Recent Progress: Bulk Scattering Models for the Remote Sensing of Ice Clouds

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Purpose: Improve ice cloud bulk scattering models for various sensors to incorporate recent advances in ice particle simulations and *in situ* microphysical measurements. For purposes of data fusion and cloud product intercomparison, the models are derived for each instrument consistently.

EOS teams using our models include MODIS, MISR, CALIPSO, AIRS

Models also being used for a 30-year AVHRR cloud climatology (PATMOS-x), the the upcoming GOES-R Advanced Baseline Imager, and aircraft sensors including the Solar Spectral Flux Radiometer (SSFR), MAS, and MASTER

Preliminary models available for MODIS Collection 6 that include:

- Advances in both measurement technology and light scattering theory
- Higher particle size resolution and includes degree of linear polarization
- New ice habits (aggregate of plates and hollow bullet rosettes)
- Order of magnitude increase in microphysical data
- In situ microphysical data for extremely cold, optically thin ice clouds
- Surface roughness (smooth, moderately roughened, or severely roughened
- New habit mixture

In situ Microphysical Data - Particle Size Distributions

Gamma size distribution* has the form:

$$N(D) = N_o D^{\mu} e^{-\lambda D}$$

where D = max diameter

N_o = intercept

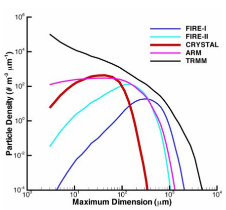
m = dispersion

λ = slope

The intercept, slope, and dispersion values are derived for each PSD by matching three moments (specifically, the 1st, 2nd, and 6th moments)

Note: when μ = 0, the PSD reduces to an exponential distribution

****Heymsfield et al., Observations and parameterizations of particle size distributions in deep tropical cirrus and stratiform precipitating clouds: Results from in situ observations in TRMM field campaigns. J. Atmos. Sci., 59, 3457-3491, 2002.***



Synoptic cirrus characteristics

- ***Relatively** narrow range of particle sizes*
- *Small particles at cloud top*
- *More often find pristine particles*

Convective cirrus characteristics

Form in an environment having much higher vertical velocities

- *Broad size distributions*
- *Large particles often present at cloud top*
- *Particles may approach cm in size.*
- *Habits tend to be more complex*

Field Campaign Data Currently Available

Field Campaign	*Location*	*Number of 5-sec averaged PSDs $T_{cld} \le -40$°C*	*Probes*
ARM-IOP (2000)	Oklahoma	1420	2D-C, 2D-P, CPI
TRMM KWAJEX (1999)	Kwajalein, Marshall Islands	201	2D-C, HVPS, CPI
CRYSTAL-FACE	Carribean	62	CAPS, VIPS
SCOUT	Darwin, Australia	475	FSSP, CIP
ACTIVE – monsoons	Darwin, Australia	4268	CAPS
ACTIVE – Hectors	Darwin, Australia	2583	CAPS
ACTIVE – squall lines	Darwin, Australia	740	CAPS
MidCiX	Oklahoma	2968	CAPS, VIPS
Pre-AVE	Costa Rica	20	VIPS

Probe size ranges (at least, usable ranges):

2D-C, ~100-1000 µm
2D-P, 200-6400 µm
HVPS (High Volume Precipitation Spectrometer), 200–5000 µm
CPI (Cloud Particle Imager), 20-2000 µm
FSSP, ~1-50 µm
VIPS (Video Ice Particle Sampler), ~10-350 µm
CAPS has 2 parts, the CAS and CIP:
CAS: Cloud and Aerosol Spectrometer, ~1-50 µm
CIP: Cloud Imaging Probe, 25-1600 µm (but can extend further)

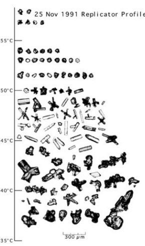
Microphysical data and ensuing bulk scattering models incorporate
- advances in measurement techniques
- data from extremely cold, optically thin ice clouds
- better characterization of the number and shape of small ice particles
- comprehensive set of microphysical measurements from combination of probes (currently about 13,000 PSDs)
- mitigation of large ice particle shattering at inlet to 2D-C (and similar) probes
- more guidance on realistic habit mixtures

Improvements to Single Scattering Properties

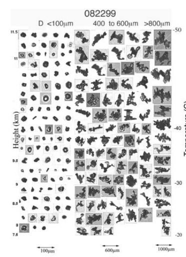
Properties for each habit/size bin include volume, projected area, maximum dimension, single-scattering albedo, asymmetry parameter, extinction/scattering cross sections as well as extinction efficiency.

What's new:

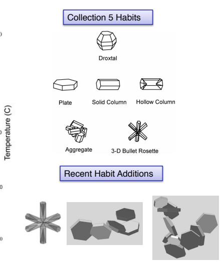
- Single scattering properties are based on revised ice index of refraction (Warren and Brandt, JGR, 2008)
- New treatment of forward scattering, within the first few degrees of the scattering angle. Important because there is no longer a delta transmission term that was present in the C5 (and earlier) models
- Efficiencies are now smooth as a function of the size parameter (proportional to ratio of particle diameter to wavelength); no longer any discontinuities in the transition between properties obtained from FDTD and IGOM models
- New habits include hollow bullet rosettes as well as small and large aggregates of plates
- Models will include extinction coefficient (β) as well as D_{eff} = f(IWC/β) per user request
- Libraries will provide full phase matrix, so we can build models for analyses of POLDER, GLORY, & CALIPSO depolarization data
- Libraries will no longer have spectral gaps so we will be able to build hyperspectral and broadband models consistently across the spectrum
- Models can be built for smooth, moderately roughened, or severely roughened particles



Synoptic Cirrus



Tropical Anvil Cirrus



Ice Habits in Scattering Calculations

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

Since each idealized ice particle has a prescribed volume, and hence mass, we can calculate *IWC* (ice water content) and D_m (median mass diameter) for each PSD. Subsequently, we can compare the *IWC* and D_m values computed with the simulated ice habits to those values estimated for each PSD from the techniques developed by Heymsfield and colleagues. This provides a constraint on the prescribed habit mixture.

Ice Particle Habit Mixture Assumed for Collection 5

C5 guidelines for habit mixture

4 size ranges defined by maximum dimension

Fixed habit percentages in each size range

Aggregate of columns: used only in small amounts because of its high density

Plates: used only for particles of intermediate size

Use more hollow than solid columns/plates/rosettes

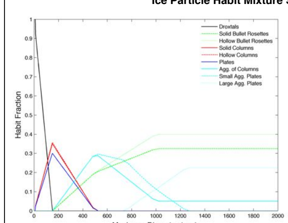
Max length < 60 µm
100% droxtals

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

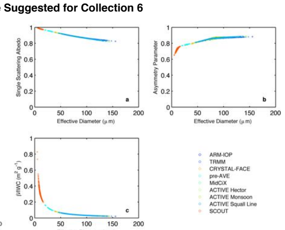
Ice Particle Habit Mixture Suggested for Collection 6



New habit mixture

Developed by Carl Schmitt at NCAR

Smooth transition of habit with maximum dimension

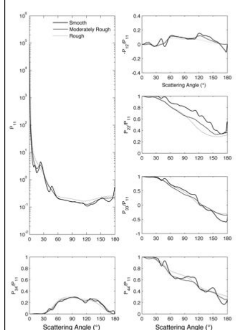


Single scattering albedo, asymmetry parameter, and extinction coefficient divided by the IWC (β/IWC) at a wavelength of 2.12 µm for severely roughened particles

Explore new areas

Polarization

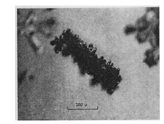
We are beginning to explore the advantages provided by satellite based polarization measurements…the example below shows the influence of particle roughening on the various phase matrix components for MODIS Band 1 (0.65 µm wavelength) using the C5 habit distribution.



Publication under development:

Baum, B. A., P. Yang, Q. Feng, and Y.-X. Hu: The impact of ice particle roughness on the scattering phase matrix. In preparation for submittal to *J. Quant. Spectrosc. Radiant. Transfer*

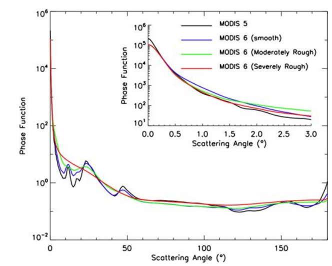
Surface Roughness



The image of a rimed column ice crystal (adapted from Ono, 1969).

C5 to C6 Comparison – Surface Roughness

Previous models assumed that particle surfaces are smooth, except for the aggregate. The new database will include both moderate and severe roughness. The example below is a comparison of the intensity (P_{11}) for MODIS Band 1 (0.65 µm wavelength). Additionally, a new treatment of forward scattering is incorporated in the C6 models.



Publication under development:

Baum, B. A., P. Yang, A. J. Heymsfield, A. Bansemer, L. Bi, C. Schmitt, and Y. Xie: Refinement of shortwave bulk scattering and absorption models for the remote sensing of ice clouds. In preparation for submittal to to *J. Appl. Meteor. Clim*

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