# Assessments of CRTM performance using Cloud and Aerosol Lookup Tables

- Demonstration of current modeling capabilities in light scattering and radiative transfer simulations

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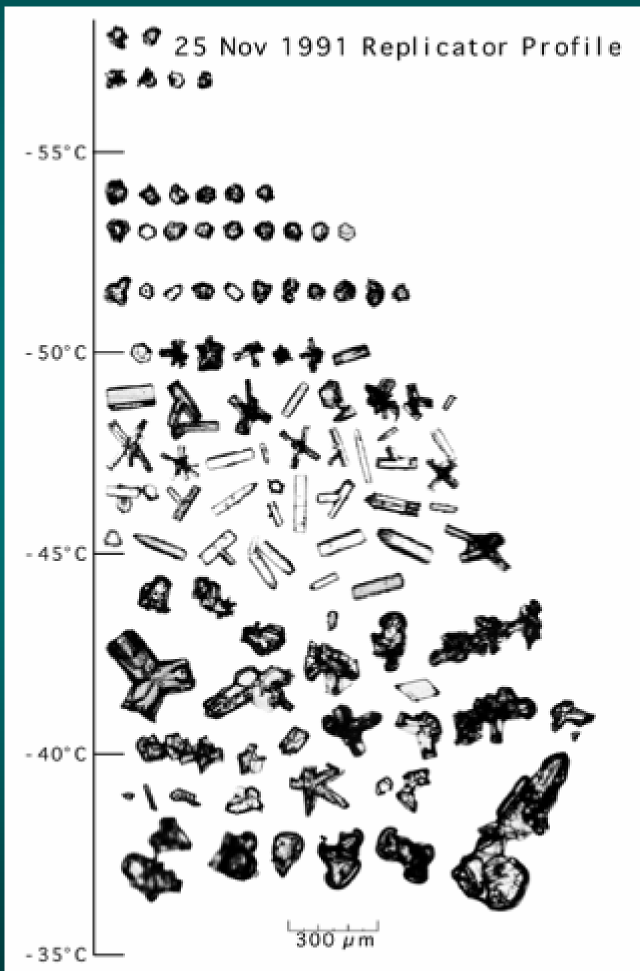
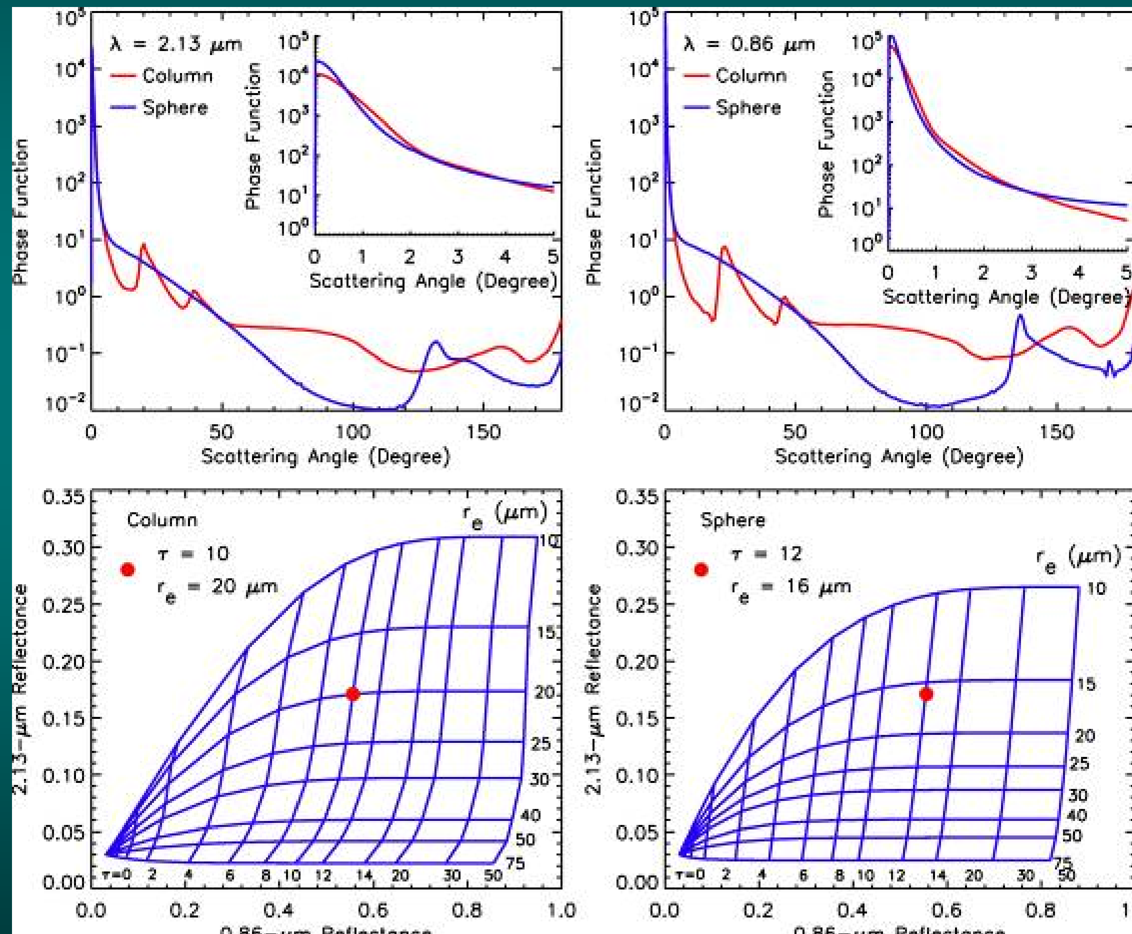
# Motivation

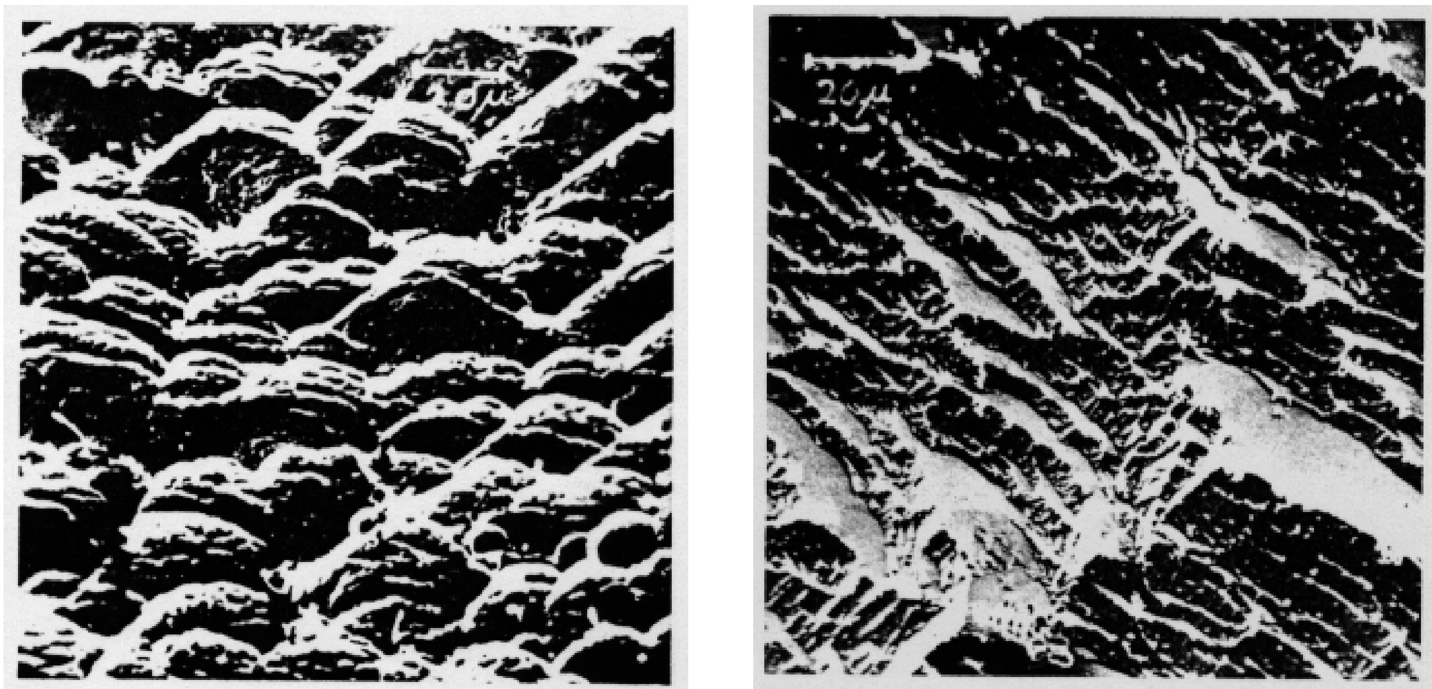
- The importance of using correct single-scattering properties of cloud particles and aerosols in radiative transfer simulations involved in implementing retrieval algorithms.



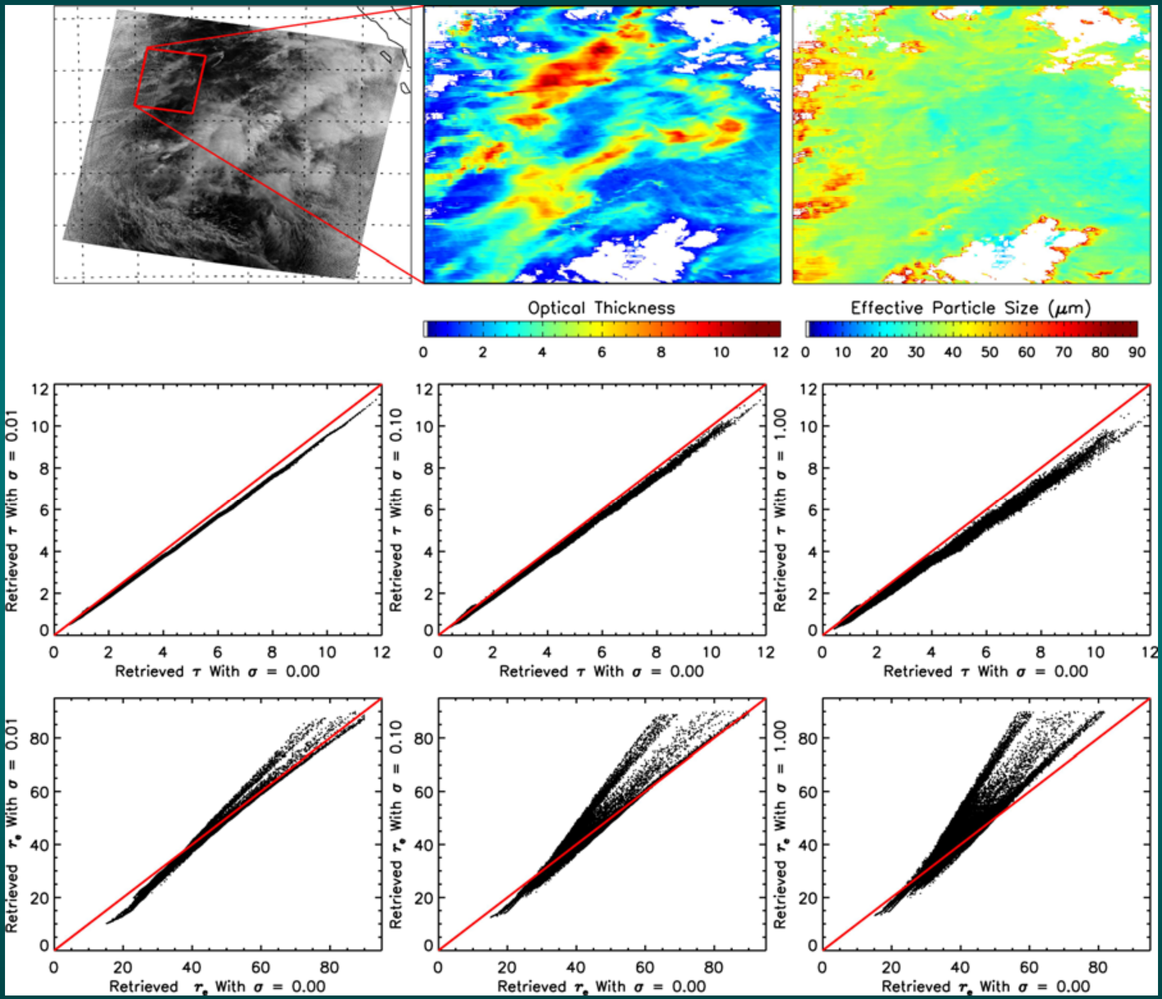

Courtesy of A. Heymsfield



# Roughness of ice crystal surface (Gross, 1968)



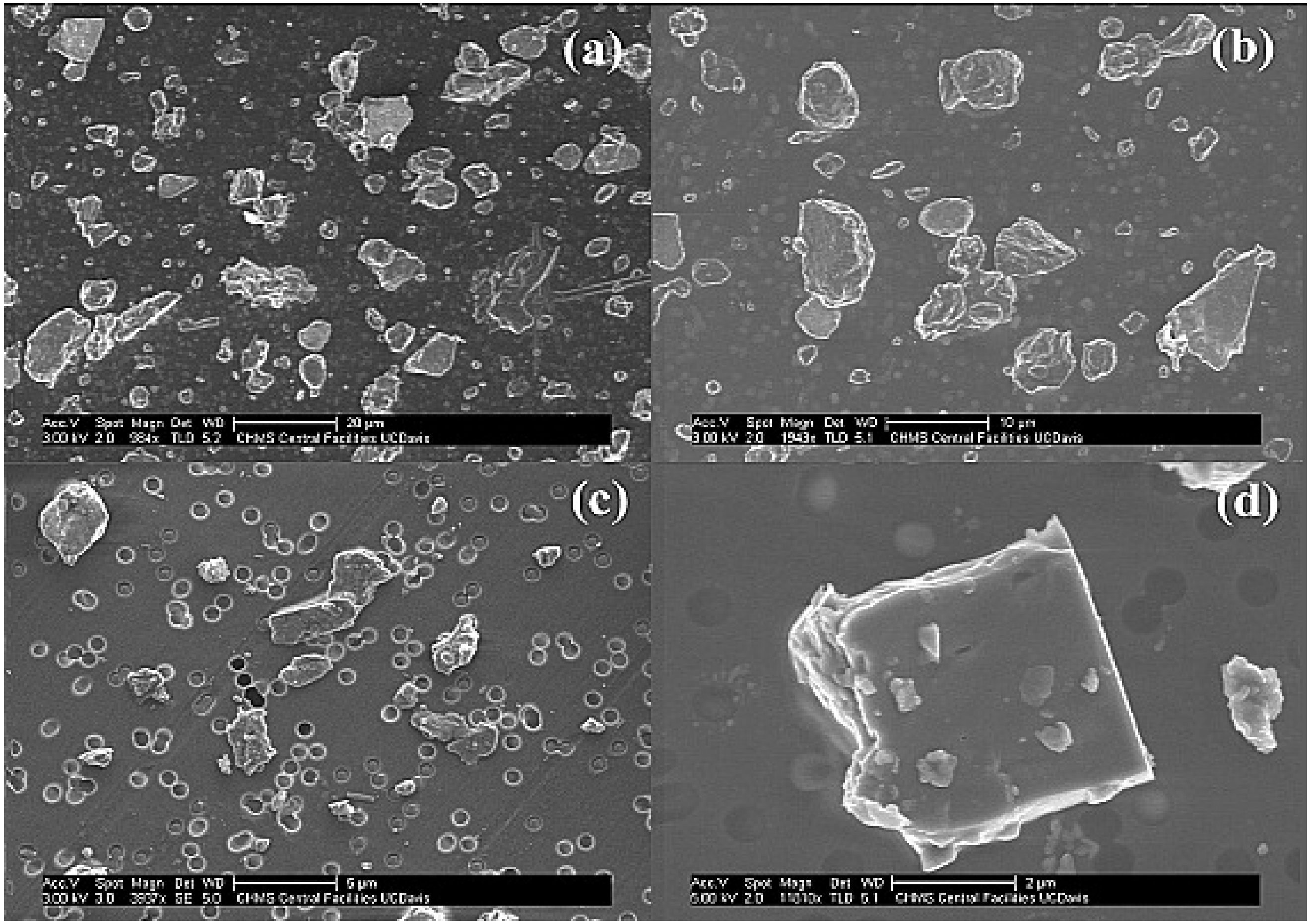
# Retrieved ice cloud optical thicknesses and effective particle sizes




The retrieved ice cloud optical thicknesses and effective particle sizes with roughness s=0.0

The comparisons of retrieved ice cloud optical thicknesses from different roughness conditions, s=0.0, 0.01, 0.1, 1.0

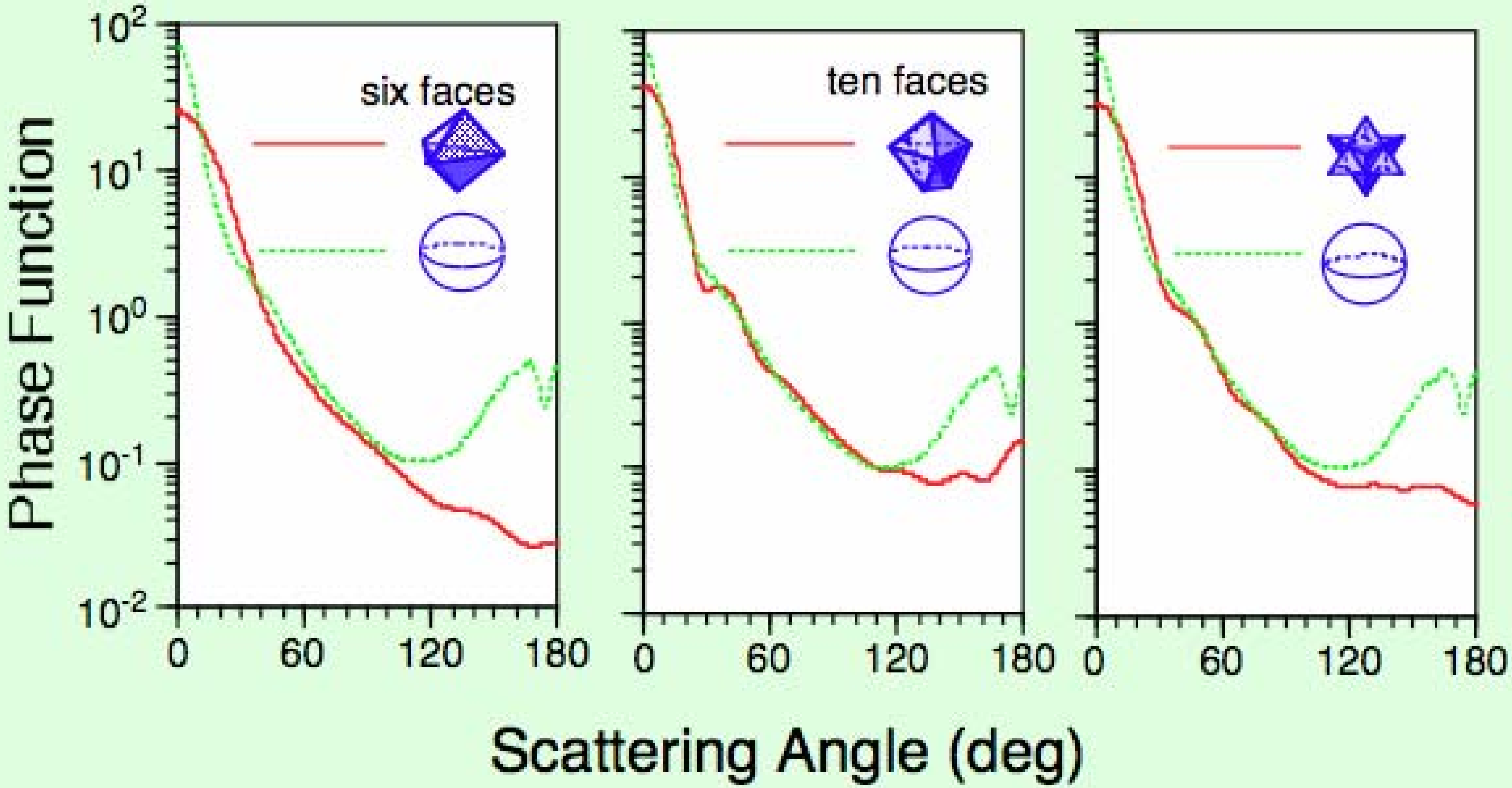
The comparisons of retrieved ice cloud effective particle sizes from different roughness conditions, s=0.0, 0.01, 0.1, 1.0




Secondary electron microscope images of dust particles collected in the Saharan Air Layer near Puerto Rico on 21 July 2000. Because some size segregation occurs on the filter substrate, size and shape distributions from individual images are not representative of the dust as a whole. (a) 1000X, (b) 2000X, (c) 4000X, and (d) 12000X.

Reid, E. A., J. S. Reid, M. M. Meier, M. R. Dunlap, S. S. Cliff, A. Broumas, K. Perry, and H. Maring (2003), Characterization of African dust transported to Puerto Rico by individual particle and size segregated bulk analysis, *J. Geophys. Res.*, *108*(D19), 8591, doi:10.1029/2002JD002935.

# Comparison of Scattering Phase Functions of Nonspherical Dust-like Aerosols with Those of "Equivalent" Spherical Counterparts




Yang, P., K. N. Liou, M. I. Mishchenko, and B.-C. Gao, 2000: An efficient finite-difference time domain scheme for light scattering by dielectric particles: application to aerosols, *Appl. Opt.*, 39, 3727-3737.

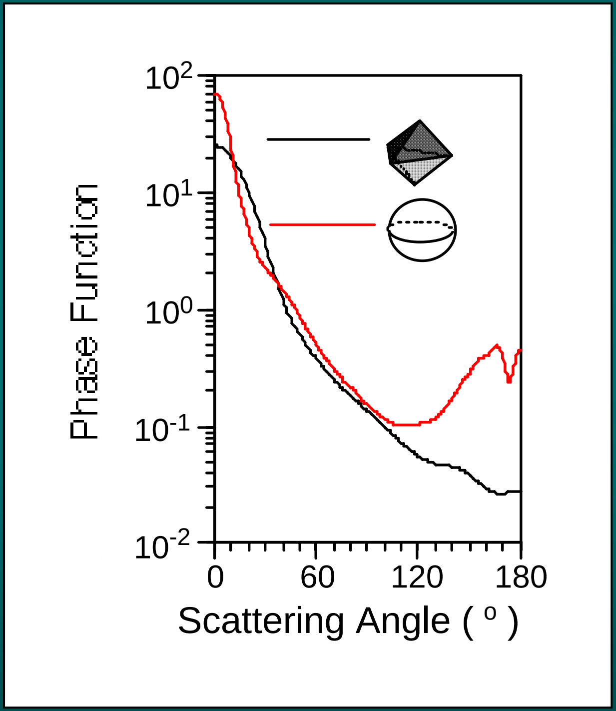
Retrieval of Aerosol Optical Depth from satellite observation:

$$\tau \sim R/P,$$

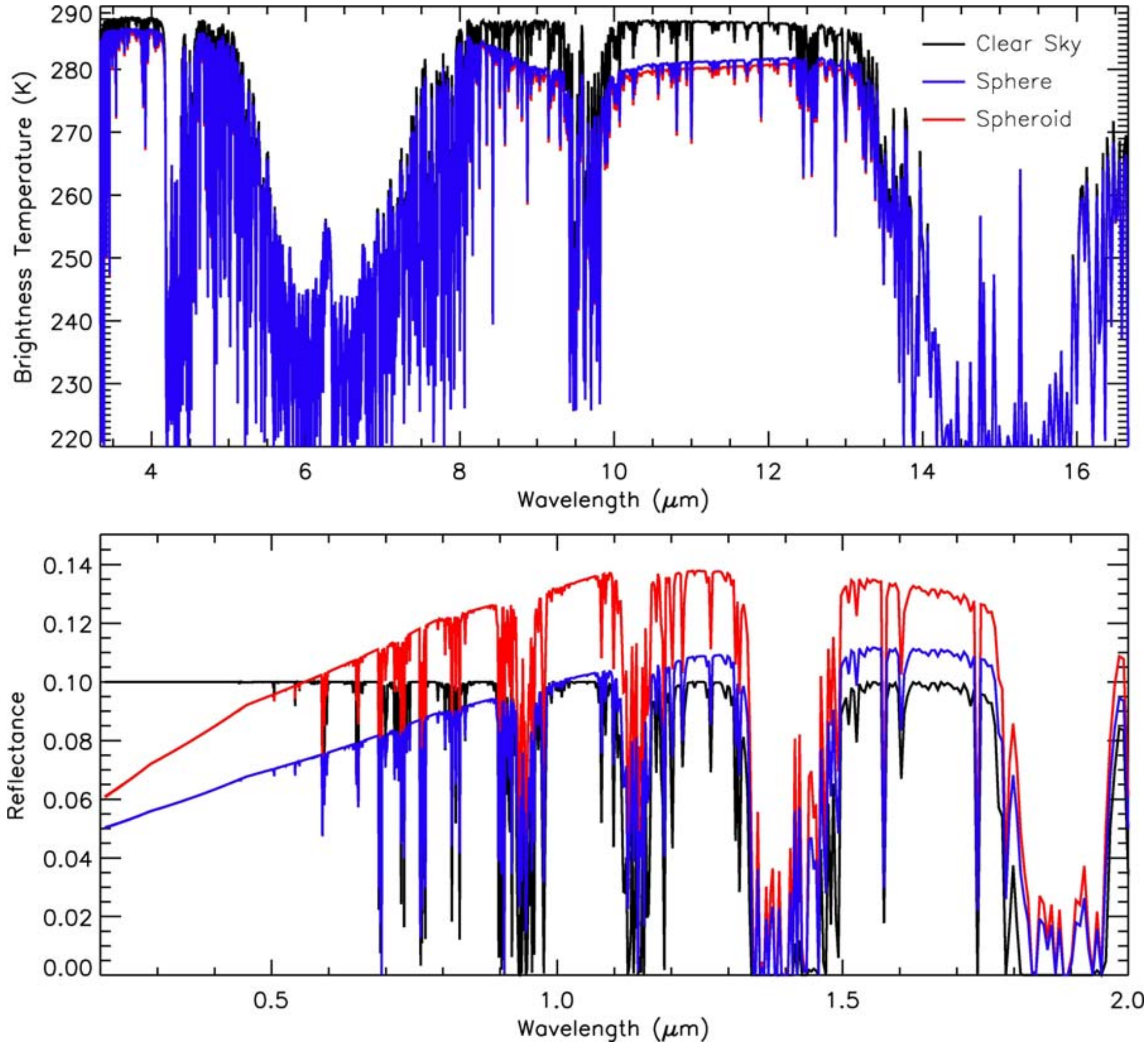
where $\tau$ = Optical-depth,

R= Reflectance,

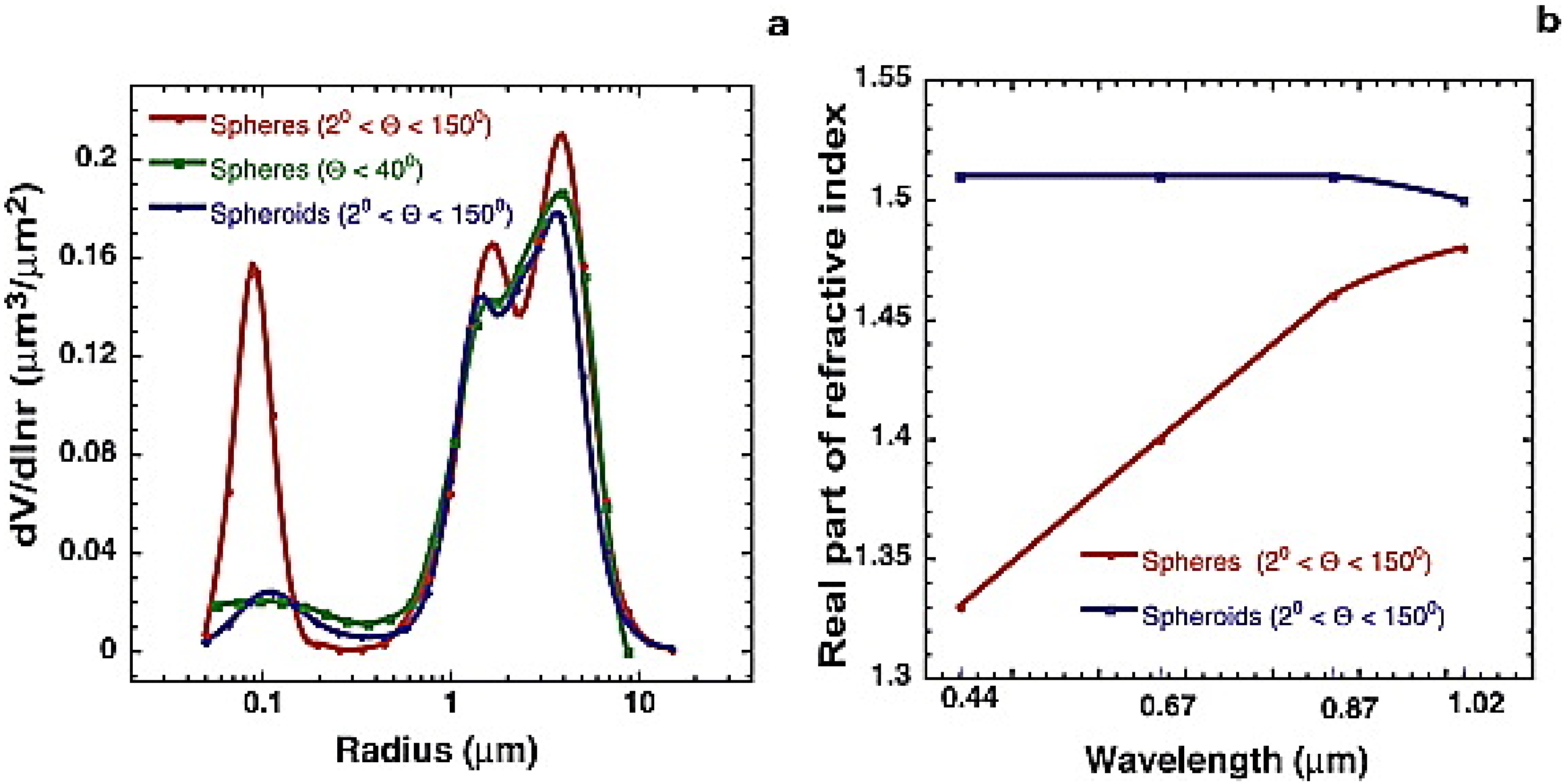
P = Phase function.



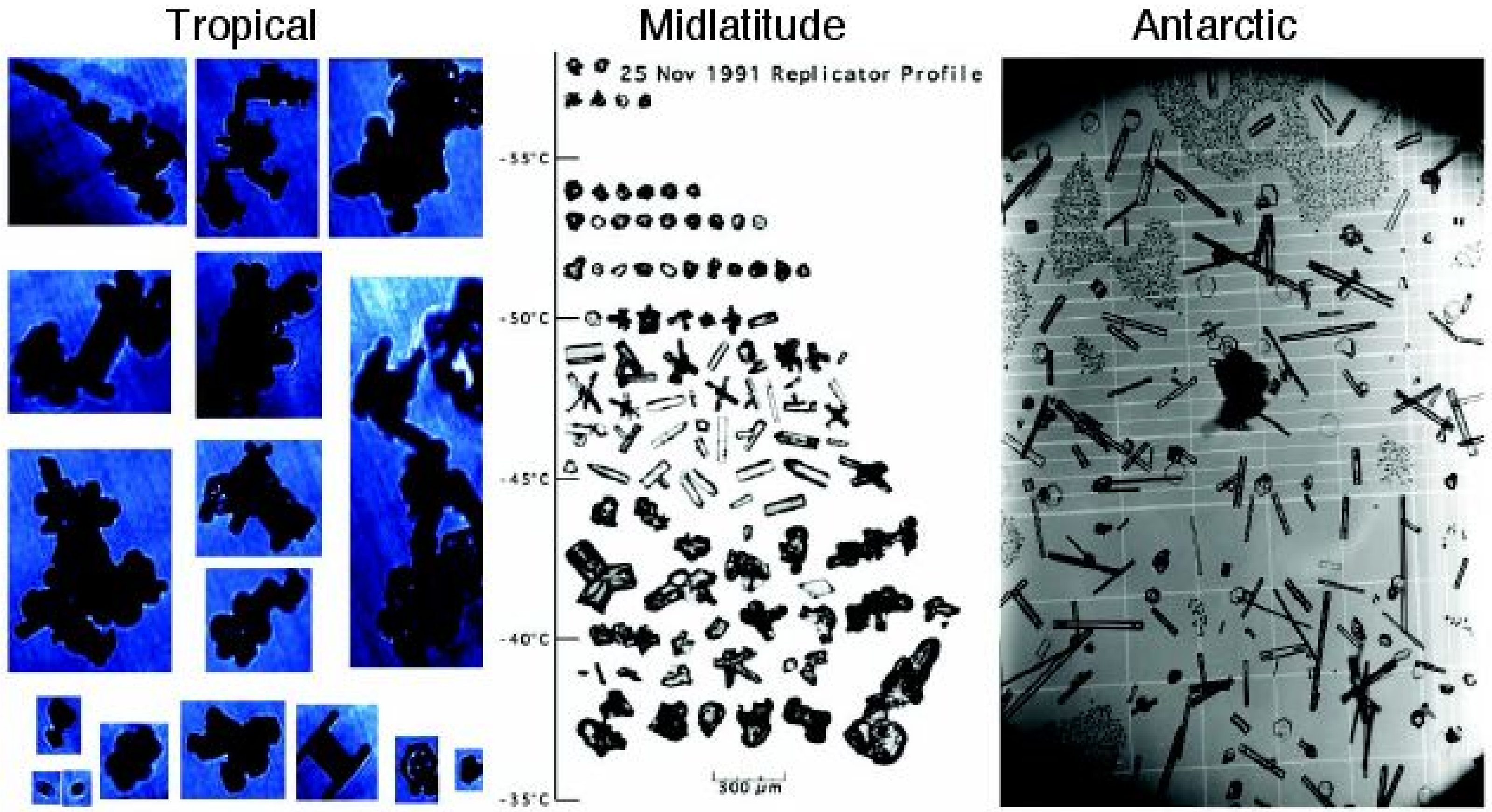

An overestimation of the phase function leads to an underestimation of the retrieved optical depth.




Simulated spectra at the top of the atmosphere for infrared radiances (upper panel) and solar reflectance (bottom panel) under clear sky, overcast dust sky with spherical particles, and overcast dust sky with nonspherical particles (Yang et al. 2007).

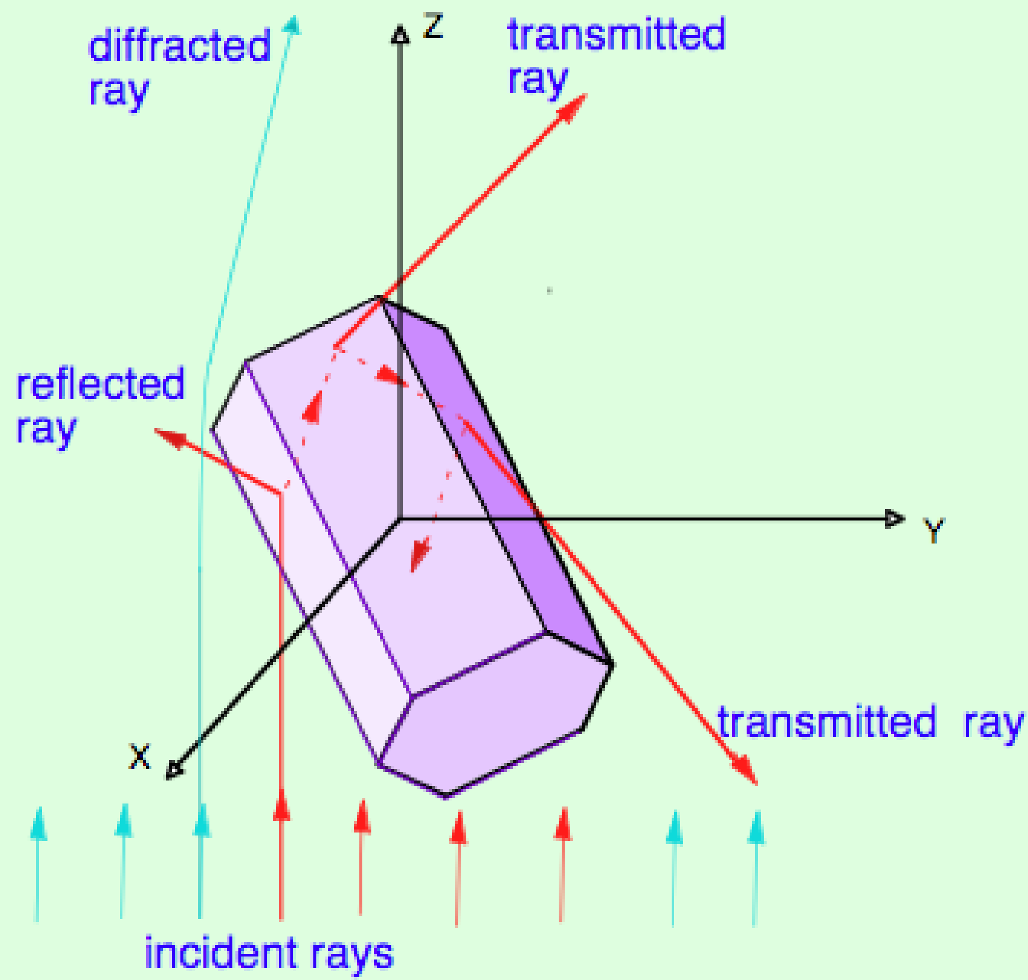



A typical situation where utilizing the spheroid scattering assumption [*Dubovik et al.*, 2002] resulted in the removal of the false fine mode in the size distribution and false spectral dependence in the real part of refractive index. Size distributions and refractive indices are retrieved assuming sphere and spheroid models from spectral radiance measurements covering the full range of scattering angles. The size distribution retrieved from the aureole only ($\Theta < 40°$, where effects of nonsphericity are minimal) and assuming spherical particles is also shown. *The figure and figure caption are adapted from Dubovik et al. (2006).*




The typical ice crystal habits for tropical (left panel), midlatitude (middle panle), and polar cirrus cloud system. Data courtesy of A. Heymsfield and his colleagues (NCAR), S. Warren (University of Washington), and P. Lawson (SPEC).

# Ray-Tracing Method for Light Scattering Calculation

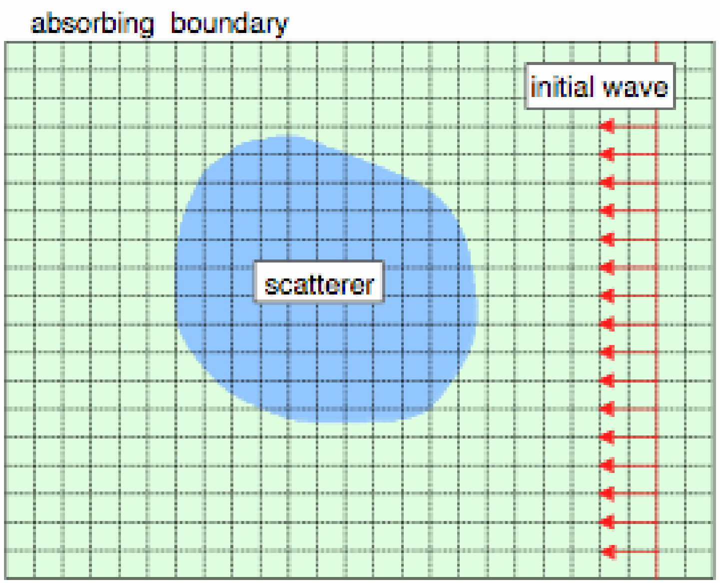


# Finite-Difference Time Domain (FDTD) Method

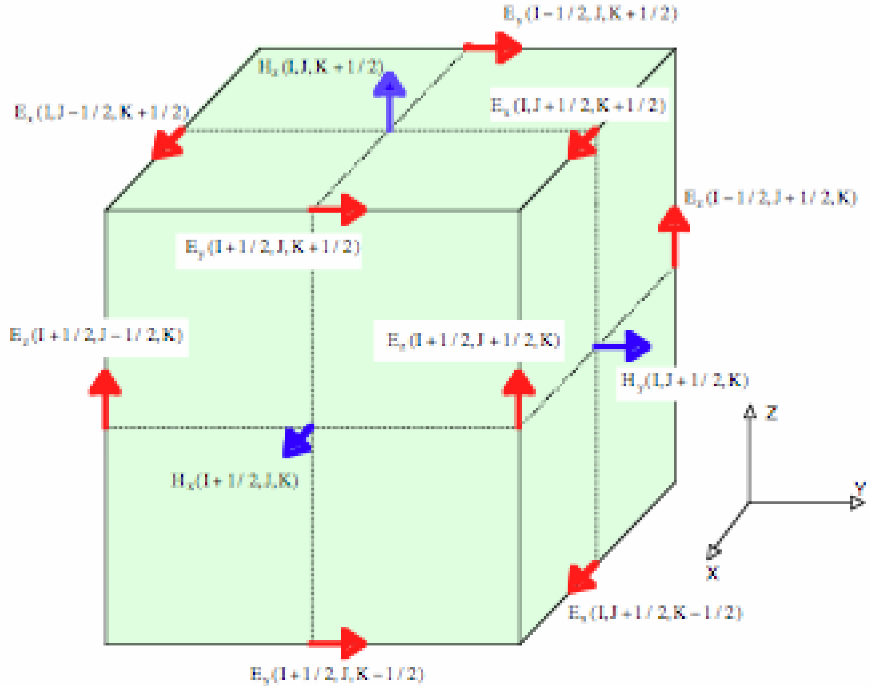
Principle: Solve the time-dependent Maxwell equations for electric (**E**) and magnetic (**H**) fields

- accurate and flexible
- expensive in terms of CPU and memory

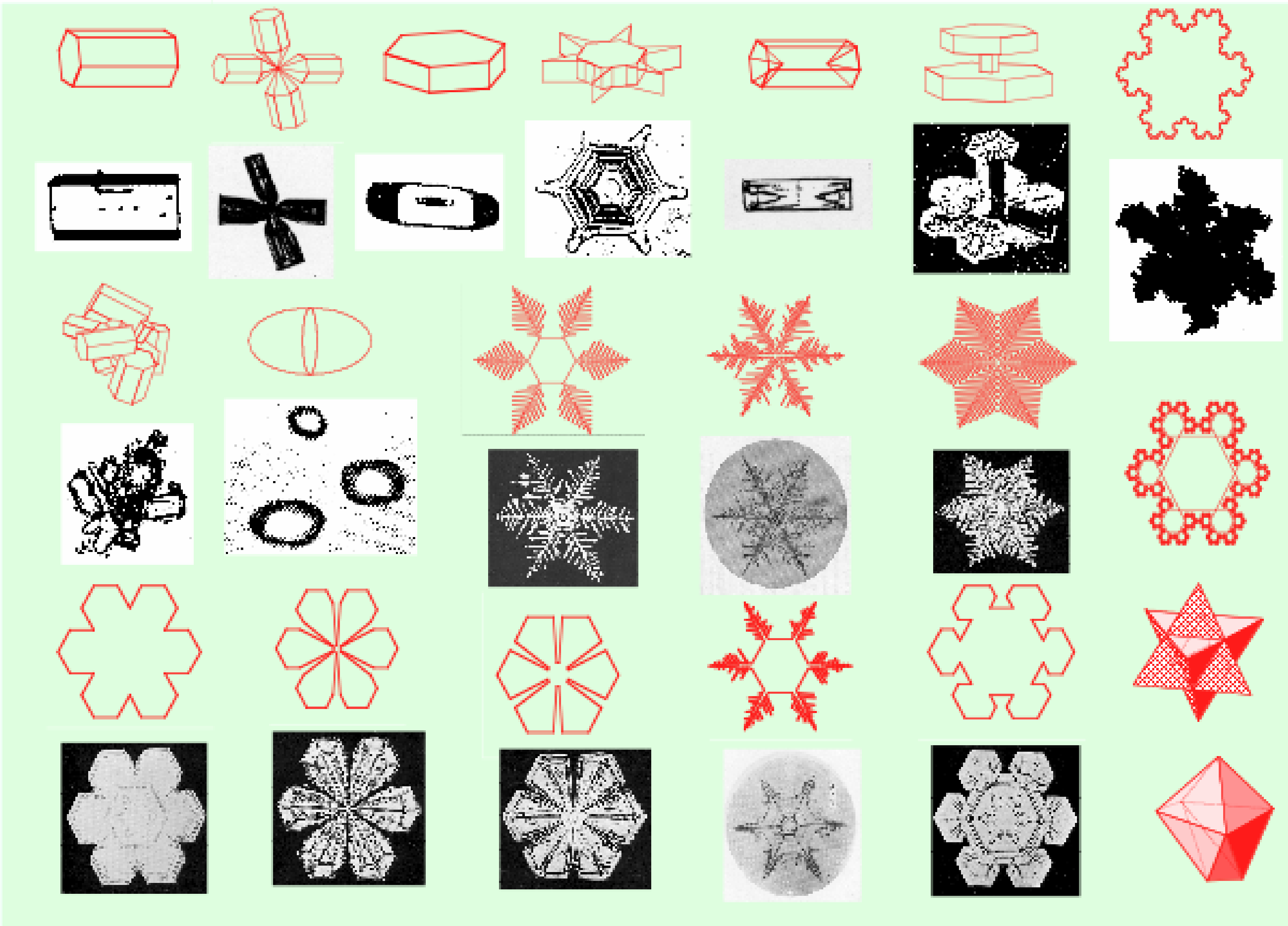
## Computational Domain




## Field Locations on a Grid Cell

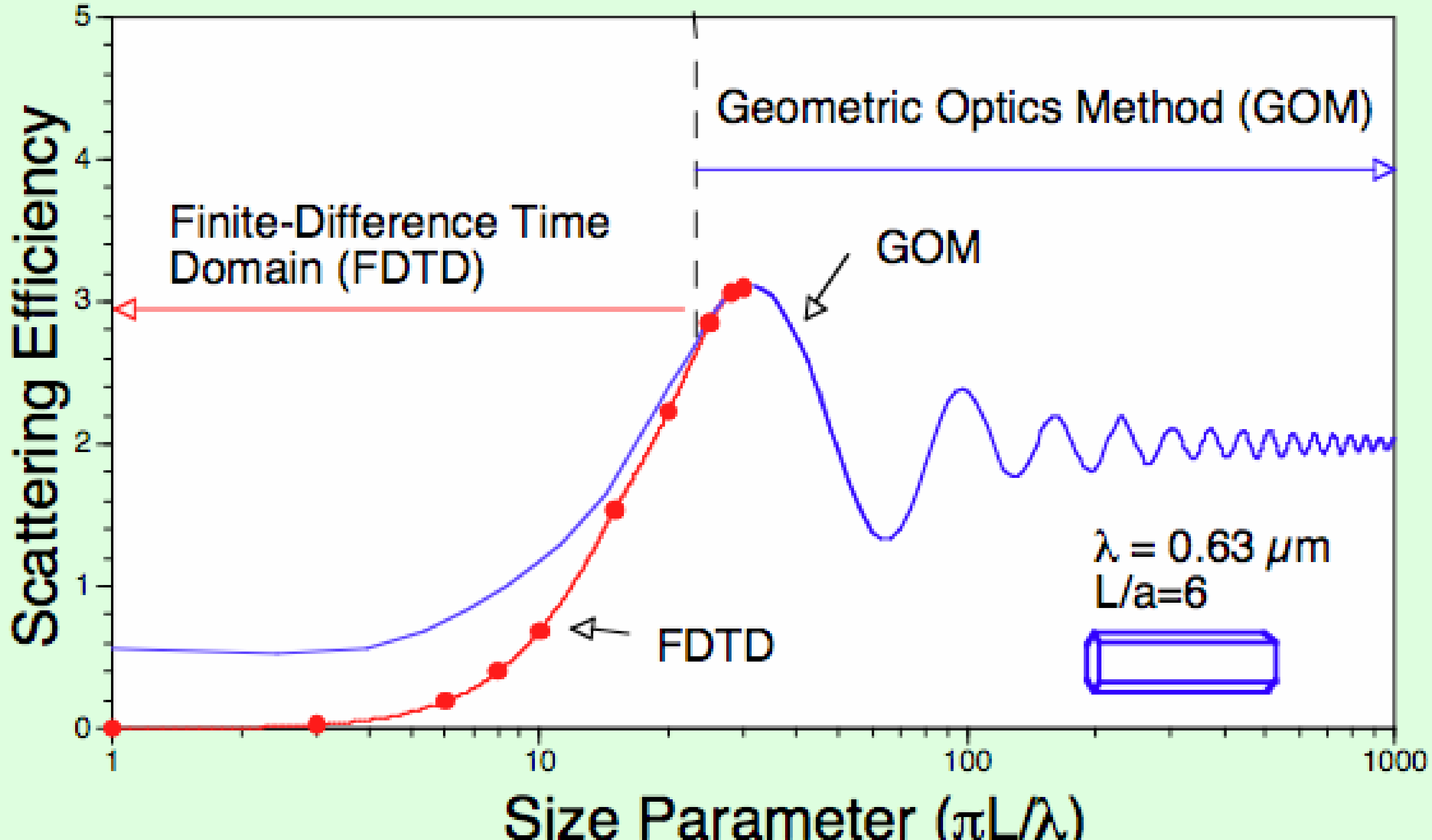



(Yee 1966)



The observed shapes are taken from the literature (Bentley, 1962; Nakaya, 1954; Kinne et al. 1994)

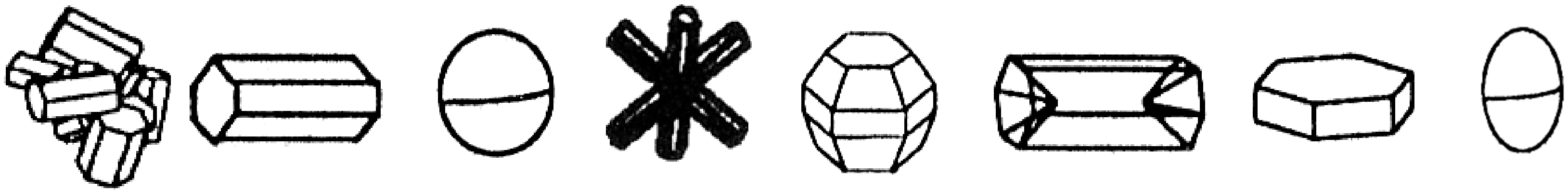
# Combination of the FDTD and Improved Geometric Optics Methods for Light Scattering Computation




(Liou, Takano, and Yang, 1999)

- Shapes of ice crystals

  Aggregates, solid hexagonal columns, Spheres, Bullet-rosettes, Droxtals, Hollow columns, Plates, and Spheroids



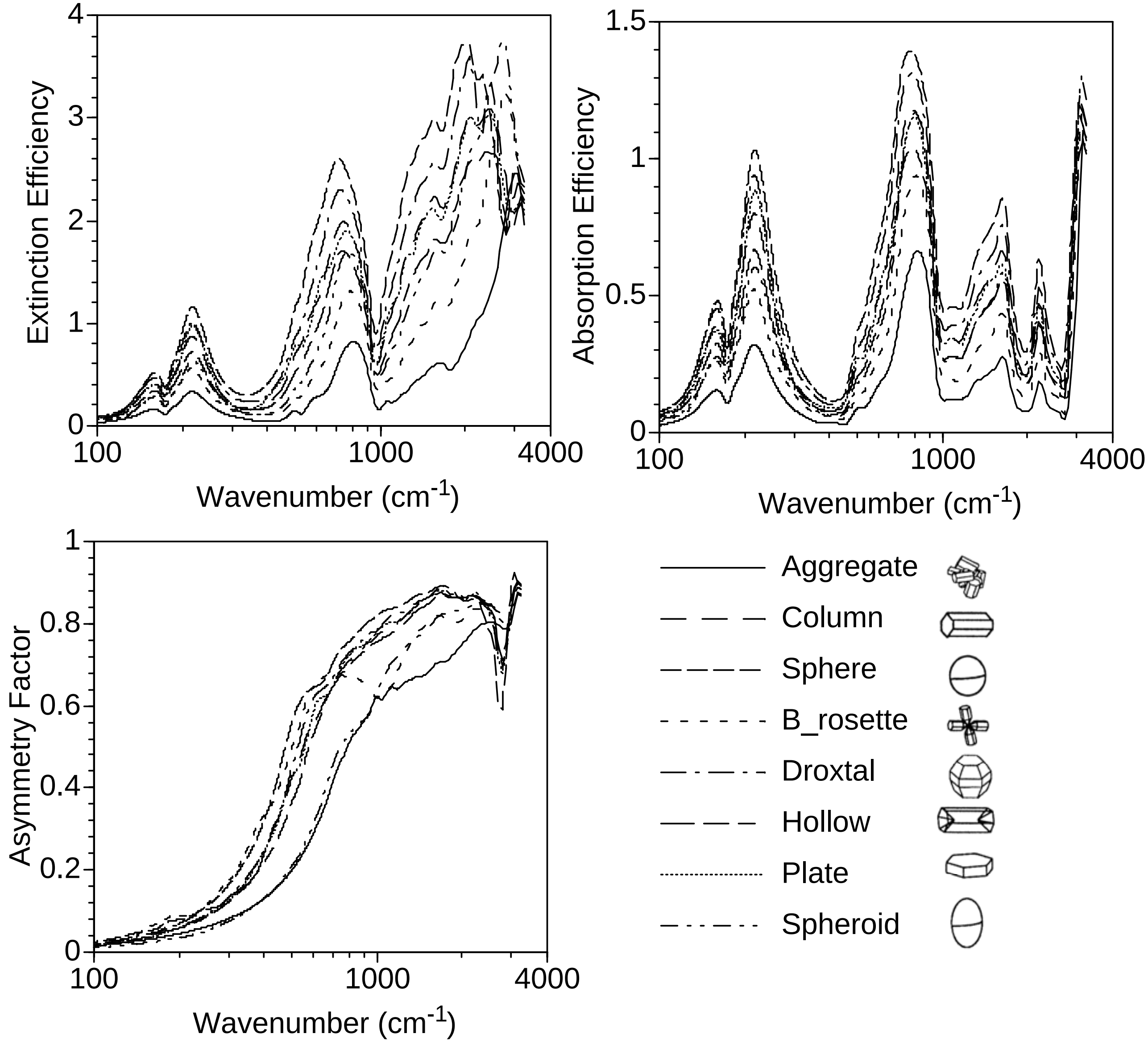
- Wavelengths:

  Wavelengths from 0.2 µm to 100 µm

- Size bins:

  45 Size bins from 2 µm to 9500 µm in terms of particle maximum dimension

# Single-scattering properties of different ice crystals vs. wavenumber (Maximum Dimension= 10 μm)



The contours of extinction efficiency, absorption efficiency and asymmetry factor as functions of wavenumber and the maximum dimension of ice crystals

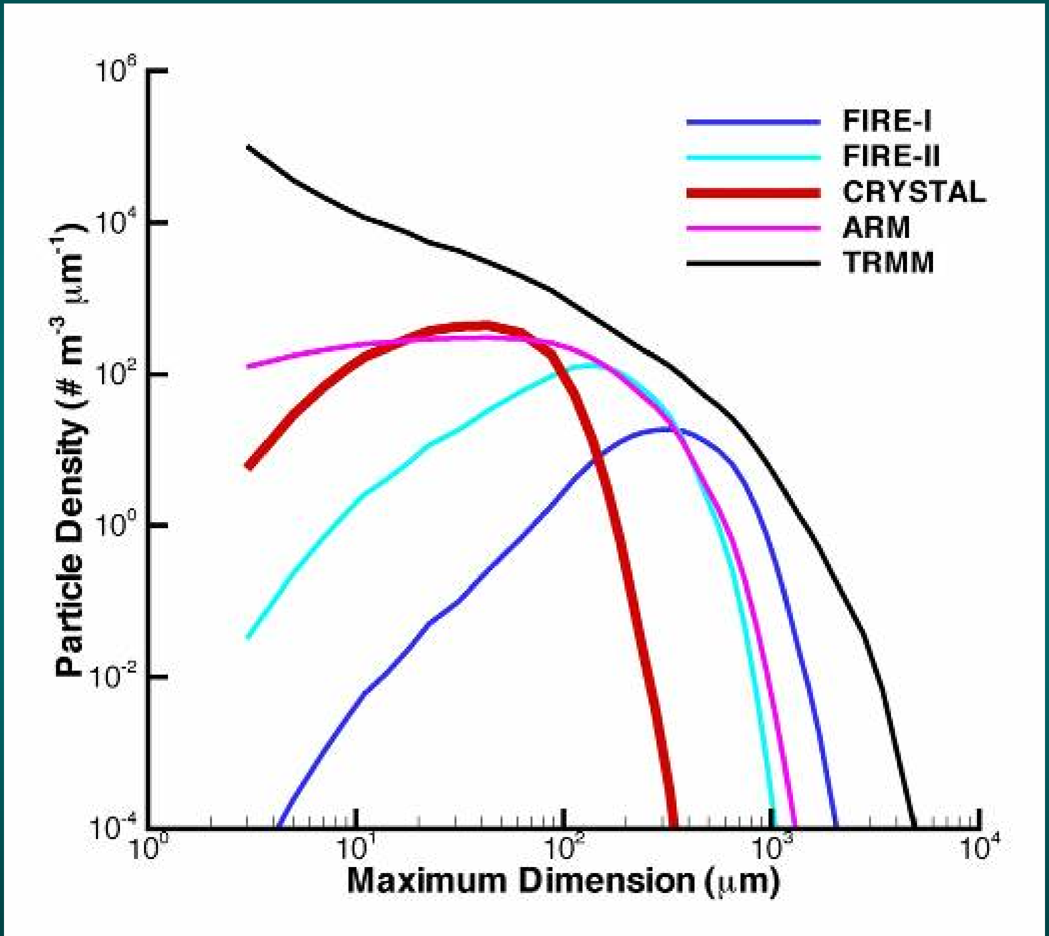
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

# Field Campaign Information

| *Field Campaign* | *Location* | *Instruments* | *Number of PSDs* |
|---|---|---|---|
| FIRE-1 (1986) | Madison, WI | 2D-C, 2D-P | 246 |
| FIRE-II (1991) | Coffeyville, KS | Replicator | 22 |
| ARM-IOP (2000) | Lamont, OK | 2D-C, 2D-P, CPI | 390 |
| TRMM KWAJEX (1999) | Kwajalein, Marshall Islands | 2D-C, HVPS, CPI | 418 |
| CRYSTAL-FACE (2002) | Off coast of Nicaragua | 2D-C, VIPS | 41 |

Probe size ranges are: 2D-C, 40-1000 μm; 2D-P, 200-6400 μm; HVPS (High Volume Precipitation Spectrometer), 200–6100 μm; CPI (Cloud Particle Imager), 20-2000 μm; Replicator, 10-800 μm; VIPS (Video Ice Particle Sampler): 20-200 μm.

# Particle Size Distributions




***Synoptic cirrus characteristics***

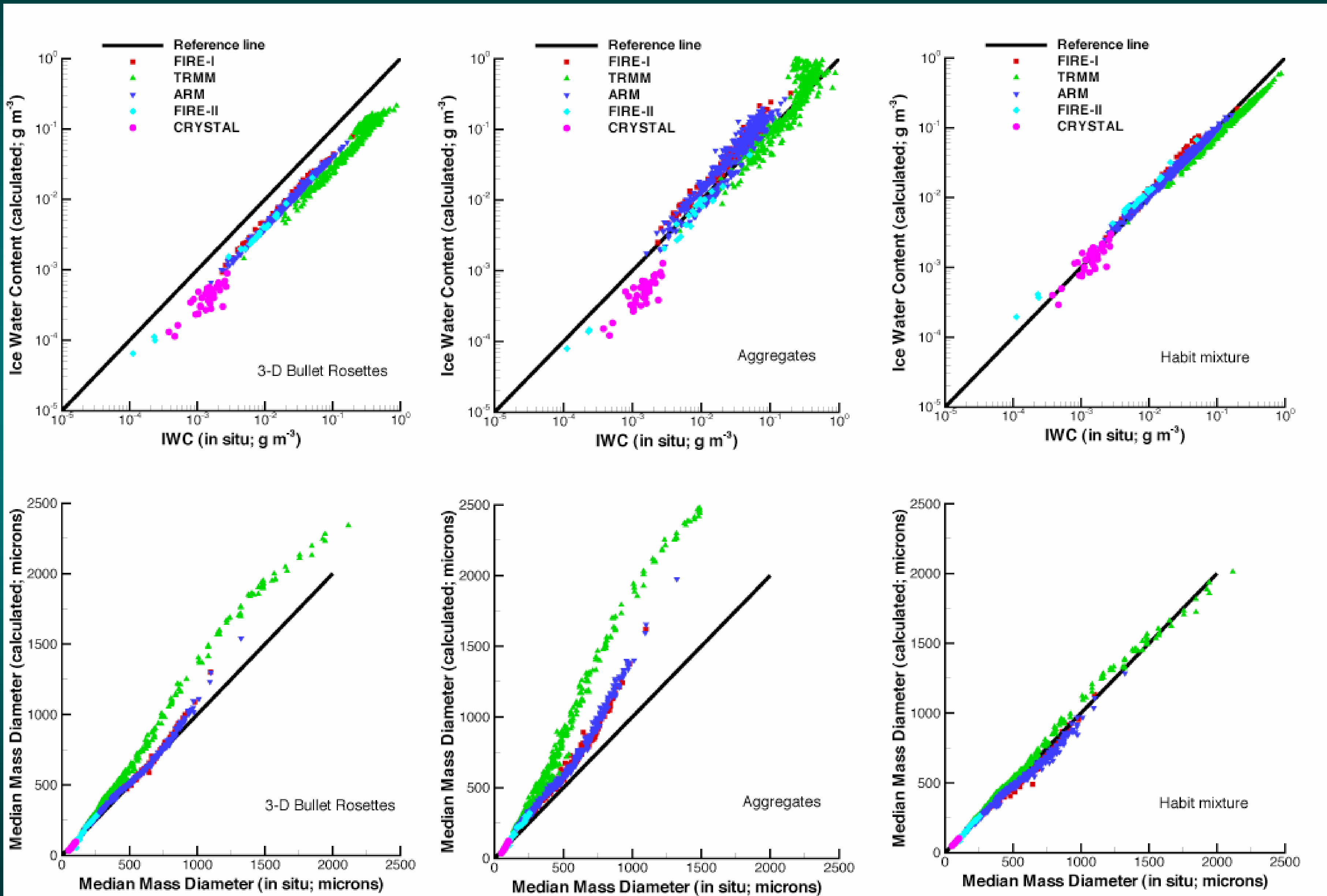
- *Low updraft velocities*
- *Size sorting more pronounced*
- *Small crystals at cloud top*
- *More often find pristine particles*

***Tropical cirrus anvil characteristics***

- *Form in an environment having much higher vertical velocities*
- *Size sorting is not as well pronounced*
- *Large crystals often present at cloud top*
- *Crystals may approach cm in size.*
- *Habits tend to be more complex*

- Note that CRYSTAL distributions tend to be the narrowest overall

# Ice Water Content and Median Mass Diameter



# Ice Particle Habit Percentages Based on Comparison of Calculated to In-situ $D_m$ and $IWC$

*Guidelines*

4 size domains defined by particle maximum length

Droxtals: used only for smallest particles

Aggregates: only for particles > 1000 μm

Plates: used only for particles of intermediate size

**Proposed ice particle habit mixture**

**Max length < 60 μm**
100% droxtals

**60 μm < Max length < 1000 μm**
15% bullet rosettes
35% hexagonal plates
50% solid columns

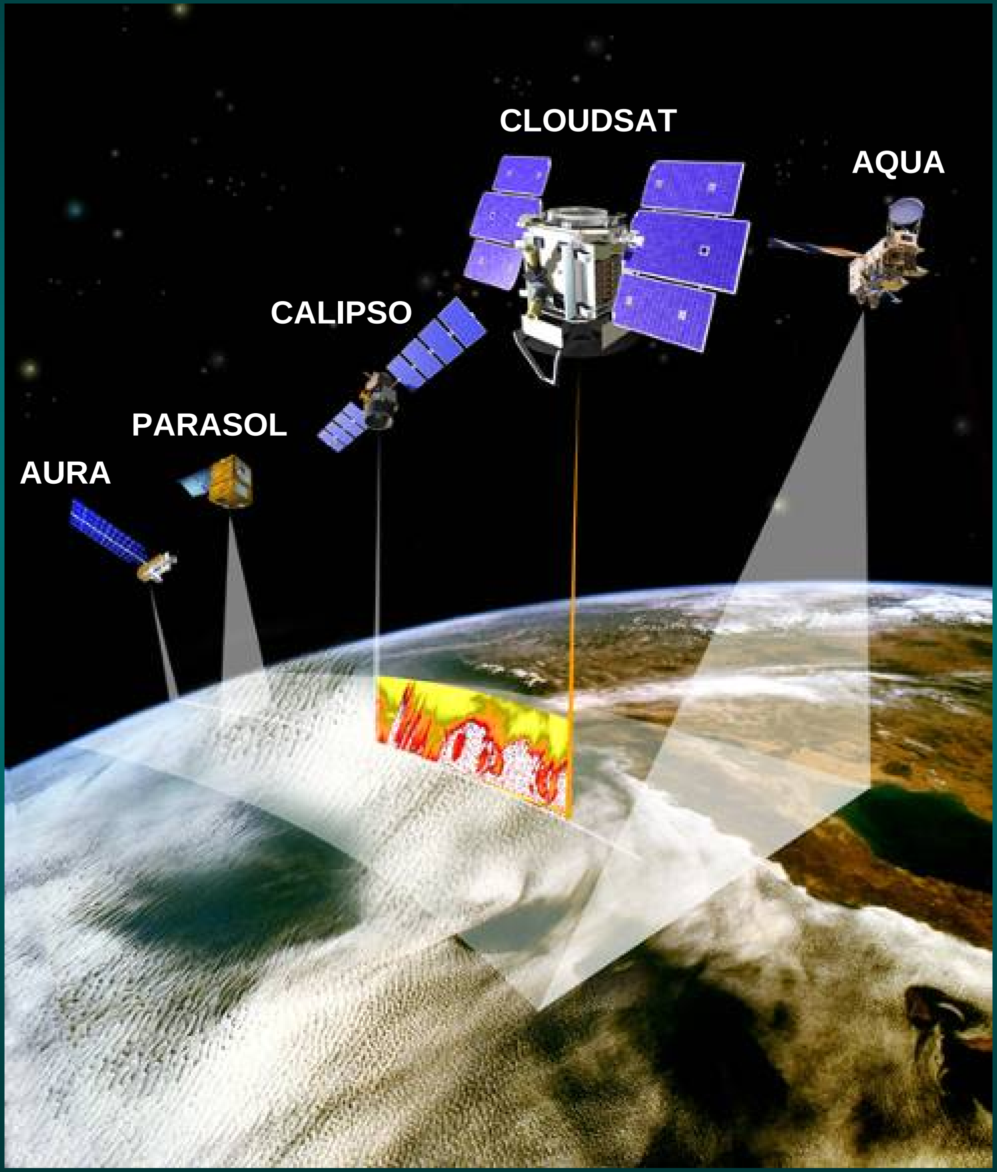
**1000 μm < Max length < 2500 μm**
45% solid columns
45% hollow columns
10% aggregates

**Max length > 2500 μm**
97% bullet rosettes
3% aggregates

**Note that this ice crystal habit distribution model has been used in the MODIS operational ice cloud retrieval.**

# Ice Cloud Measurements at Multiple Wavelengths

How much consistency in the inferred cloud properties should one expect for analysis of an ice cloud observed by multiple instruments that take measurements over different parts of the spectrum?



# Bulk Optical Models at Discrete Values of $D_{eff}$

Provide microphysical and single scattering properties (mean and std. dev.) at $D_{eff}$ from 10 μm to 180 μm (increments of 10 μm ) for

- IWC
- volume
- asymmetry factor
- single-scattering albedo
- delta transmission energy
- median mass diameter
- projected area
- scattering phase function (498 angles)
- extinction efficiency / cross section

Narrowband models available at **http://www.ssec.wisc.edu/~baum**:

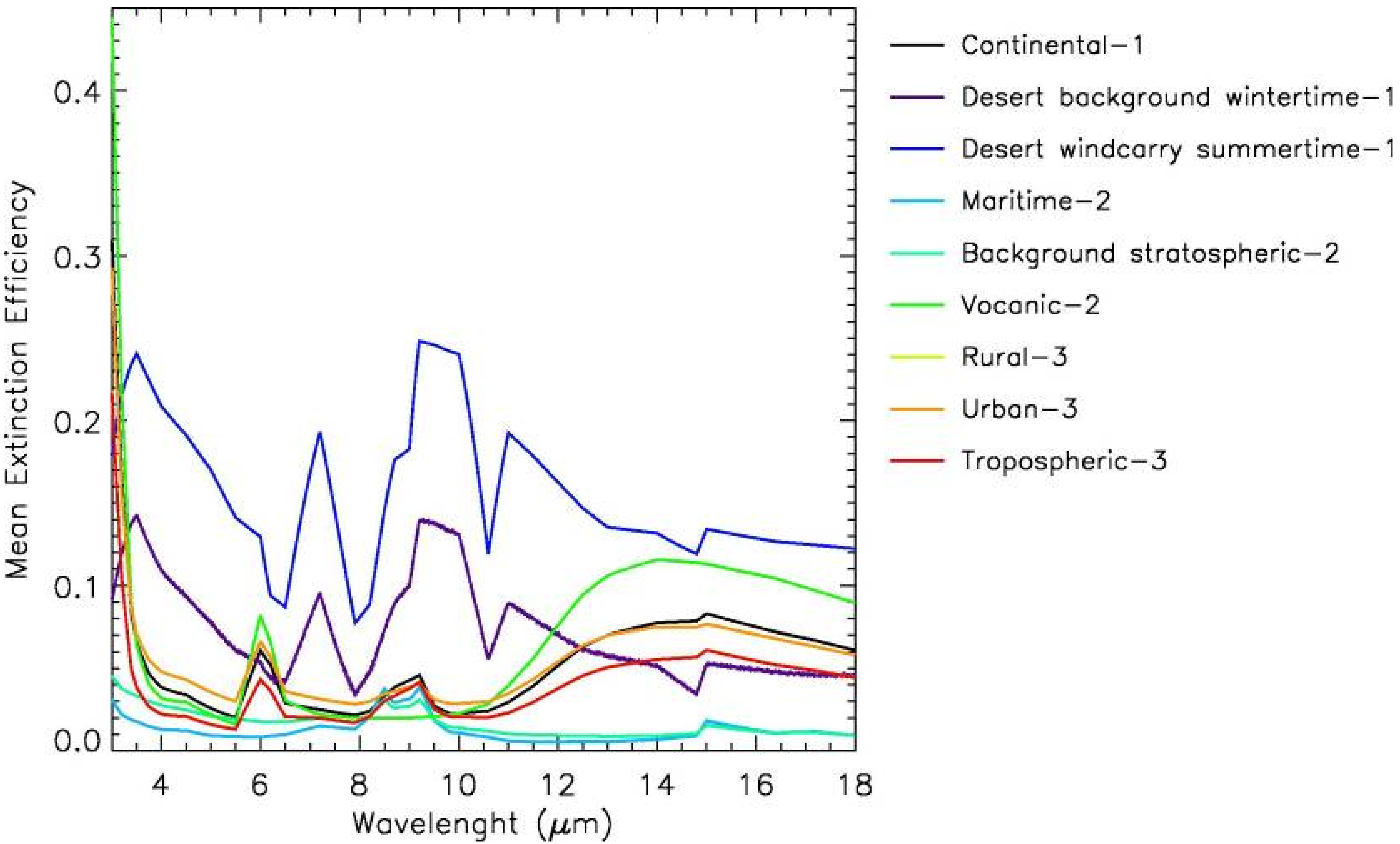
- MODIS
- AATSR
- MISR
- MAS
- VIRS
- POLDER
- AVHRR
- GOES-R Advanced Baseline Imager (ABI)
- SEVIRI (Spinning Enhanced Visible InfraRed Imager)

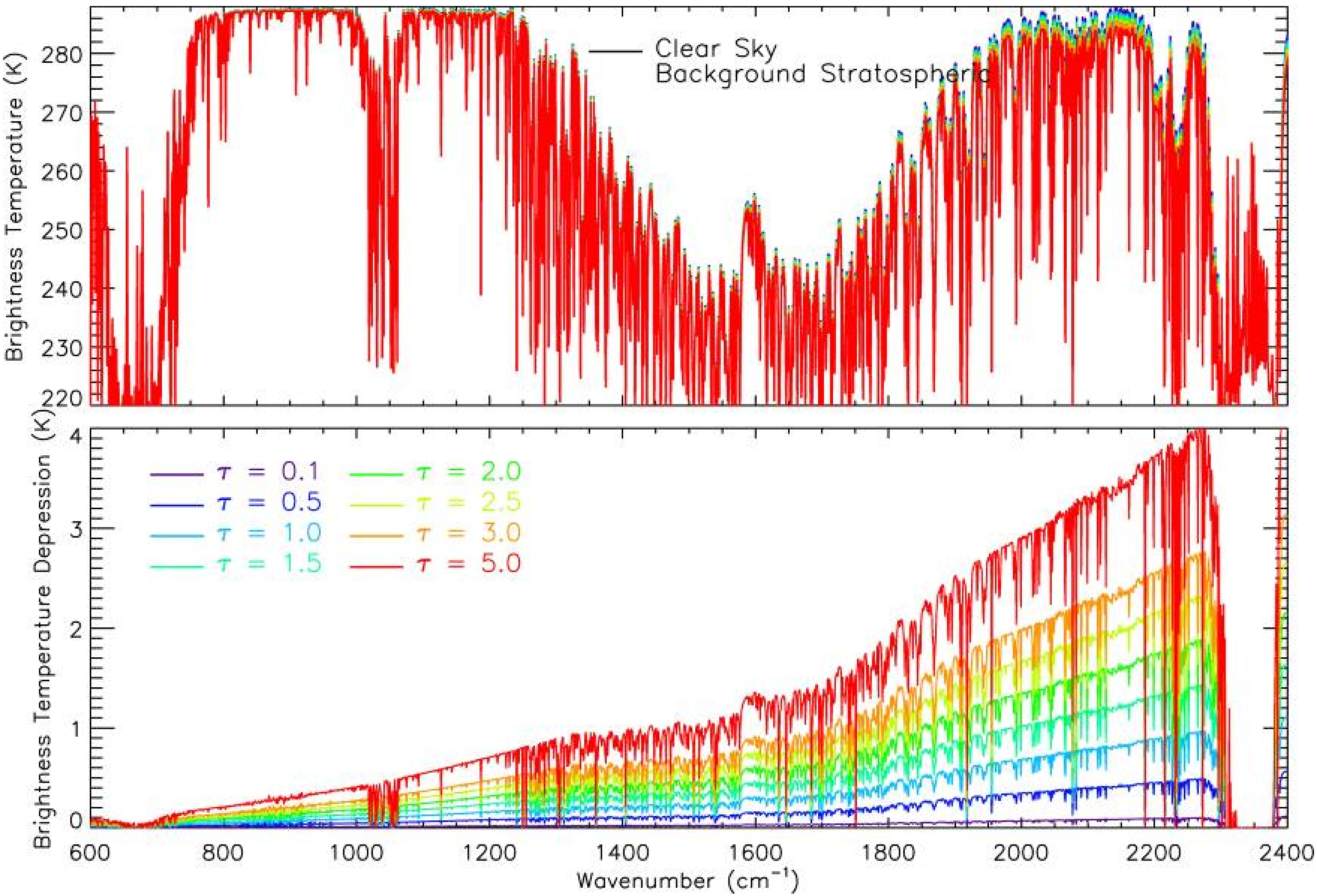
Hyperspectral models available for MWIR-IR-FarIR (100 $cm^{-1}$ to 3250 $cm^{-1}$ at 1 $cm^{-1}$ resolution)

VIS/NIR spectral models (144 wavelengths between 0.4 - 2.2 μm at 1 μm resolution)

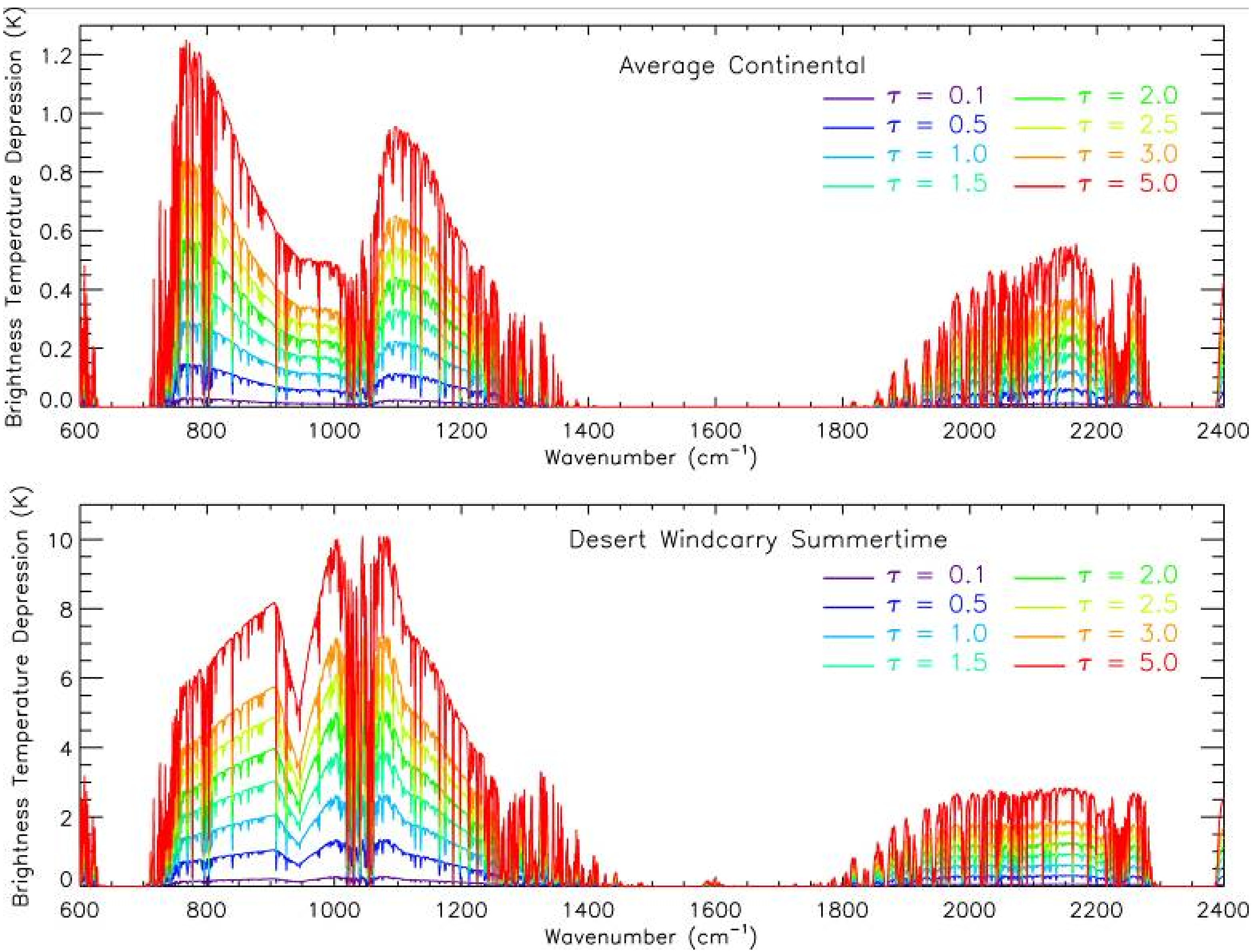
Polarization models available at 7 wavelengths from 0.35 μm to 2.1 μm

# Bulk Optical Properties

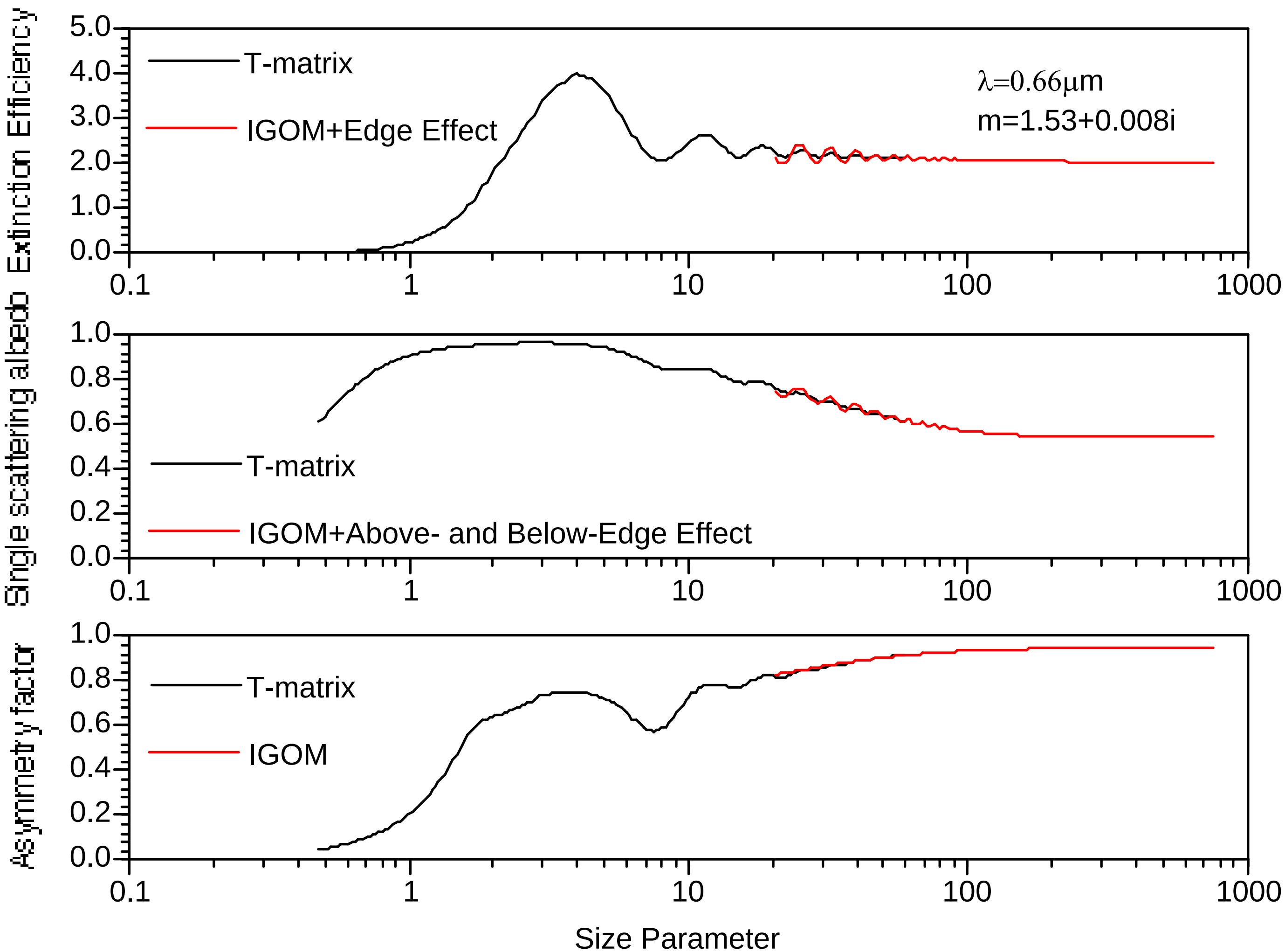




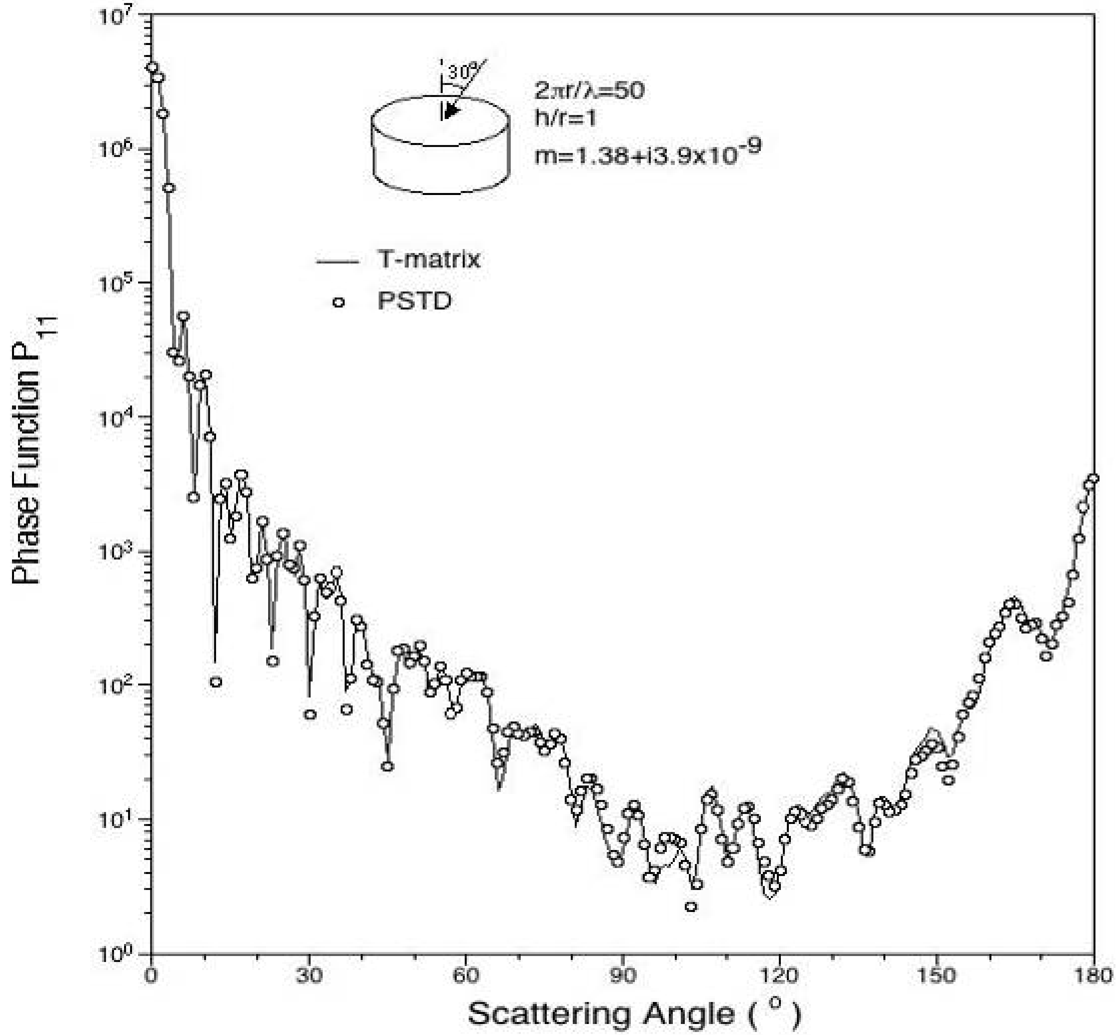
Clear Sky
Background Stratospheric
Brightness Temperature (K)
280
270
260
250
240
230
220
τ = 0.1
τ = 0.5
τ = 1.0
τ = 1.5
τ = 2.0
τ = 2.5
τ = 3.0
τ = 5.0
Brightness Temperature Depression (K)
4
3
2
1
0
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Wavenumber (cm⁻¹)



Average Continental
τ = 0.1
τ = 0.5
τ = 1.0
τ = 1.5
τ = 2.0
τ = 2.5
τ = 3.0
τ = 5.0
Brightness Temperature Depression (K)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Wavenumber (cm⁻¹)
Desert Windcarry Summertime
τ = 0.1
τ = 0.5
τ = 1.0
τ = 1.5
τ = 2.0
τ = 2.5
τ = 3.0
τ = 5.0
Brightness Temperature Depression (K)
0
2
4
6
8
10
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Wavenumber (cm⁻¹)




Comparison between the T-matrix solutions and their counterparts computed from the complex angular momentum (CAM) approximation (for the extinction efficiency) and the improved geometric optics method (IGOM, for the single-scattering albedo and asymmetry factor) for the single-scattering properties of dust particles. The particle shape is assumed to be a prolate spheroid with an aspect ratio of 1:1.7. The size parameter indicated in the x-axis is defined in terms of that for the equivalent-volume sphere.




Comparison of T-matrix and Pseudo-spectral time-domain (PSTD) solutions.

# Fast Infrared Radiative Transfer Models (FIRTM) for Hyperspectral Remote Sensing

- Motivation:

  For applications to

  - Remote sensing of clouds from high-spectral-resolution data
  - Satellite data assimilation in NWP & climate simulations
  - Proxy data for algorithm development & risk reduction regarding future satellite sensors

- FIRTM series
  - FIRTM1:

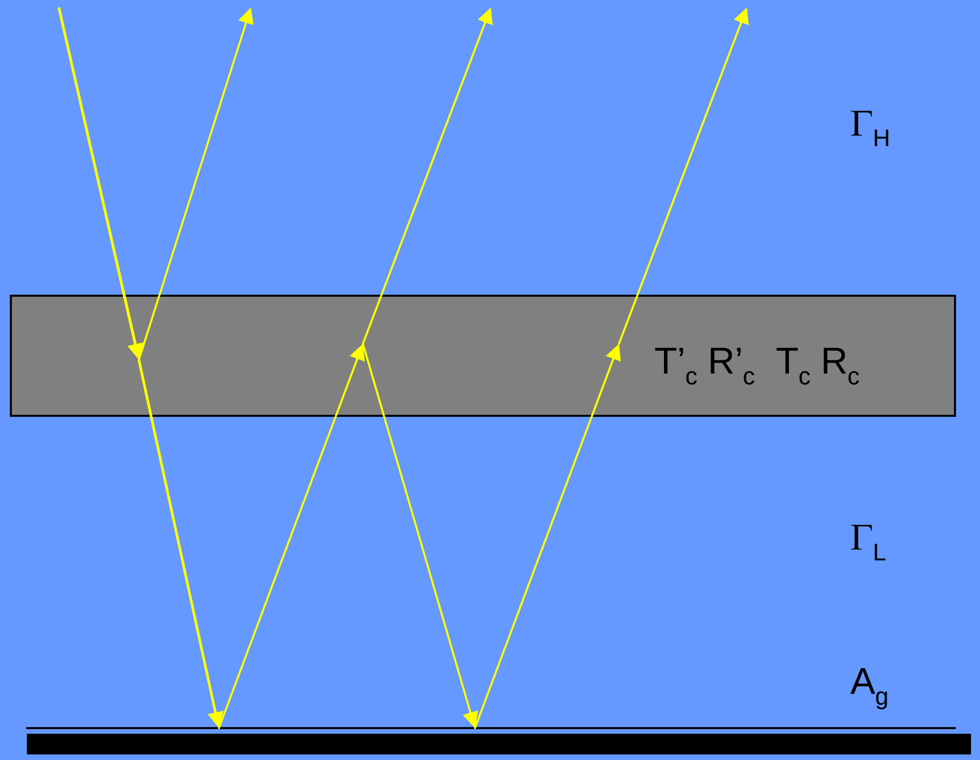
    **Wei, H., P. Yang, J. Li, B. A. Baum, H.-L. Huang, S. Platnick, Y. X. Hu, and L. Strow**, 2004: Retrieval of ice cloud optical thickness from Atmospheric Infrared Sounder (AIRS) measurements. *IEEE Trans Geosci. and Remote Sensing*, 42, 2254-2265.
  - FIRTM2:

    Niu, J., P. Yang, H. Huang, J. Davis, J. Li, B. Baum and Y. Hu, 2007: A fast infrared radiative transfer model for overlapping clouds, *J. Quant. Spectros. Rad. Transfer,* 103, 447-459.
  - FIRTM-AD:

    **Zhang, Z., P. Yang, G. W. Kattawar, H.-L. Huang, T. Greenwald, J. Li, B. A. Baum, D. K. Zhou, and Y. X. Hu**, 2007: A fast infrared radiative transfer model based on the adding-doubling method for hyperspectral remote sensing applications, *J. Quant. Spectros. Rad. Transfer*, (in press).

# Fast Shortwave Radiative Transfer Model (FSRTM)

$$R = \Gamma_H^0 \Gamma_H \left[ R_c + \frac{A_g T_c T_c' \Gamma_L^2}{1 - R_c' A_g \Gamma_L^2} \right].$$




**Cloud assumptions:**

- **located at any height**
- **horizontally & vertically homogenous cloud**
- **Lambertian surface**

# Summary

- We have developed modeling capabilities to compute the single-scattering properties of cloud particles and aerosol particles.
- We have developed fast IR and shortwave radiative transfer models to simulate the radiances at the top of a cloudy or dusty atmosphere.
- These modeling capabilities can be integrated into the CRTM in a straightforward way.