A new ice parameterization for broadband radiative transfer simulations in comparison with CERES observations

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Main Objectives

- Develop an ice cloud habit model that is able to achieve spectral consistency in satellite-based cloud property retrievals across the visible and infrared bands. Two-habit ice particle model is an optimal choice in terms of spectral consistency.

- Evaluate the performance of the two-habit model for broadband radiative transfer simulations.

Basic equations for parameterization

$$\tau = IWP(a + b / r_e)$$

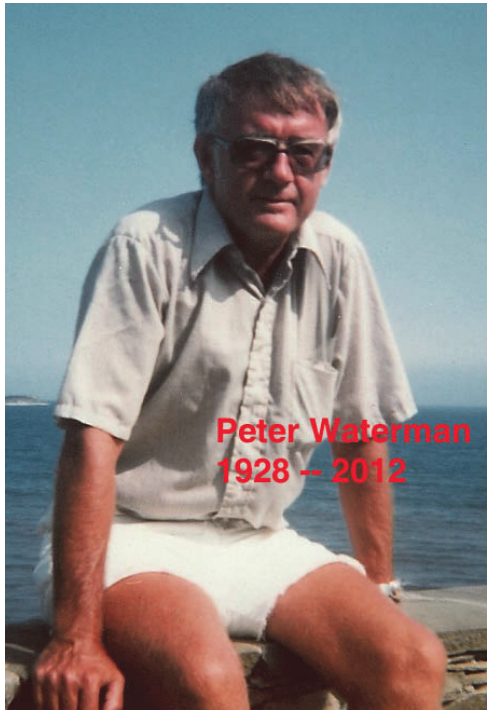
$$1 - \tilde{\omega}_i = c + d \ r_e$$

$$g = e + f \ r_e$$

Overview of ice cloud radiative property parameterization

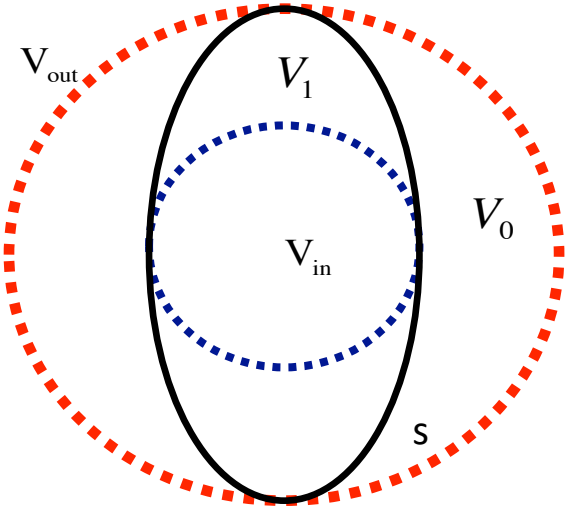
- Early efforts parameterized cirrus optical properties in terms of cloud temperature (Platt and Harshvardhan, 1988).
- Slingo (1989) first proposed a water cloud radiative property parameterization for GCM, assuming spherical water cloud particles.
- Ebert and Curry (1992) followed Slingo's idea and developed the ice cloud radiative property parameterization assuming smooth single column ice particles.
- Many ice optical property parameterizations follow the single column ice particle model (Fu, 1996; Fu et al., 1999; Fu et al., 2007).
- Other studies propose the use of different ice particle habits, i.e., Chebyshev particles (McFarquhar et al., 2002) and various ice habits (Key et al., 2002; Chou et al., 2002)
- Need innovative & accurate light scattering modeling capabilities

The Waterman T-Matrix Method



(Mishchenko and Martin, JQSRT, 123:2-7, 2013)

$$T = -RgQ[Q]^{-1}$$

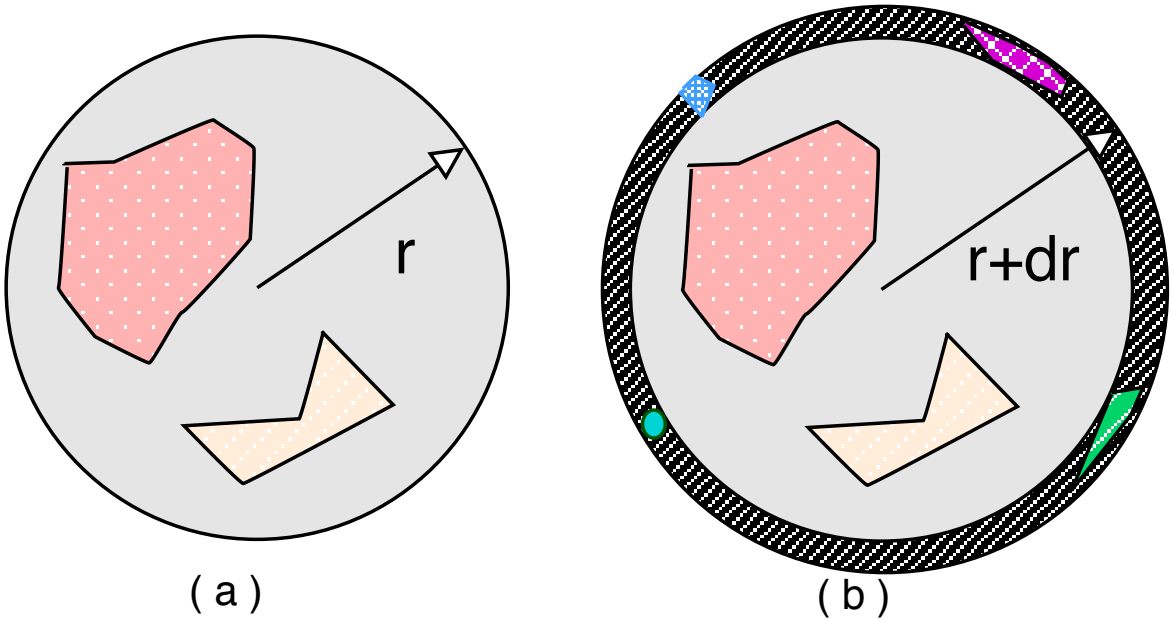


Extended boundary condition

$$\vec{E}^{inc}(\vec{r}') = -\int_s ds\{i\omega\mu_0[\hat{n}\times\vec{H}(\vec{r})]\bullet\overleftrightarrow{G}(\vec{r},\vec{r}') + [\hat{n}\times\vec{E}(\vec{r})]\bullet[\nabla\times\overleftrightarrow{G}(\vec{r},\vec{r}')]\}, \qquad \vec{r}'\in V_1$$

$$\vec{E}^{sca}(\vec{r}') = \int_s ds\{i\omega\mu_0[\hat{n}\times\vec{H}(\vec{r})]\bullet\overleftrightarrow{G}(\vec{r},\vec{r}') + [\hat{n}\times\vec{E}(\vec{r})]\bullet[\nabla\times\overleftrightarrow{G}(\vec{r},\vec{r}')]\}, \qquad \vec{r}'\in V_0$$

Break-through in Light Scattering Computation -- Invariant Imbedding T-matrix Method



Maxwell's equations

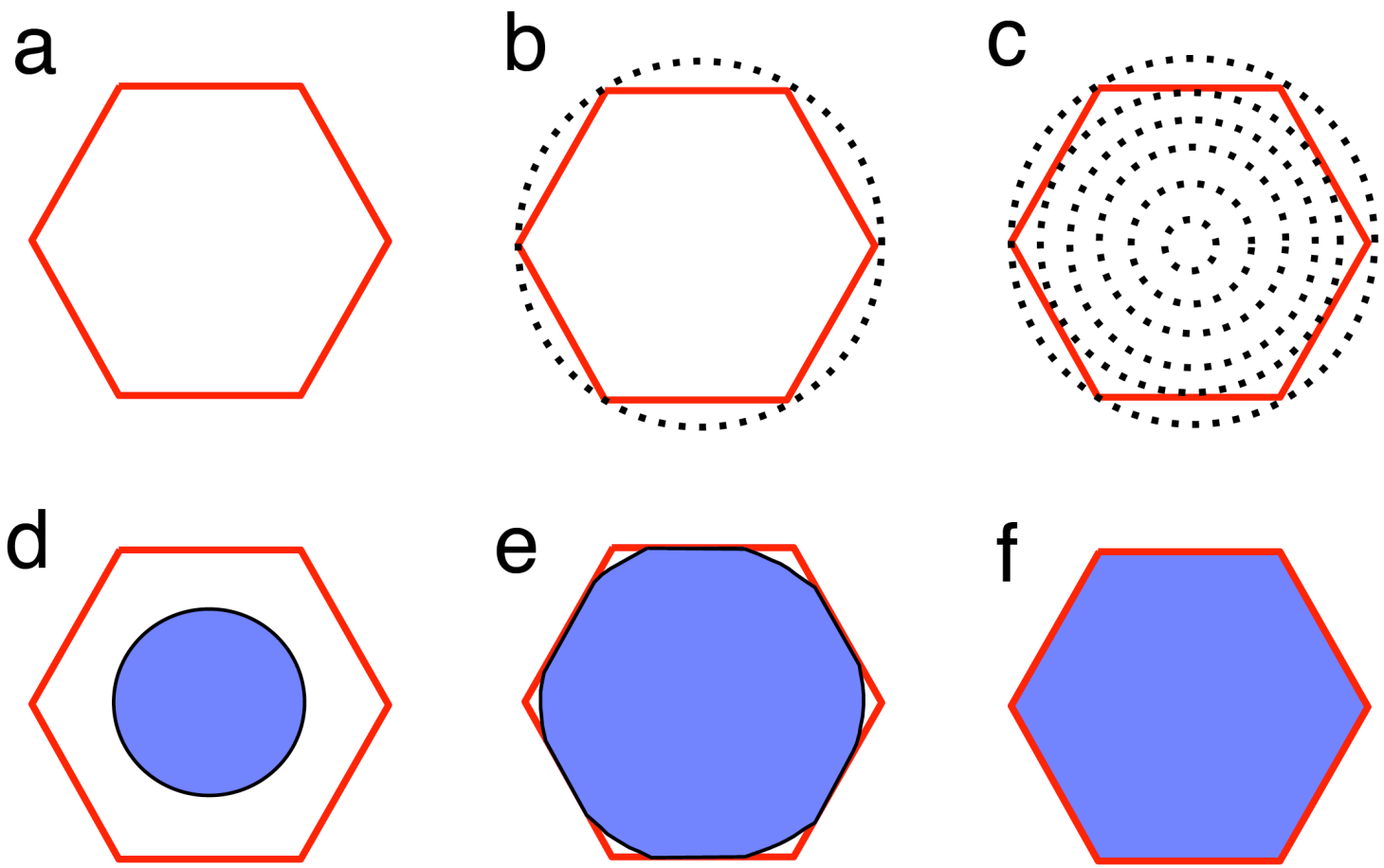
$$\vec{E}(\vec{r}) = \vec{E}_{inc}(\vec{r}) + k^2 \int \left(m^2 - 1\right) \overleftrightarrow{G}(\vec{r} - \vec{r}\,') \cdot \vec{E}(\vec{r}\,') d^3\vec{r}\,'$$

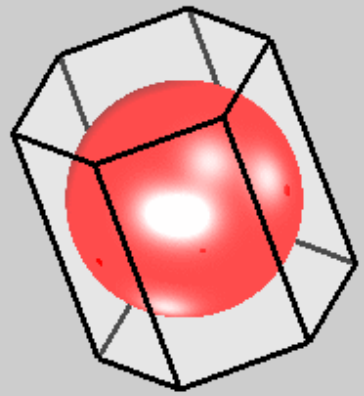
Volume Integral Equation

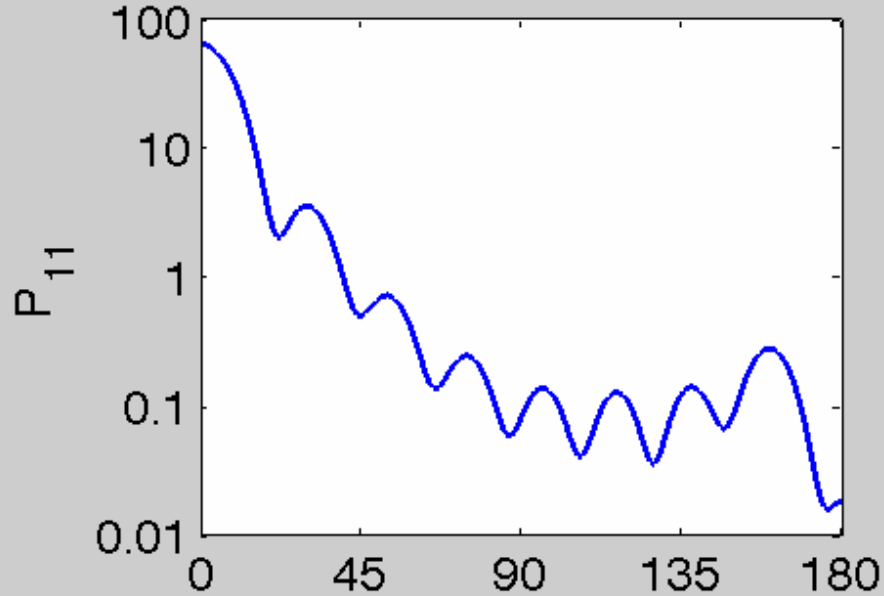
$$\boxed{T_{mnmn'}(r+dr)} = Q_{11}^m(r+dr) + \left[\mathbf{I} + Q_{12}^m(r+dr)\right]\left[\mathbf{I} - \boxed{T_{mnmn'}(r)} Q_{22}^m(r+dr)\right]^{-} \boxed{T_{mnmn'}(r)} \left[\mathbf{I} + \tilde{Q}_{12}^m(r+dr)\right]$$

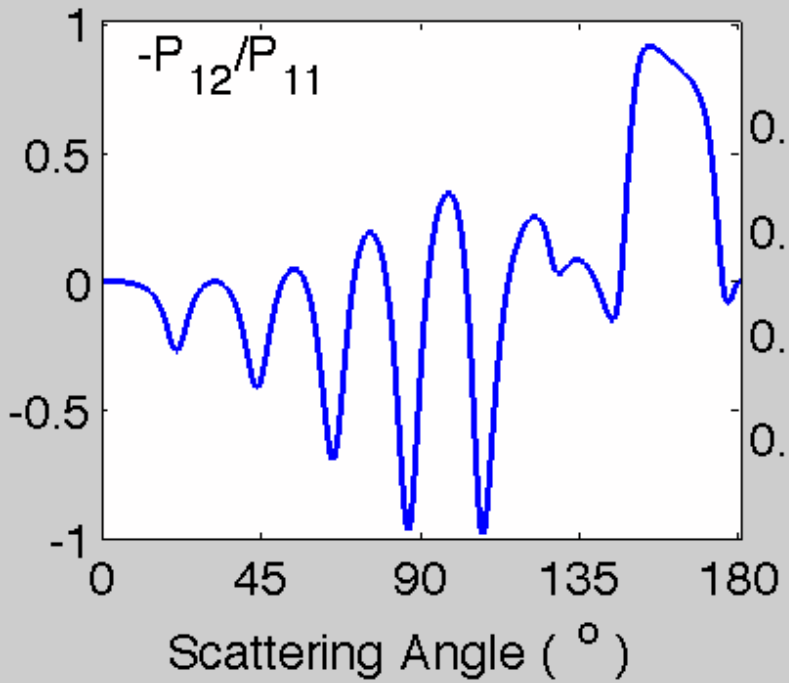
Johnson (1988); Bi, Yang, Kattawar, and Mishchenko, (2013)

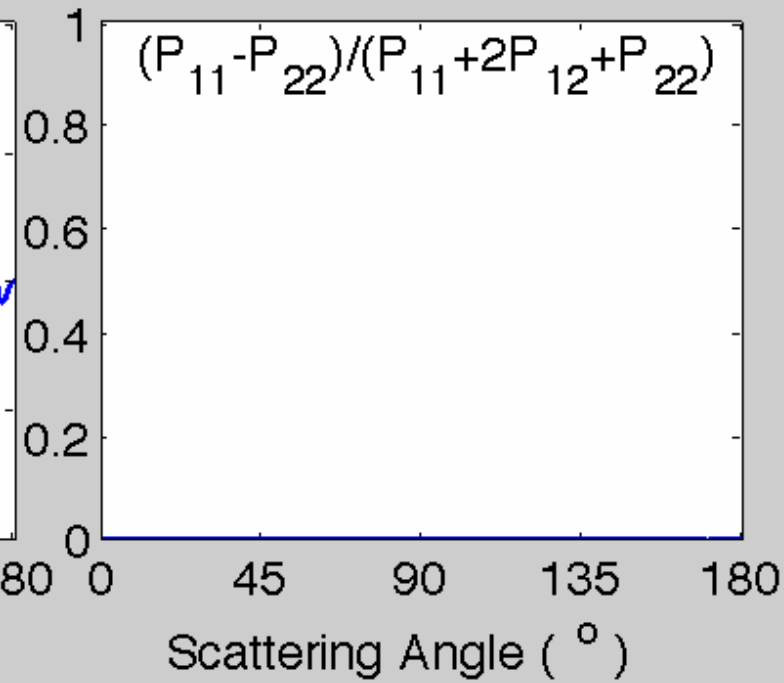
An innovative way to think about light scattering by a nonspherical particle



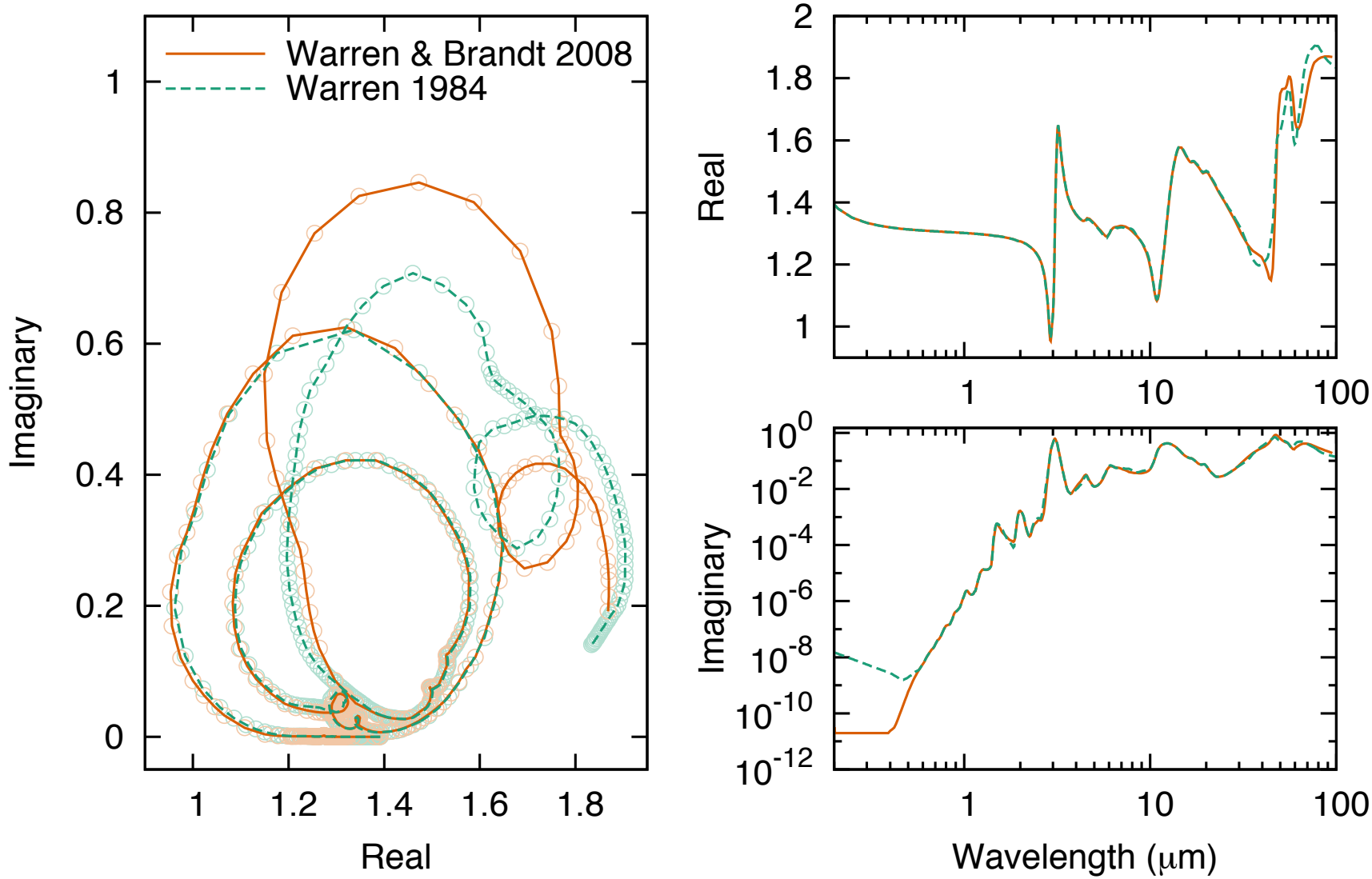



100
10
1
0.1
0.01
P11
0
45
90
135
180


-P12/P11
1
0.5
0
-0.5
-1
0
45
90
135
180
Scattering Angle (o)


(P11-P22)/(P11+2P12+P22)
1
0.8
0.6
0.4
0.2
0
0
45
90
135
180
Scattering Angle (o)

Ice Refractive Index

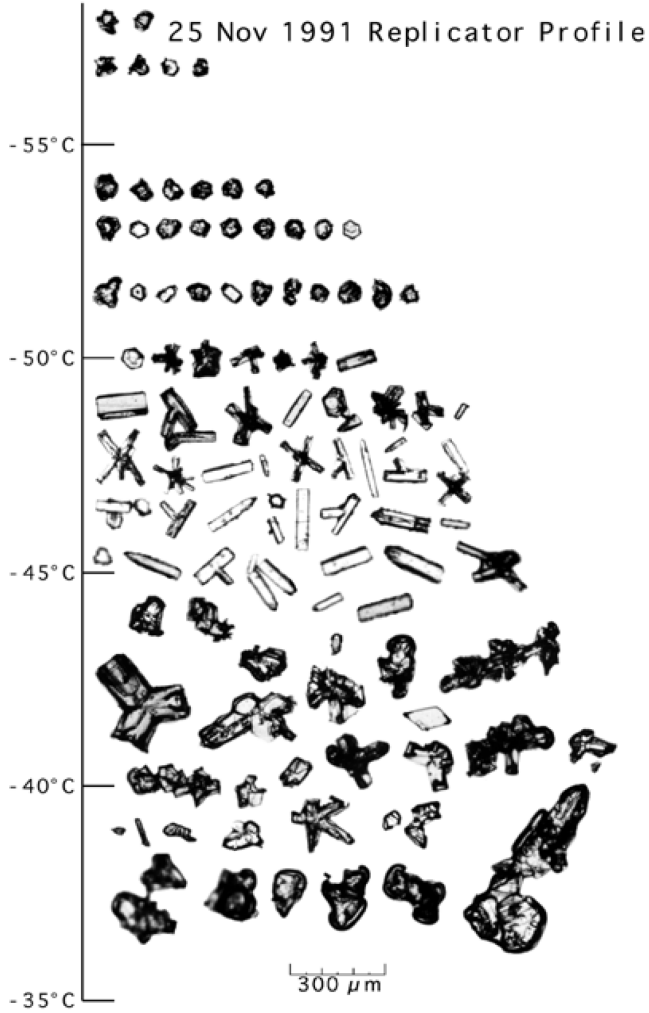


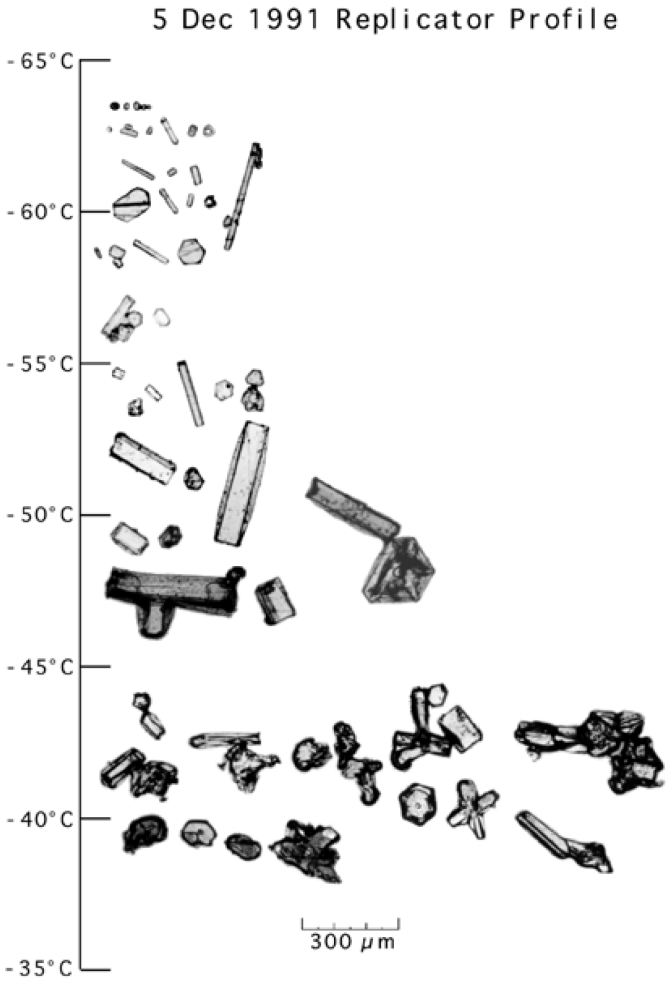
Overview of ice cloud radiative property parameterization-continued

- Ice habit mixture models are established based on the fact that realistic ice clouds are composed of ice particles with various habits; for example, ice aggregate model (Baran and Francis, 2004), MODIS Collection 4,5, and 6 models (King et al., 2004; Baum et al., 2011; Platnick et al. 2014).
- It has been extensively debated how much complexity with respect to ice habit should be included in a parameterization scheme.
- RTM and GCM applications require a relatively simple and flexible ice parameterization which can maintain good accuracy.

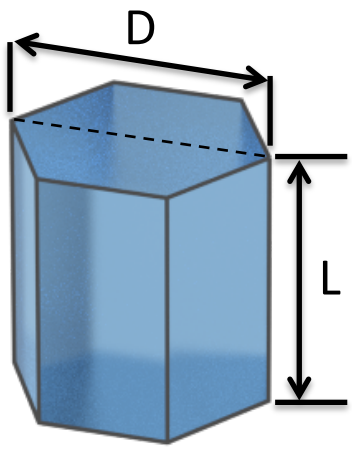
Replicator Ice Crystal Profiles for FIRE Cirrus II Campaign

(Data courtesy of A. Heymsfield, L. Miloshevich, S. Aulenbach, NCAR)





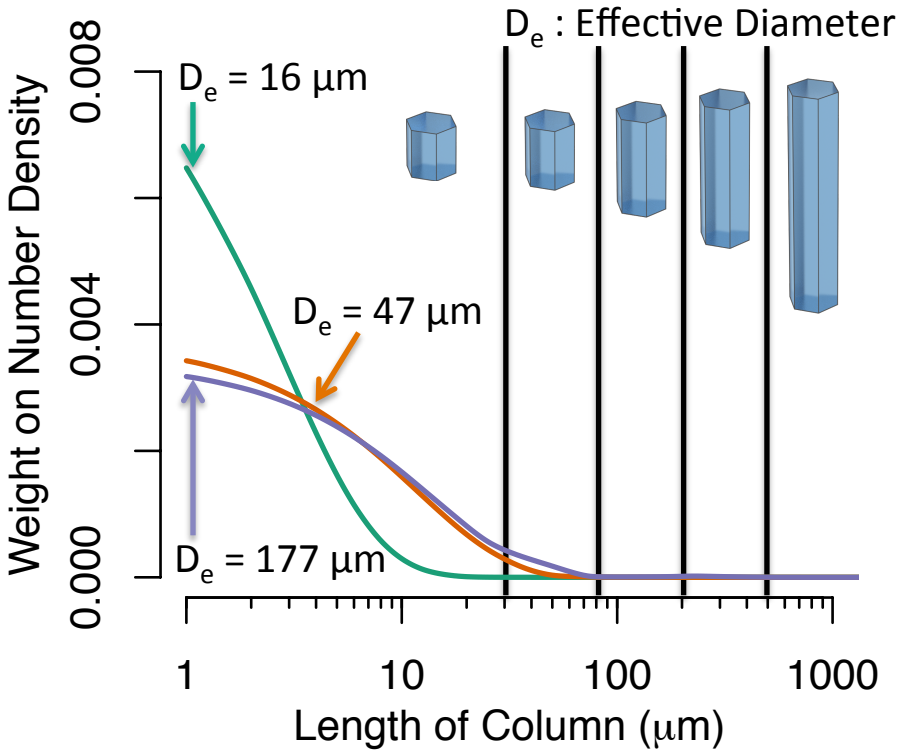
Q. Fu 1996 Single Column Model



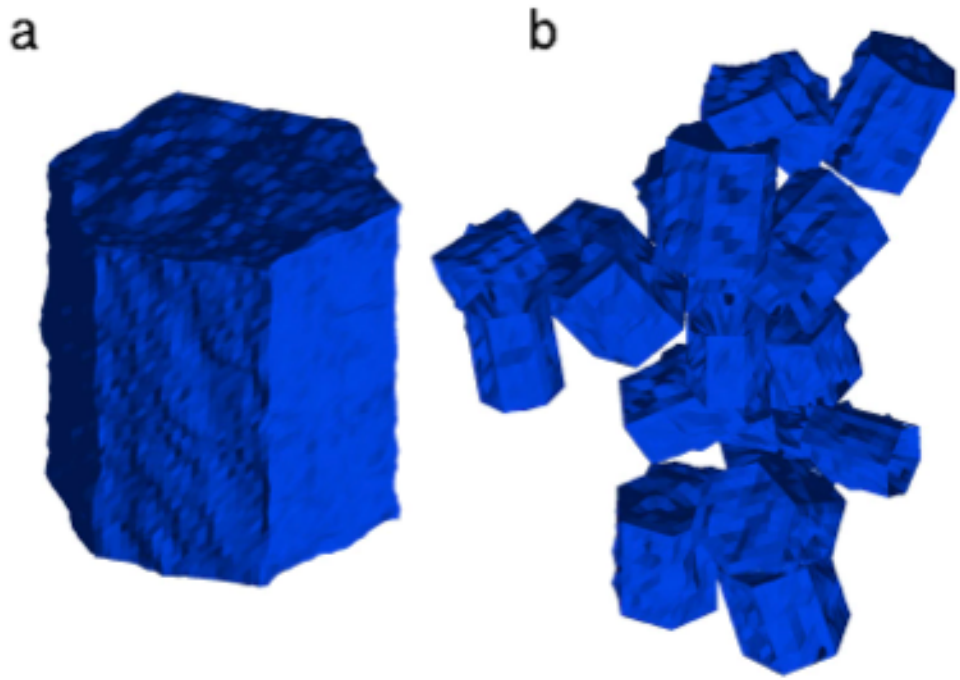
Aspect Ratio = D/L

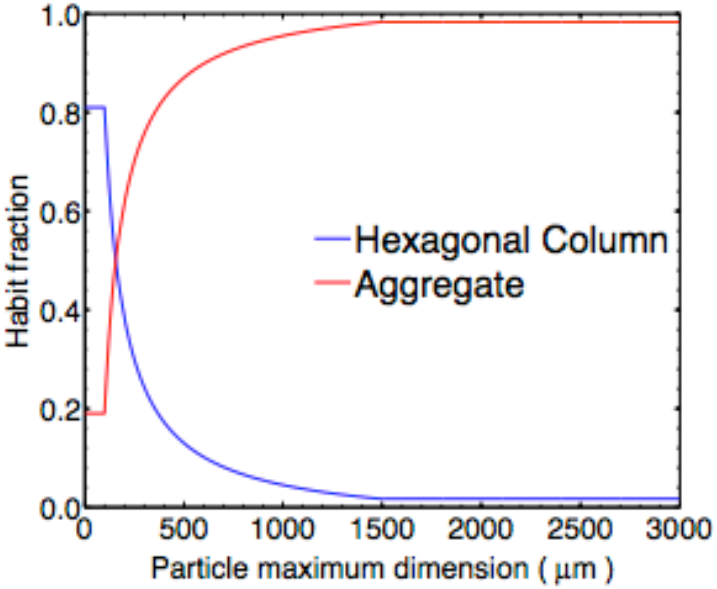
Length of Column	Aspect ratio
0 µm < L ≤ 30 µm	1.0
30 µm < L ≤ 80 µm	0.8
80 µm < L ≤ 200 µm	0.5
200 µm < L ≤ 500 µm	0.34
500 µm < L	0.22

- Smooth column particles
- Five aspect ratios
- Particle size distributions from in-situ observations



Two-habit ice particle model

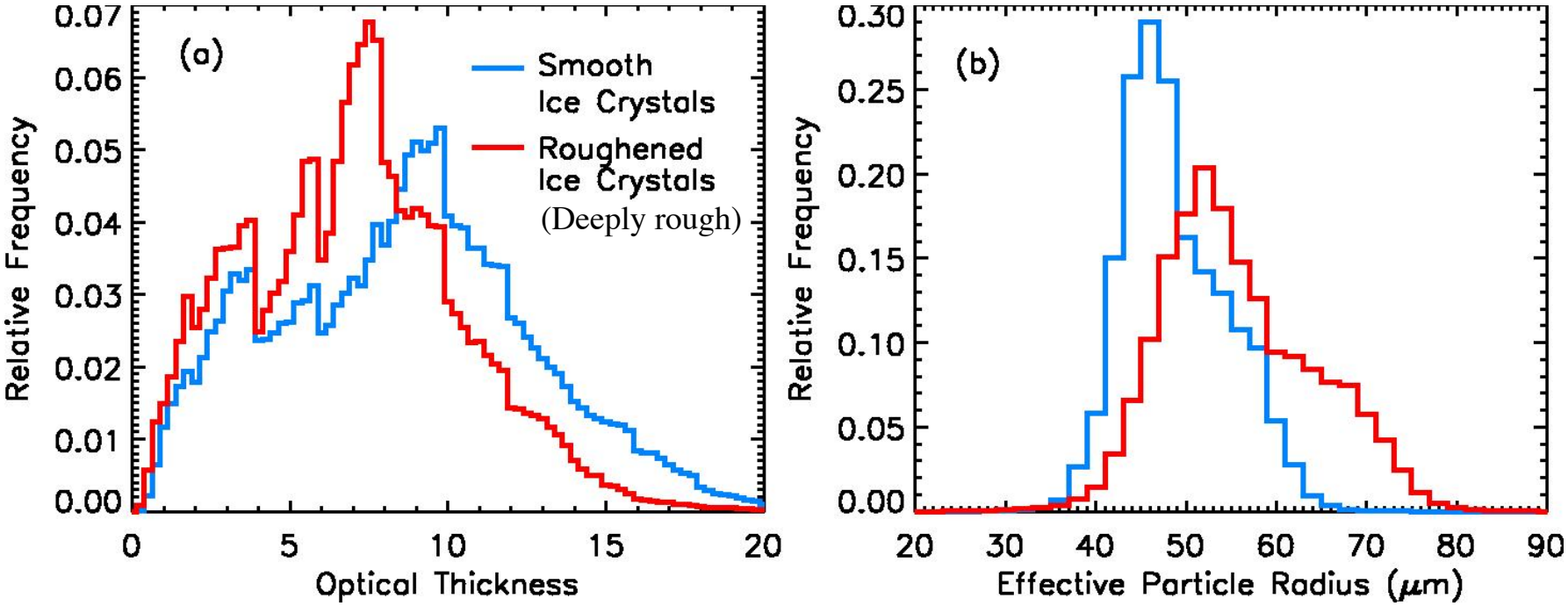




(a) Single hexagonal column with an aspect ratio of unity;
(b) Hexagonal aggregate with 20 solid or hollow columns.

Liu, Yang, Minnis, Loeb, Kato, Heymsfield, Schmitt, 2014

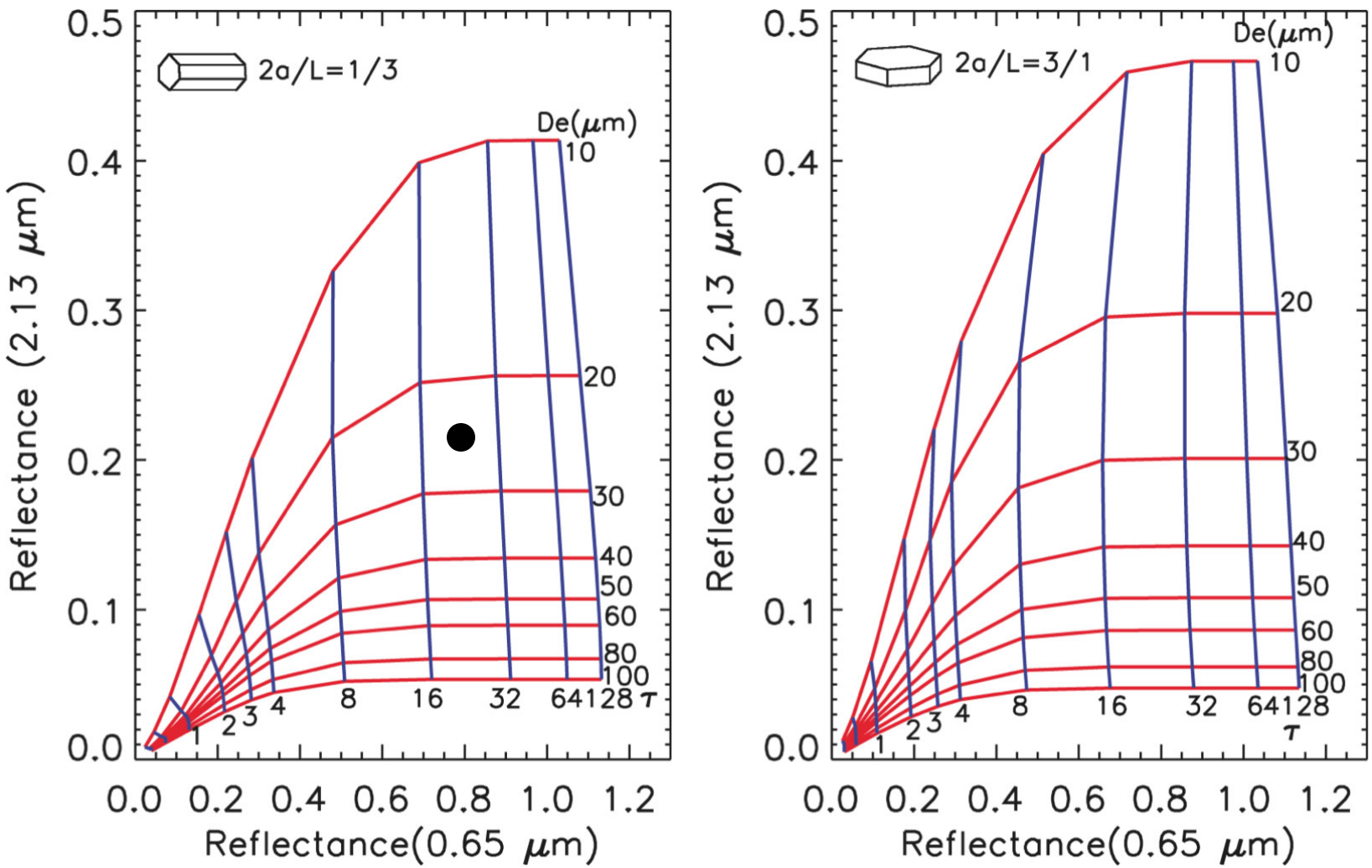
Effect of particle surface roughness on retrievals: Ice cloud optical thickness and effective particle size

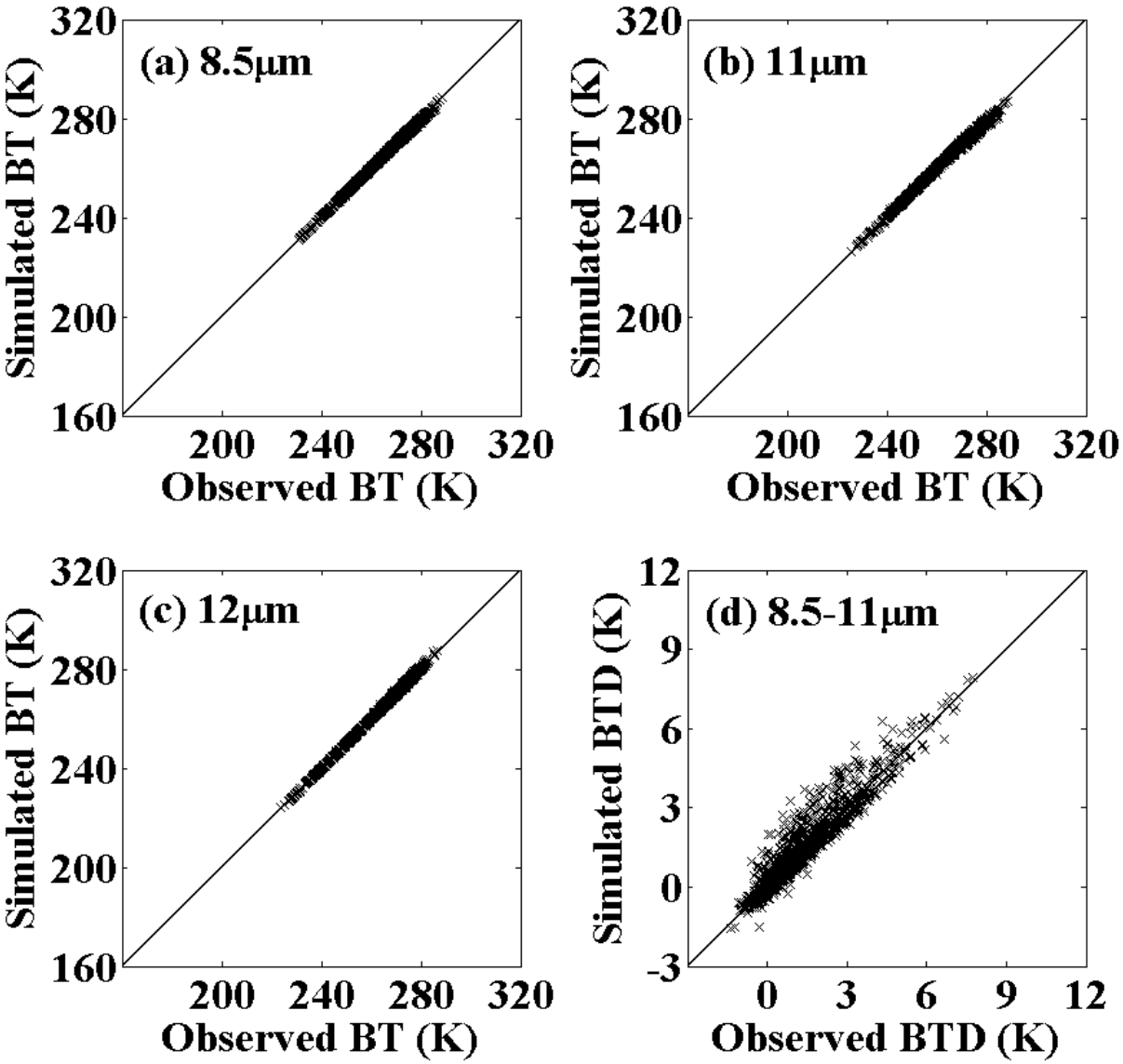


Yang, Hong, Kattawar, Minnis, Hu, 2008

Cloud optical and microphysical properties

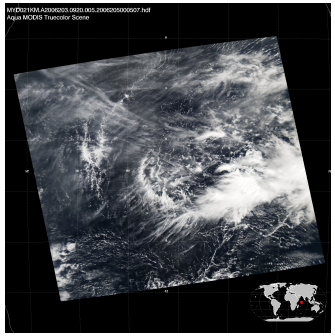
Nakajima-King Retrieval Algorithm





$$\tau_{VIS} = \tau_{IR} \langle Q_{VIS} \rangle / \langle Q_{IR} \rangle$$

Scatter plots of MODIS observed TOA BTs and BTD (8.5-11mm) vs. simulated BTs and BTD by using the optimal t and D_{eff} (after Wang et al. 2011).

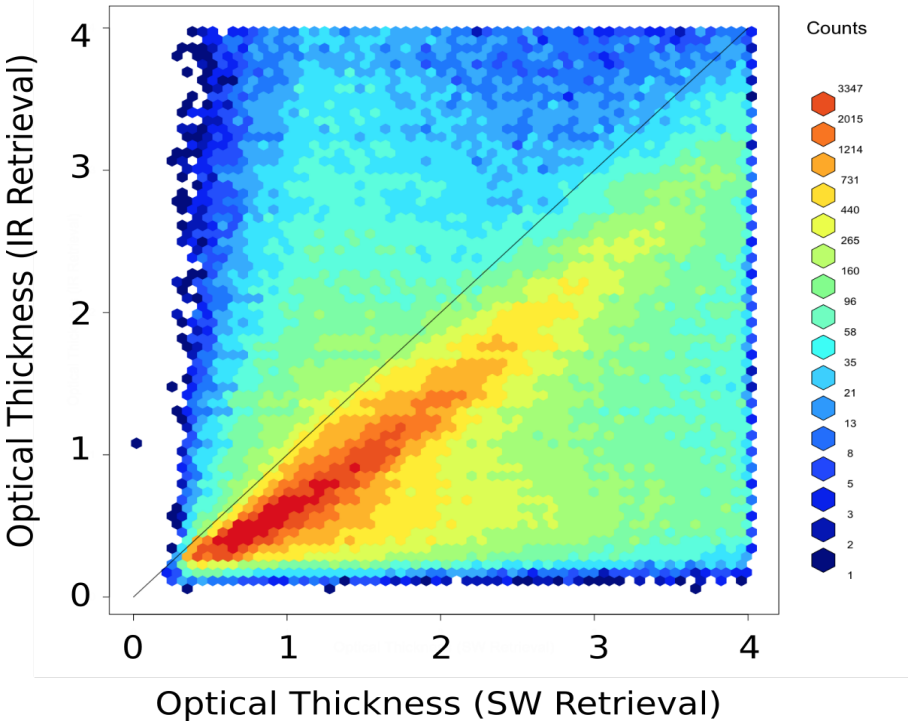


In this granule, pixels with scattering angle between 100° and 140° are used in the analysis.

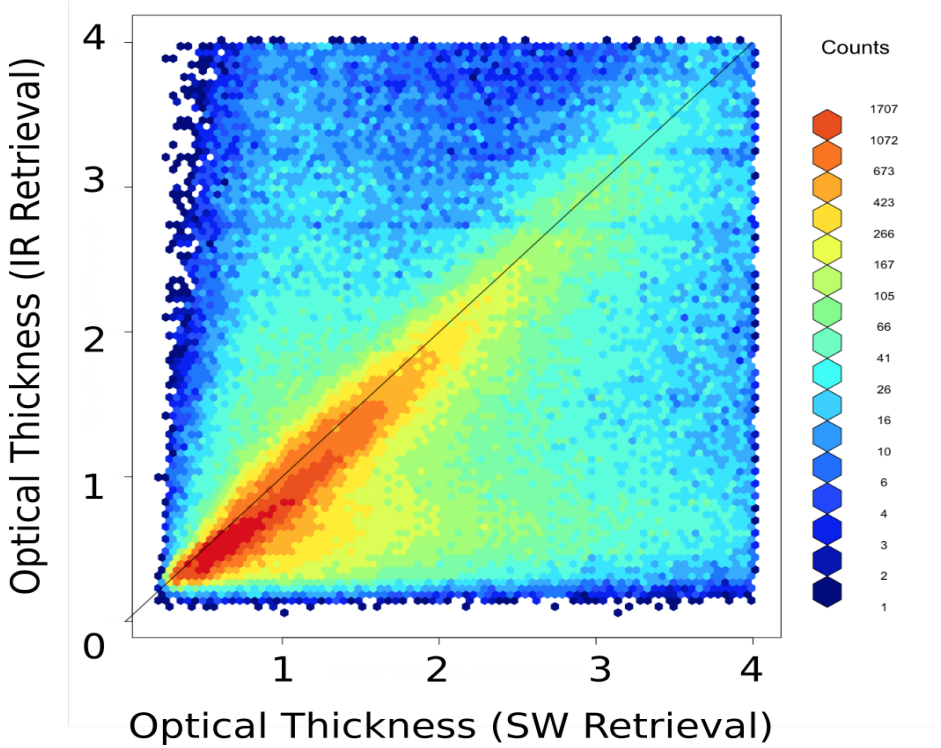
Spectral Consistency of Optical Thickness Retrievals

Optical thickness retrieved from shortwave bi-spectral method and infrared split-window method are consistent when the Two Habit Model is used.

Single Column Model (Fu, 1996)

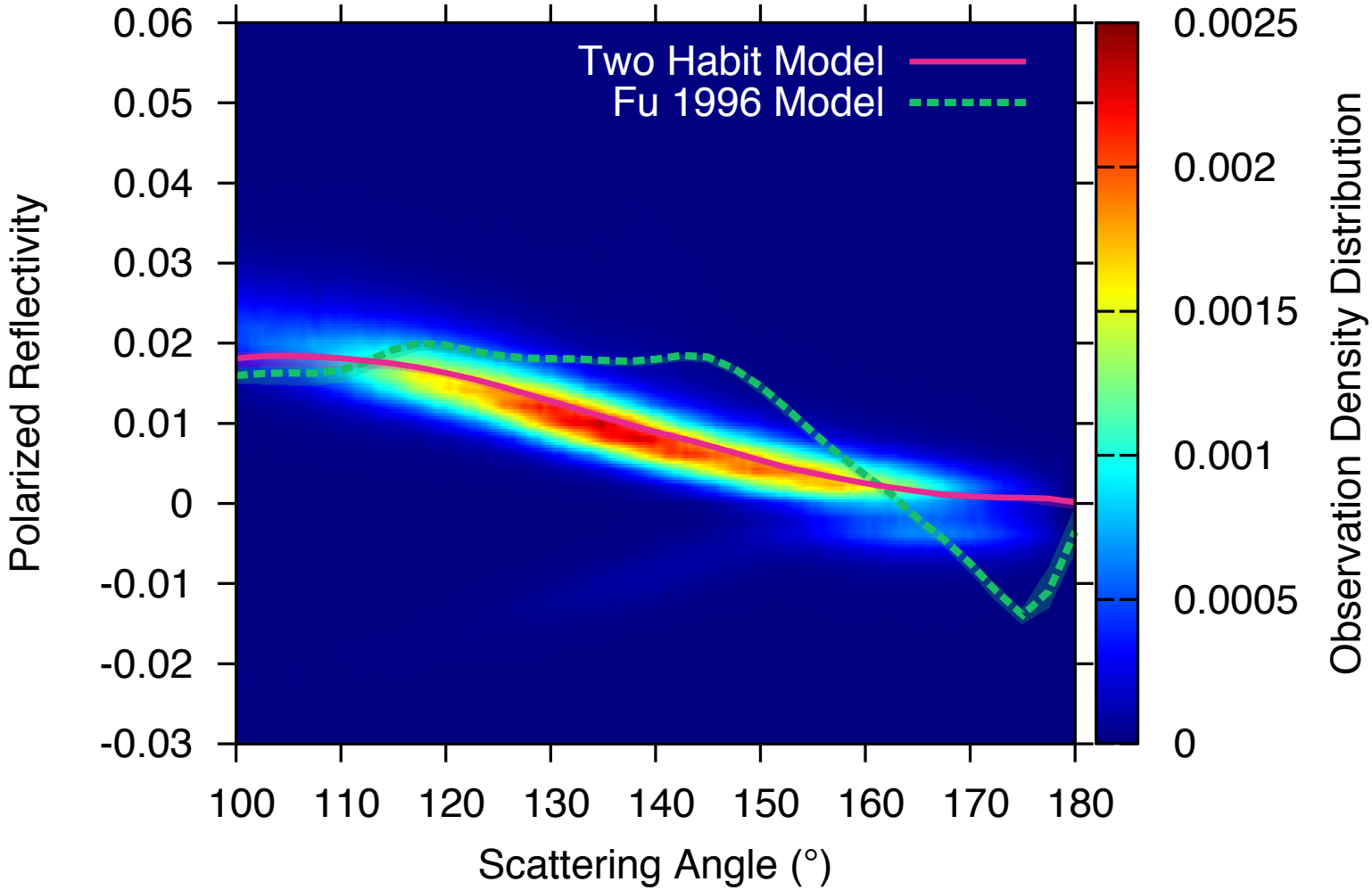


Two Habit Model



Courtesy of S. Hioki and Y. Ding

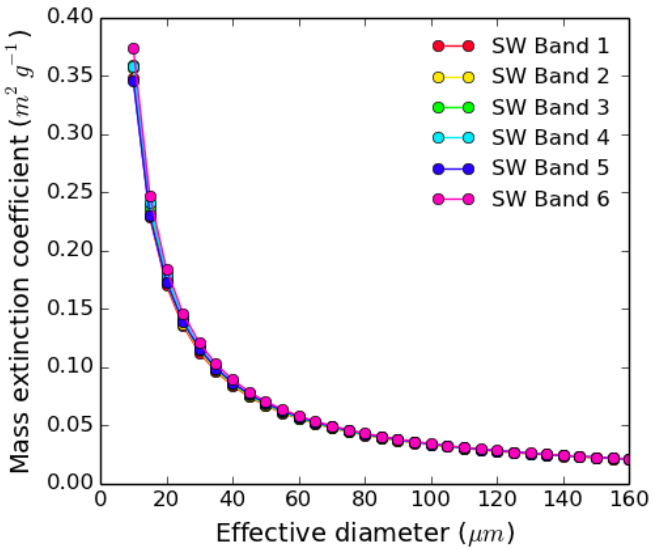
Cloud Polarized Reflectivity

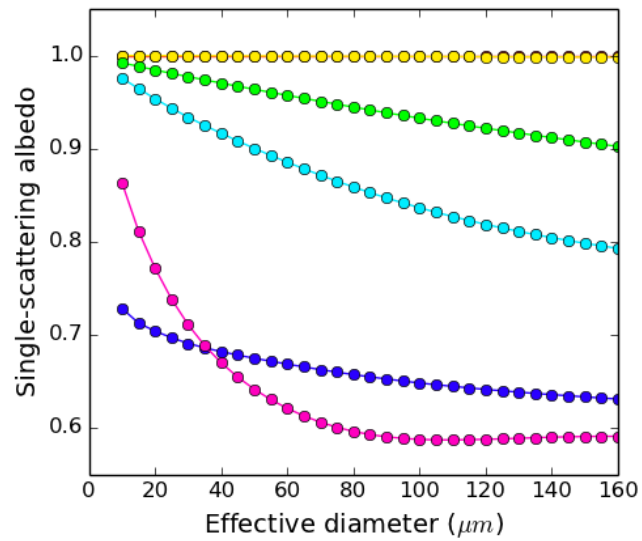


The Two Habit Model is consistent with global cloud polarized reflectivity data collected by PARASOL satellite during September 2005. Samples are from cold clouds over ocean.

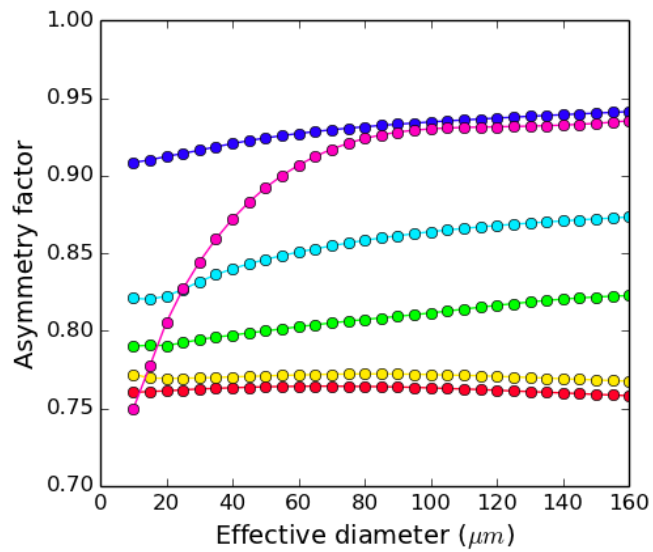
Courtesy of S. Hioki

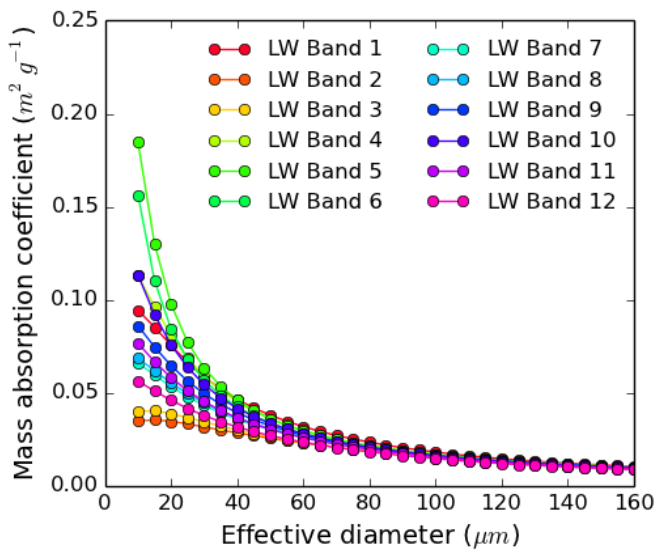
Band-averaged ice cloud bulk optical properties based on the two-habit model for the Fu-Liou RTM



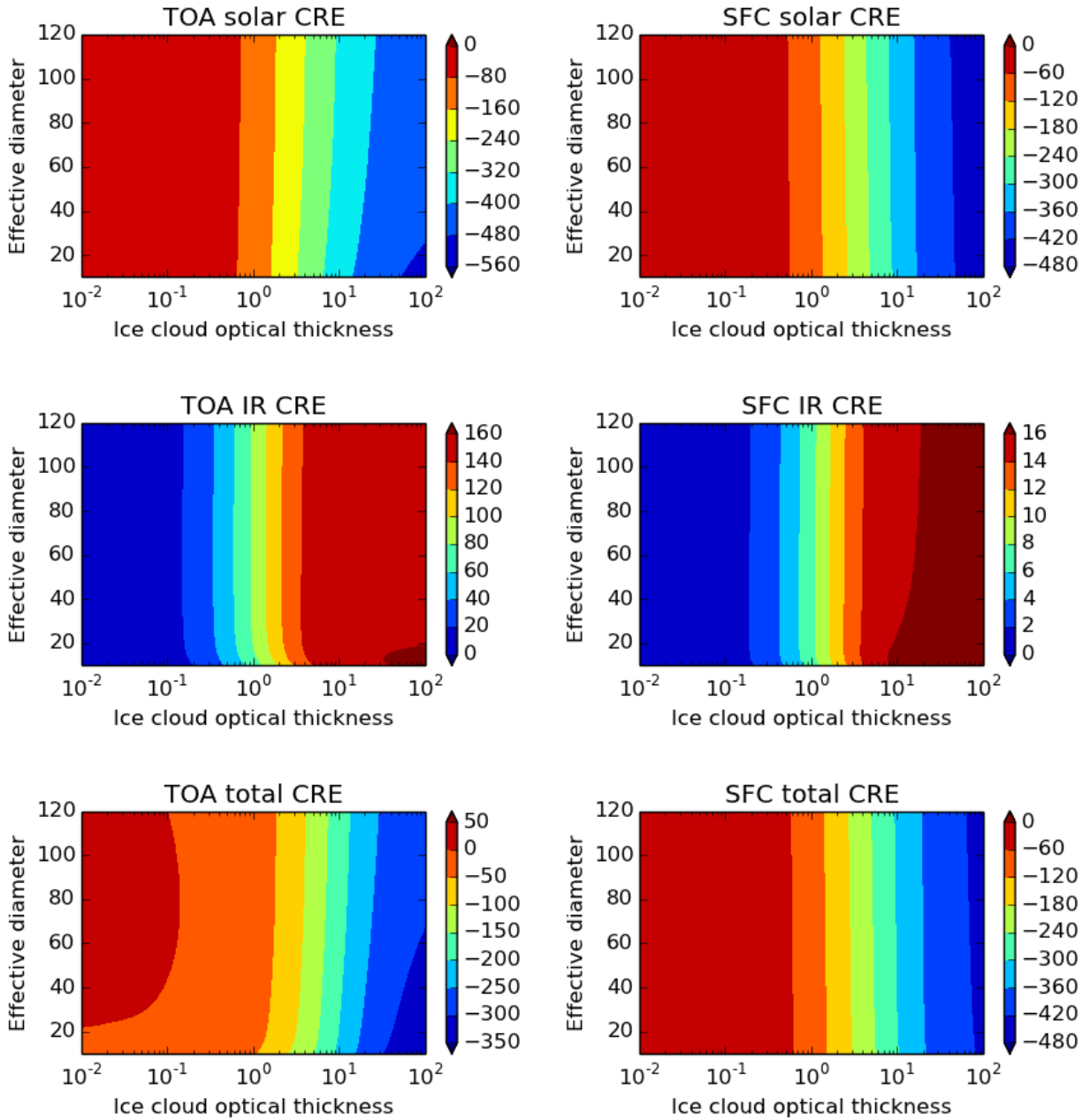


Fu-Liou			
SW		LW	
Band	Unit: μm	Band	Unit: cm^{-1}
1	0.2-0.7	1	0-280
2	0.7-1.3	2	280-400
3	1.3-1.9	3	400-540
4	1.9-2.5	4	540-670
5	2.5-3.5	5	670-800
6	3.5-4.0	6	800-980
		7	980-1100
		8	1100-1250
		9	1250-1400
		10	1400-1700
		11	1700-1900
		12	1900-2200





Ice cloud radiative forcing simulated as a function of the effective diameter and optical thickness



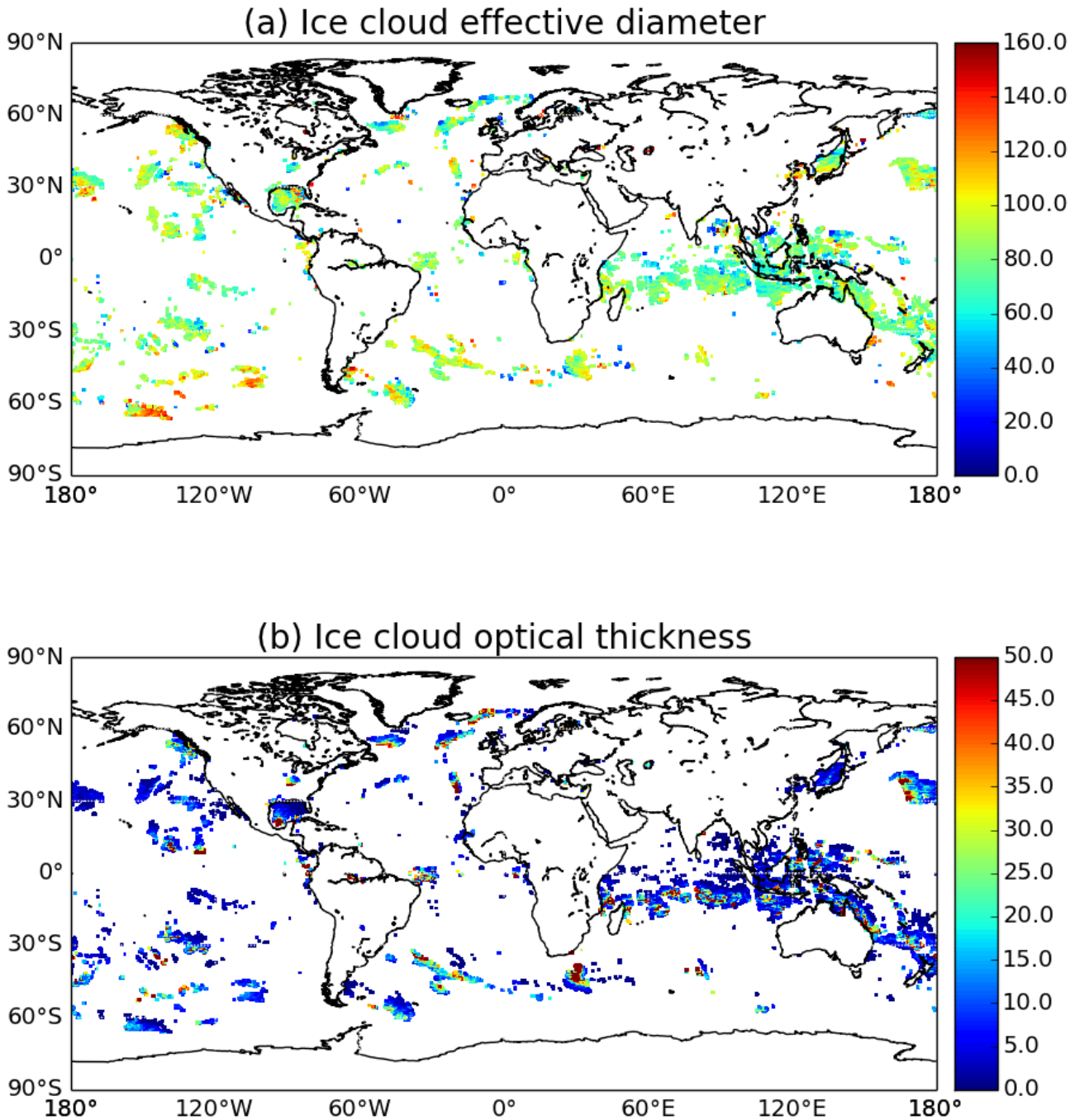
Comparison between CERES observations and simulations by Fu-Liou RTM

- CERES data:
  - Aqua CERES SSF (Single Satellite Footprint) FM3 level-2 pixel-level instantaneous observations containing cloud information (cloud phase, optical thickness, cloud fraction, effective diameter, etc.); SW and LW flux at the TOA under cloudy-sky conditions.
  - CERES EBAF-TOA (Energy Balanced And Filled) data edition 2.8 providing the net balanced TOA fluxes in monthly 1x1 degree resolution.
- Data range:
  - 24 granules observed on 11 Feb 2008, about 33,005 footprints with ice clouds for the SSF level-2 data
  - 2002-2011 CERES EBAF-TOA fluxes
- Simulations:
  - MERRA reanalysis 3-hourly atmospheric profiles are used;
  - Fu-Liou RTM is used with the Two-habit model ice optics parameterization
  - CAM5 AGCM is used with the Two-habit model ice optics parameterization

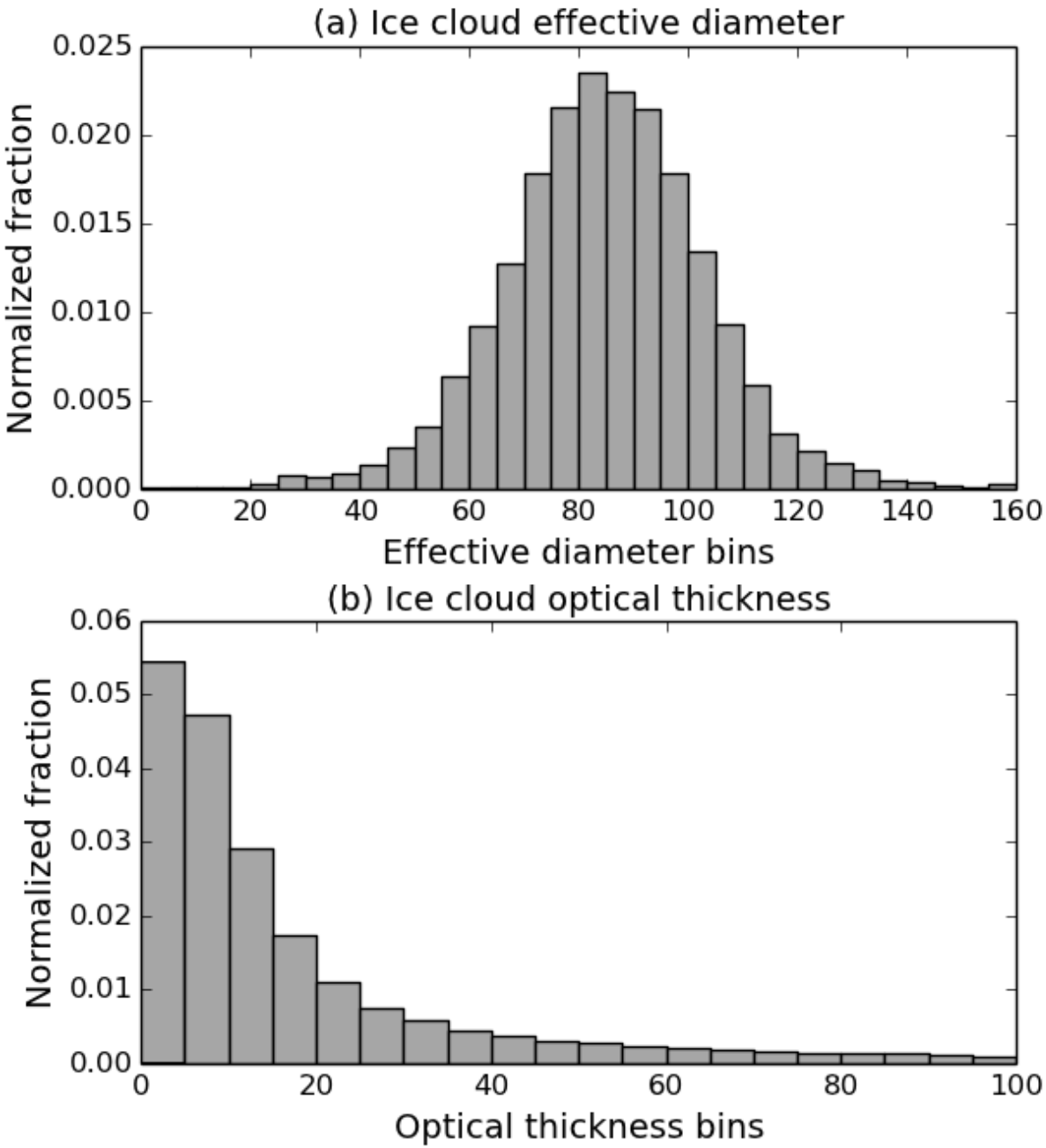
Definition: CRF at TOA = TOA cloudy-sky flux – TOA clear-sky flux

Methodology

- RTM simulations:
  - Find the instantaneous pixels where only ice clouds exist by using CERES MODIS cloud phase product;
  - Interpolate the corresponding vertical atmospheric profile from MERRA 3-hourly reanalysis data;
  - Determine the cloud level in the atmospheric profile by CERES MODIS cloud top pressure;
  - Collect the necessary cloud parameters for RTM simulations including cloud fraction, cloud optical thickness, and cloud effective diameter;
  - Carry out Fu-Liou RTM simulations for clear-sky and cloudy-sky (with two-habit model ice optics) conditions;
  - Calculate the cloudy-sky TOA radiative flux and ice cloud radiative forcing, and compare the simulations against CERES observations.
- AGCM simulations:
  - Ten-year global simulation at 1.9x2.5 degree resolution from 2002 to 2011 forced with historical observed sea surface temperature with 2 year spin-up.

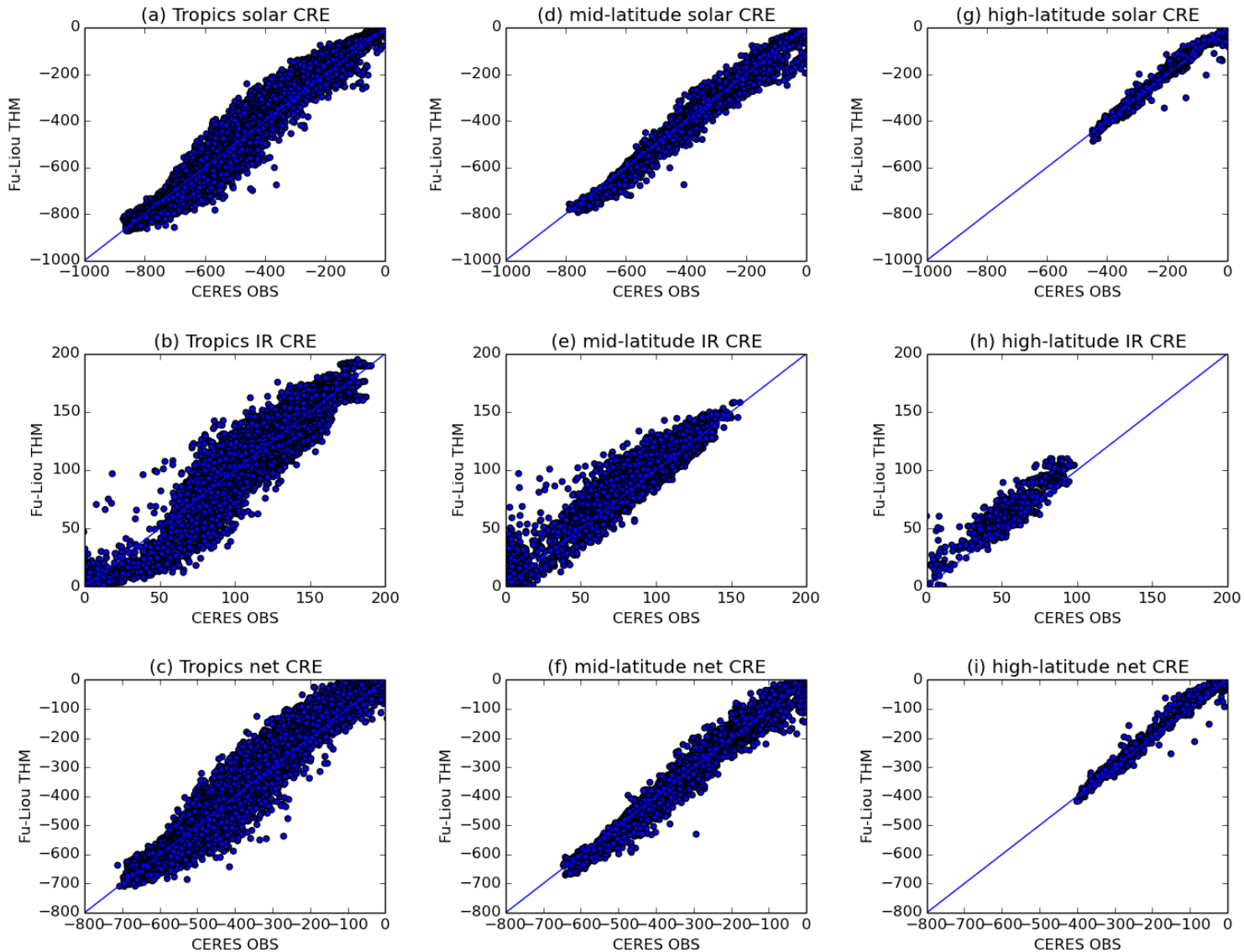


Spatial distribution of the CERES ice cloud footprints (11 February 2008)



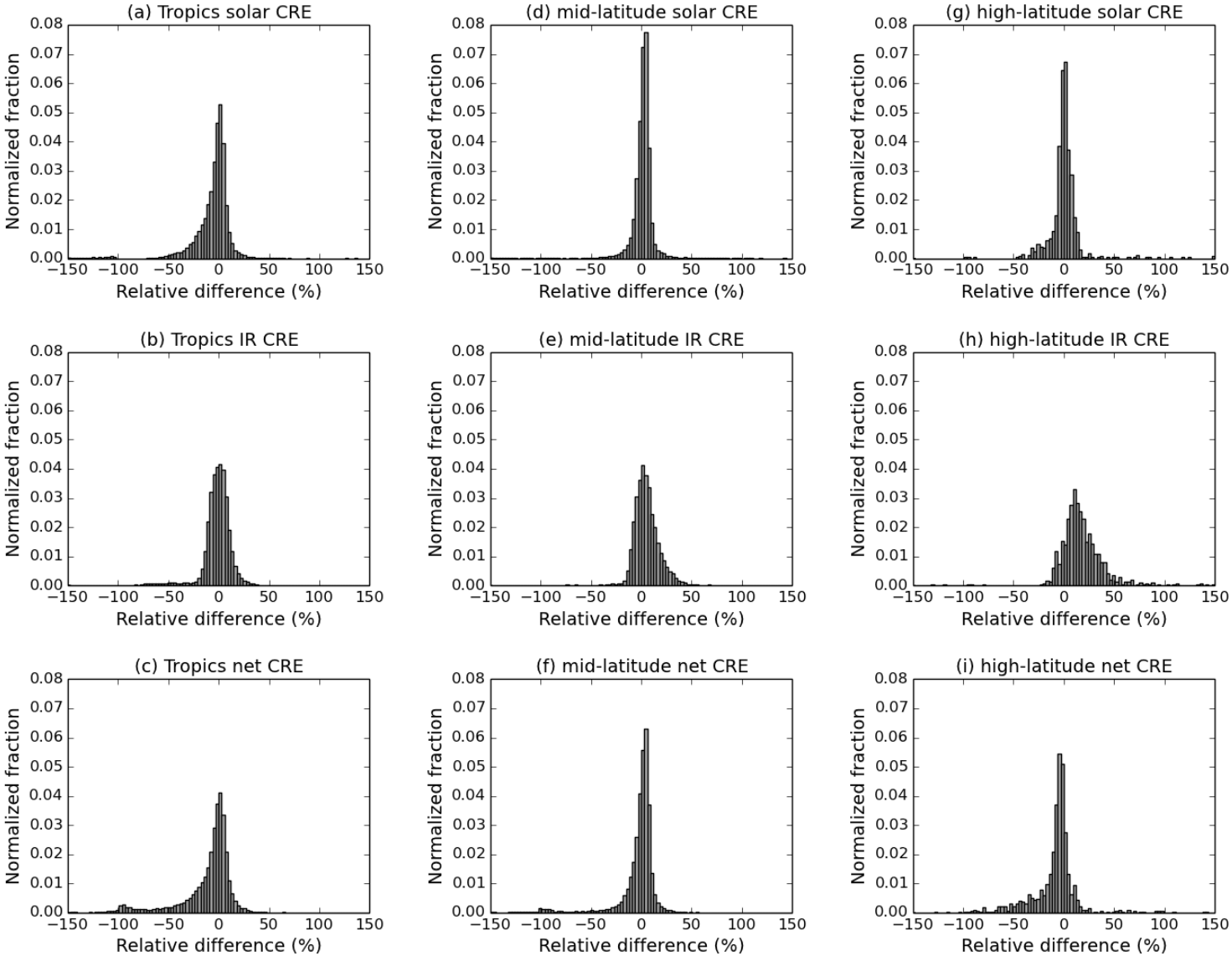
Frequency distribution of the CERES ice cloud footprints selected from 11 February 2008

CERES TOA observed ice cloud radiative effects versus simulated ice cloud radiative effects with Fu-Liou RTM

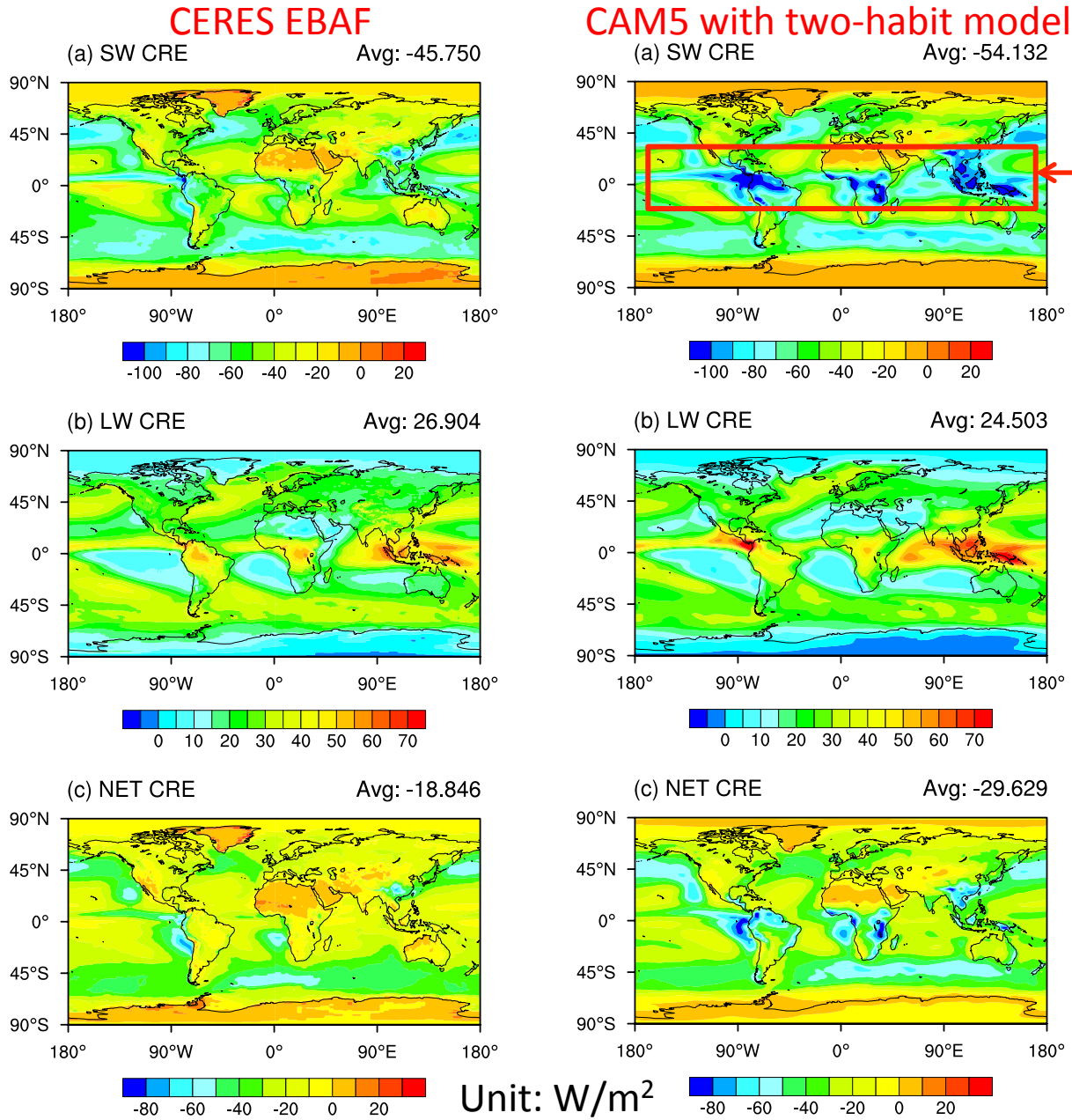


Unit: W/m^2

Frequency distribution of the relative percentage difference between simulated and observed CRE

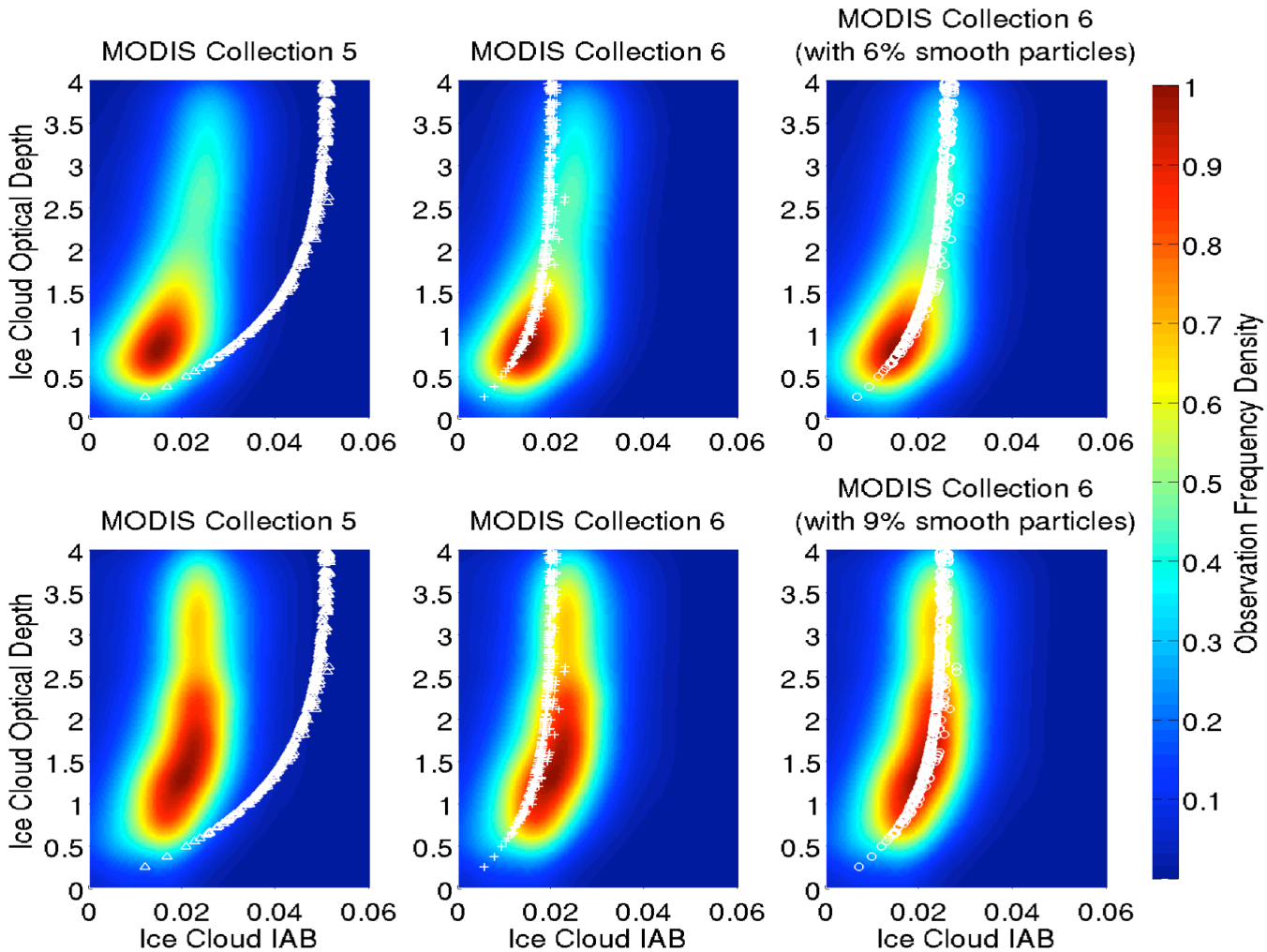


Cloud radiative forcing: observation vs simulation



deep convection **microphysics** parameterization problem

CALIOP/CALIPSO simulator vs Observations



Comparison of simulated IAB-ICOD relation and observation at 532 nm.
IAB= integrated attenuated backscatter; ICOD= ice cloud optical thickness
Top row: 30N to 30S. Bottom row: 30N to 60N and 30S to 60S (Ding, Yang et al. to be submitted).

Conclusions

- The Two-habit ice cloud optics parameterization schemes are developed based on the broadband structures of the Fu-Liou and RRTMG single-column RTMs and the CAM5.1 ACGM.
- Ice cloud radiative effects calculated from the Fu-Liou RTM with the implementation of the two-habit parameterization yield good agreement with the CERES real-time satellite observations of radiative fluxes measured at the top of the atmosphere.
- Especially over the mid-latitude region, the THM ice cloud optical property parameterization scheme works the best.
- However, AGCM simulations of cloud radiative effects still have large bias in the global averaged results largely due to some possible problems in deep convection cloud simulation in the tropical region.
- The major finding of this study indicates that a physically consistent cloud microphysics-radiation parameterization is particularly important for GCM applications.
- MODIS-CALIOP/CALIPSO comparison suggests that **ice crystals are not completely rough: a few percent of ice crystals may be smooth.**