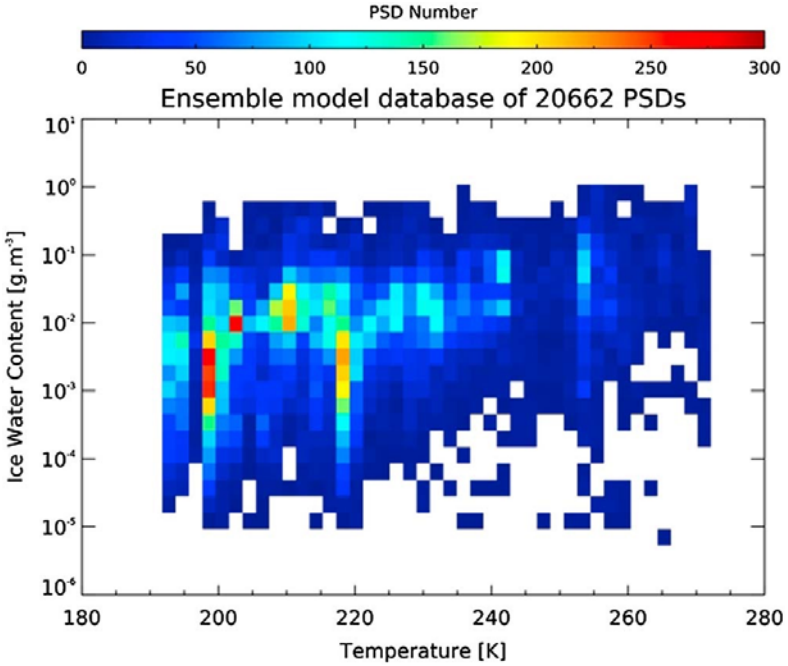
https://www.nwpsaf.eu/site/software/rttov/download/coefficients/coefficient-download/

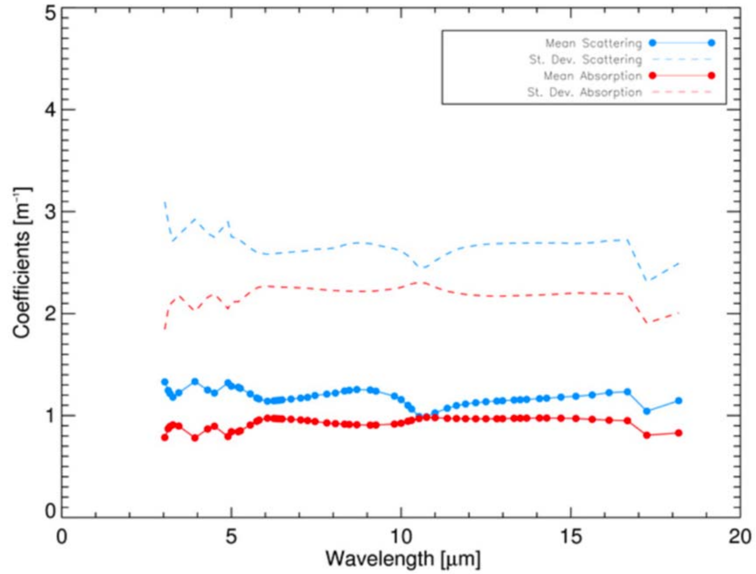
RTTOV ice cloud optical properties

- Two options for ice cloud optical properties
- **SSEC/Baum ice scheme**
  - These optical properties are stored in terms of ice effective diameter.
  - RTTOV provides 4 parameterizations of ice effective diameter.
  - Alternatively you can specify the effective diameters explicitly.
- **Baran ice scheme**
  - These optical properties are parameterized in terms of ice water content and temperature.
  - Ice cloud concentrations are also input to RTTOV, but there is no explicit dependence on effective diameter.

https://www.nwpsaf.eu/site/software/rttov/download/coefficients/coefficient-download/

Optical properties parameterized in terms of IWC and temperature





$$\log_{10}[\beta_{\text{abs}}(\lambda, T, \text{IWC})] = A_a + B_a T + C_a \log_{10}(\text{IWC}) + D_a T^2, + E_a(\log_{10}(\text{IWC}))^2 + F_a T \log_{10}(\text{IWC})$$

$$\log_{10}[\beta_{\text{sca}}(\lambda, T, \text{IWC})] = A_s + B_s T + C_s \log_{10}(\text{IWC}) + D_s T^2 + E_s(\log_{10}(\text{IWC}))^2 + F_s T \log_{10}(\text{IWC}),$$

Vidot et al., 2015; Saunders et al., 2013

$$b(\lambda, T, \text{IWC}) = A_b + B_b T + C_b \log_{10}(\text{IWC}).$$

Remaining problems and Future work

- Parameterizations:
  - Choice of cloud particle model?
  - Choice of PSD?
  - Contributions of mixed phase clouds? And other hydrometers (snow, graupel, etc.)?
  - Dependency on cloud temperature
  - Consistency between cloud microphysics and optics
- Modeling:
  - Treatment of cloud overlap
- Exploration of microphysical-optical consistent cloud particle model (Dr. Marco Matricardi)
- Etc…

Thank you for your attention!

Questions?