Recent advances in the development of ice cloud bulk scattering and absorption models for use with hyperspectral IR data

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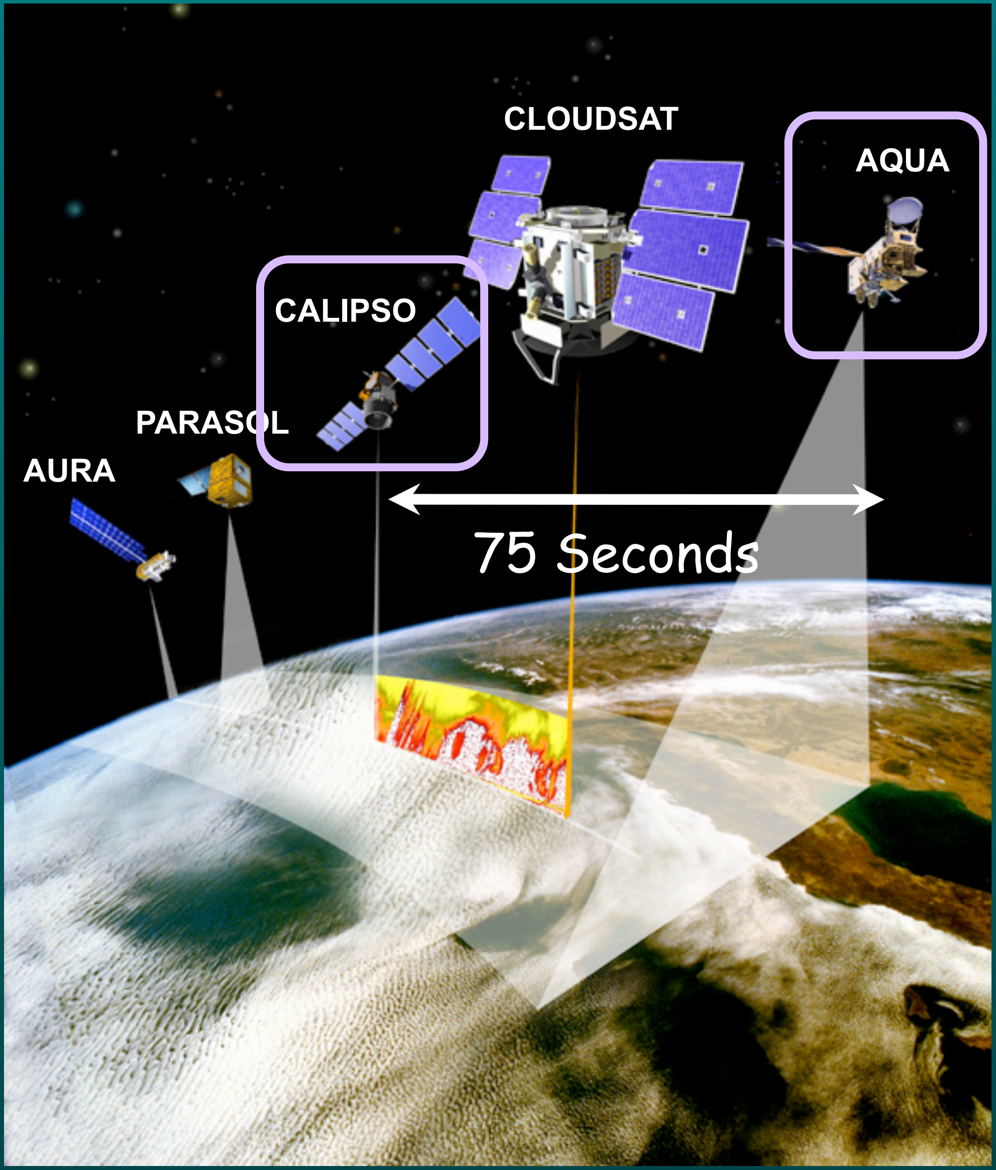
Ice Cloud Observations by Multiple Sensors

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?



Ice Cloud Microphysical and Optical Models

Goal: Facilitate intercomparison of retrieved ice cloud properties from multiple sensors

Incorporate
- latest computational light scattering research (optical properties)
- a variety of ice habits
- microphysical data from multiple field campaigns (D_m, IWC, PSD)

Develop a more comprehensive set of ice cloud single-scattering models

Incorporate imager-specific spectral response functions during integration of single scattering properties over particle and habit distributions

Develop similar models for a variety of imagers, interferometers, and other sensors

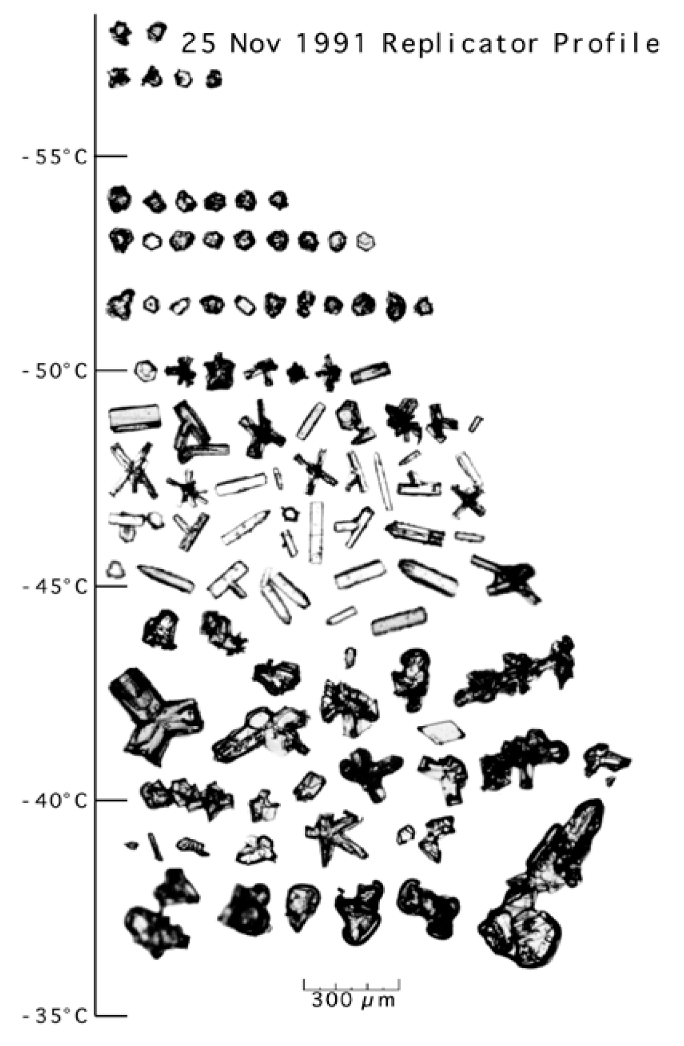
Recent articles:

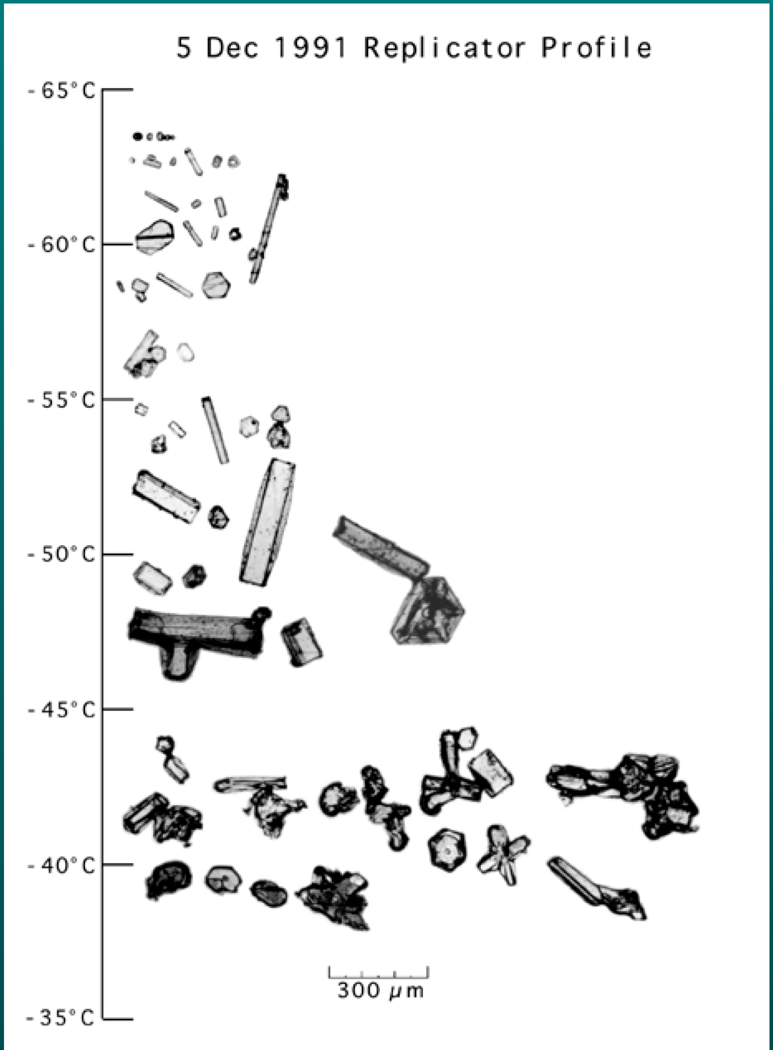
Baum, B. A., A. J. Heymsfield, P. Yang, and S. Thomas, 2005a: Bulk scattering models for the remote sensing of ice clouds. 1: Microphysical data and models, J. Appl. Meteor., **44**, 1885-1895.

Baum, B. A., P. Yang, A. J. Heymsfield, S. Platnick, M. D. King, Y.-X. Hu, and S. Thomas, 2005b: Bulk scattering models for the remote sensing of ice clouds. 2: Narrowband models, J. Appl. Meteor., **44**, 1896-1911.

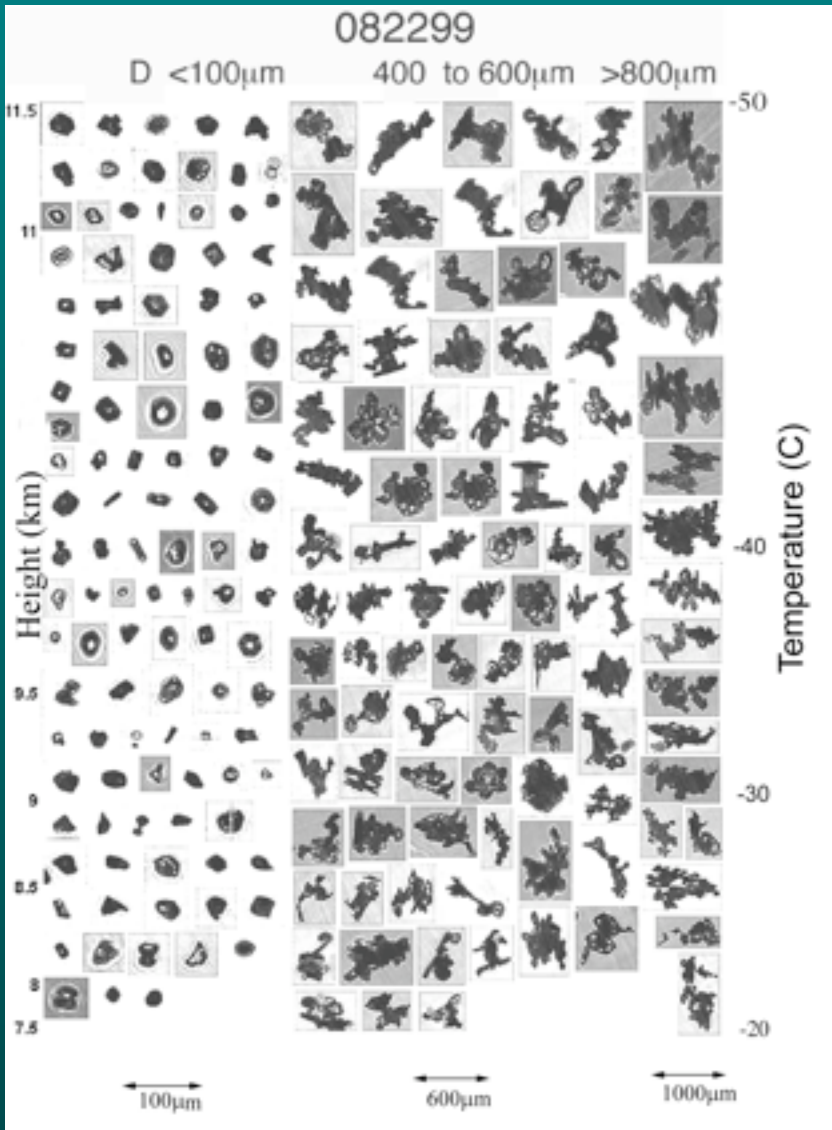
Baum, B. A., P. Yang, S. L. Nasiri, A. K. Heidinger, A. J. Heymsfield, and J. Li, 2007: Bulk scattering properties for the remote sensing of ice clouds. Part 3: High resolution spectral models from 100 to 3250 cm^{-1}. J. Appl. Meteor. Clim., **46**, 423-434

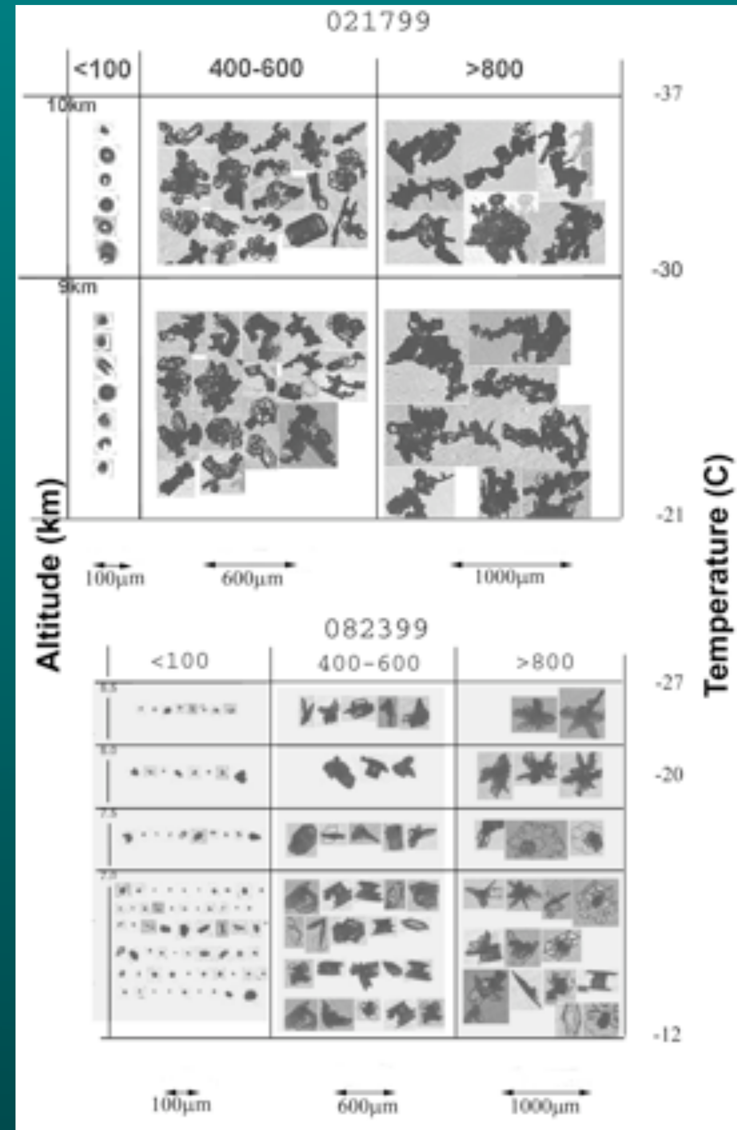
Ice Particle Profiles from Replicator during FIRE-II





Ice Particle Profiles from Tropical Cirrus Anvils





Ice Particle Size Distributions

Gamma size distribution* has the form:

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

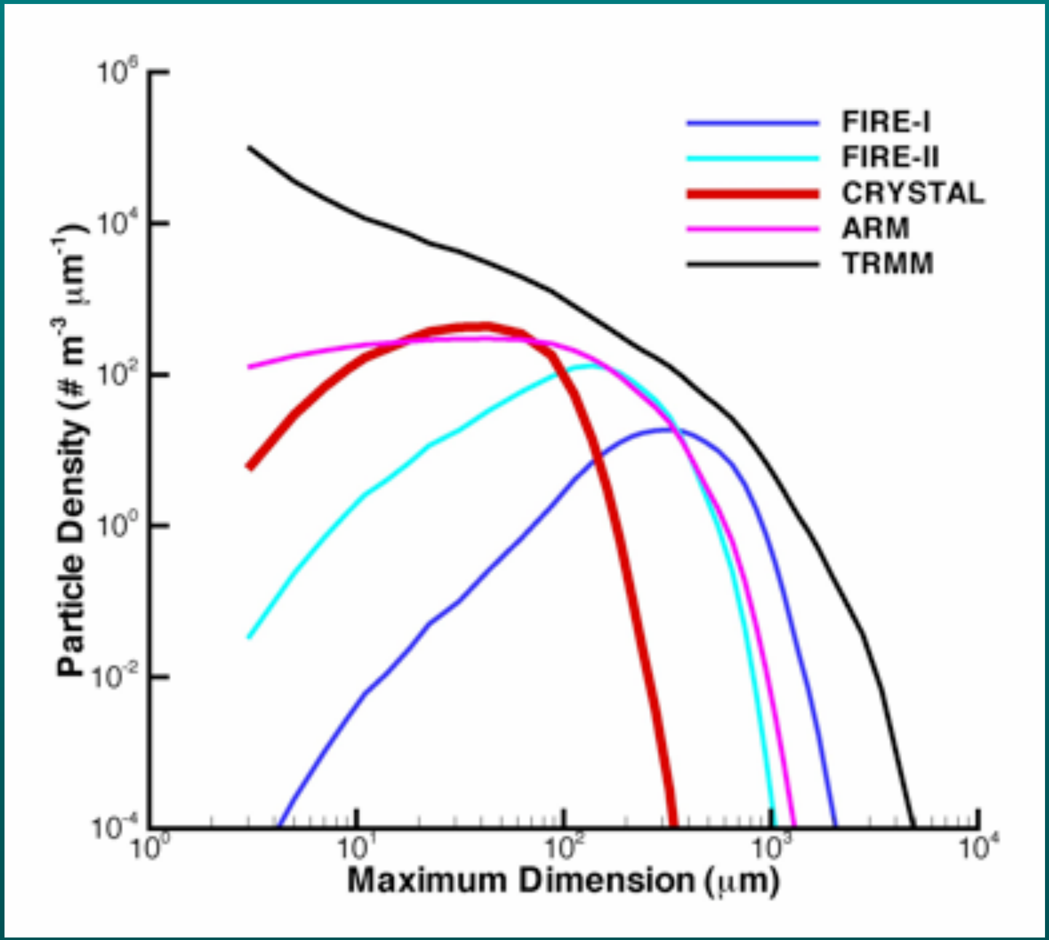
where

- ***D = max diameter***
- ***N_o = intercept***
- ***μ = 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.***

Particle Size Distributions

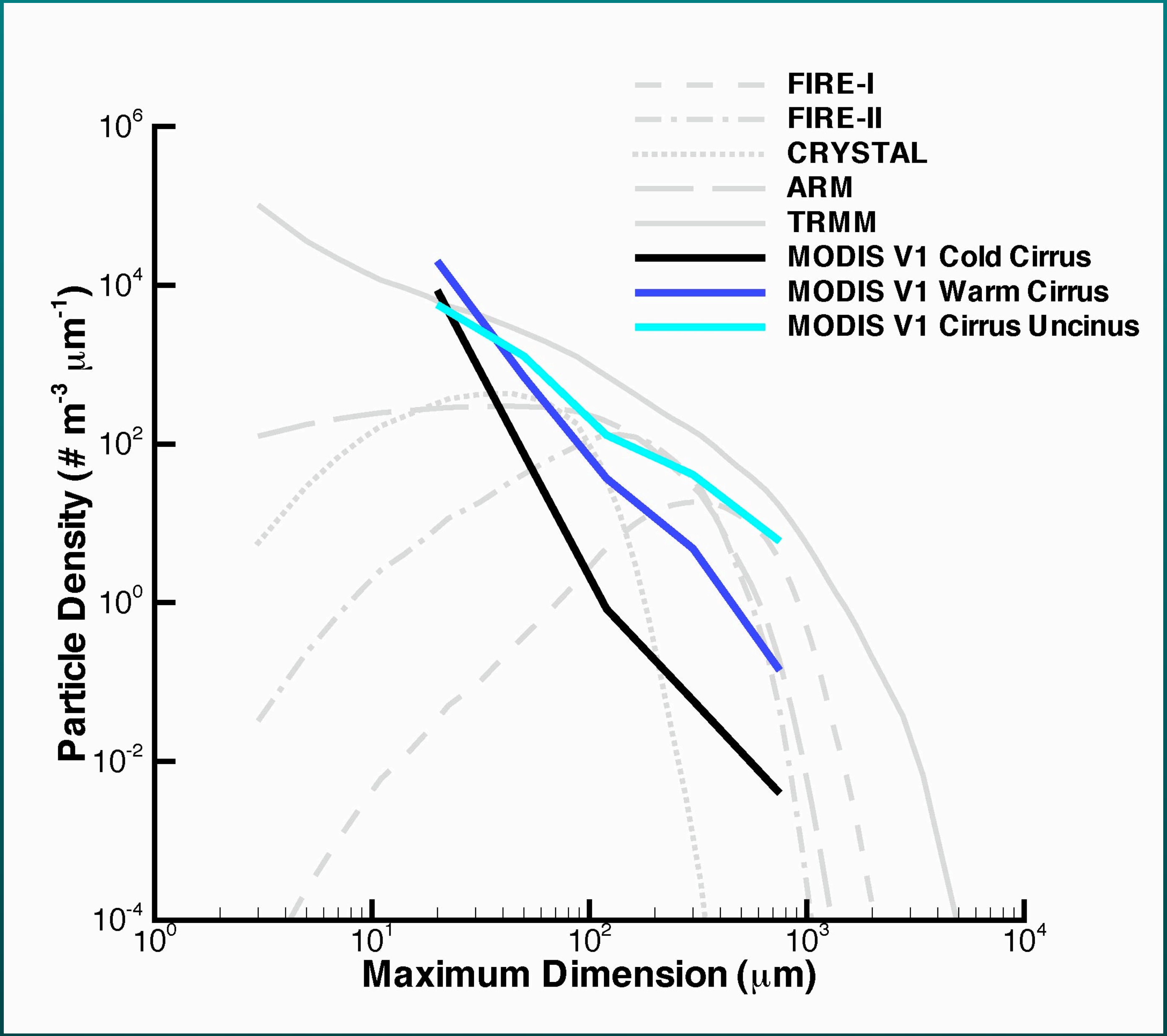


Synoptic cirrus characteristics

- 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



FIRE-I
FIRE-II
CRYSTAL
ARM
TRMM
MODIS V1 Cold Cirrus
MODIS V1 Warm Cirrus
MODIS V1 Cirrus Uncinus
Particle Density (# m^{-3} μm^{-1})
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Maximum Dimension (μm)

Field Campaign Information Used In Earlier Studies

Field Campaign	Location	Instruments	# PSDs
FIRE-I (1986)	Madison, WI	2D-C, 2D-P	246
FIRE-II (1991)	Coffeyville, KS	Replicator	22
ARM-IOP (1990)	Lamont, OK	2D-C, 2D-P, CPI	390
TRMM-KWAJEX (1999)	Kwajalein, Marshall	2D-C, HVPS, CPI	418
CRYSTAL-FACE (2002)	Nicaragua (one flight track)	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.

New Microphysical Data Becoming Available

Controversy about the number of small ice particles has now been largely resolved

2D-C data reprocessed to mitigate the influence of shattered ice particles

Currently working with nearly 5000 PSDs (increase from ~1100 PSDs used previously)

New data: IWC range now covers 5 orders of magnitude (10^{-5} to ~1 g m^{-3}):

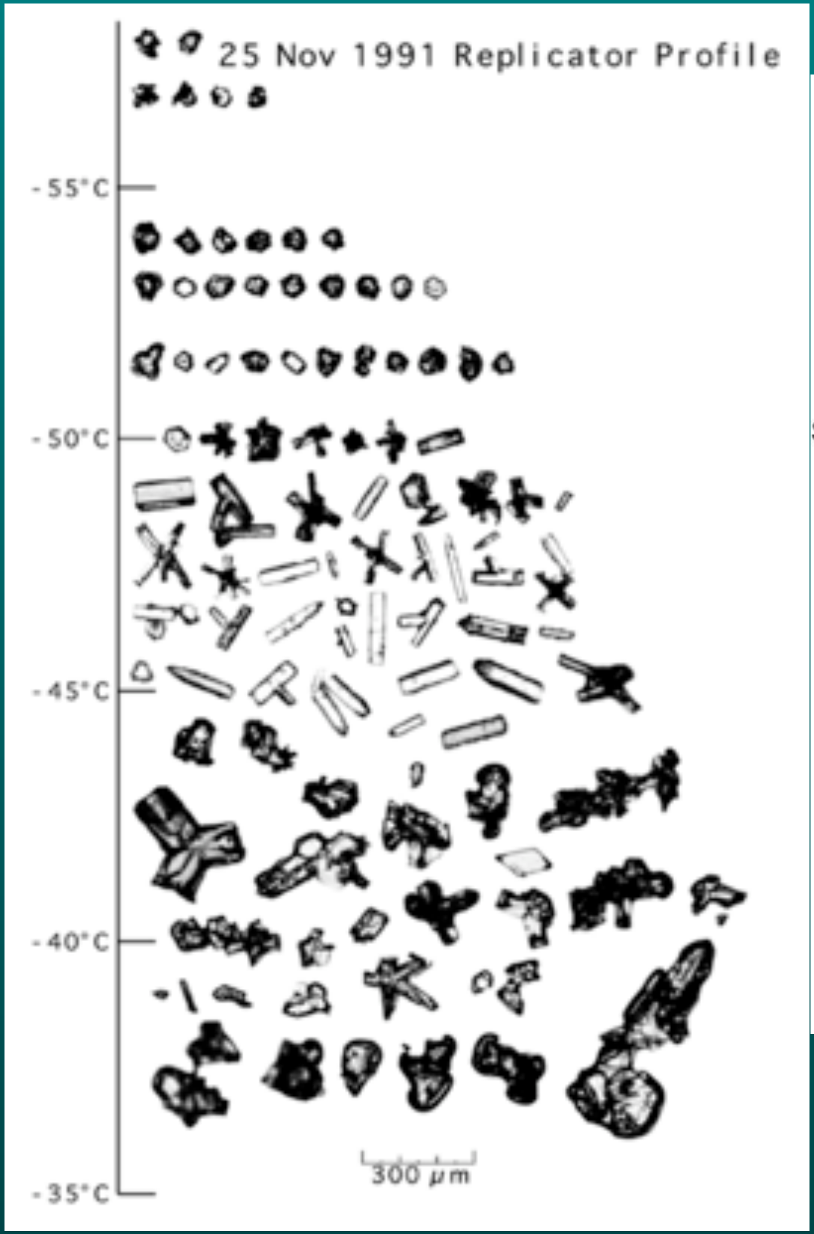
- Pre-AVE: Pre-Aura Validation Experiment (2004)
- ACTIVE/SCOUT/TWP-ICE: Tropical Western Pacific International Cloud Experiment (2005-2006)
- MidCiX (Middle Latitude Cirrus Experiment), 2004
- NASA TC-4: Tropical Composition, Cloud and Climate Coupling (2007)
- ICE-L: Ice in Clouds Experiment – ice cloud nucleation measurements (2007)

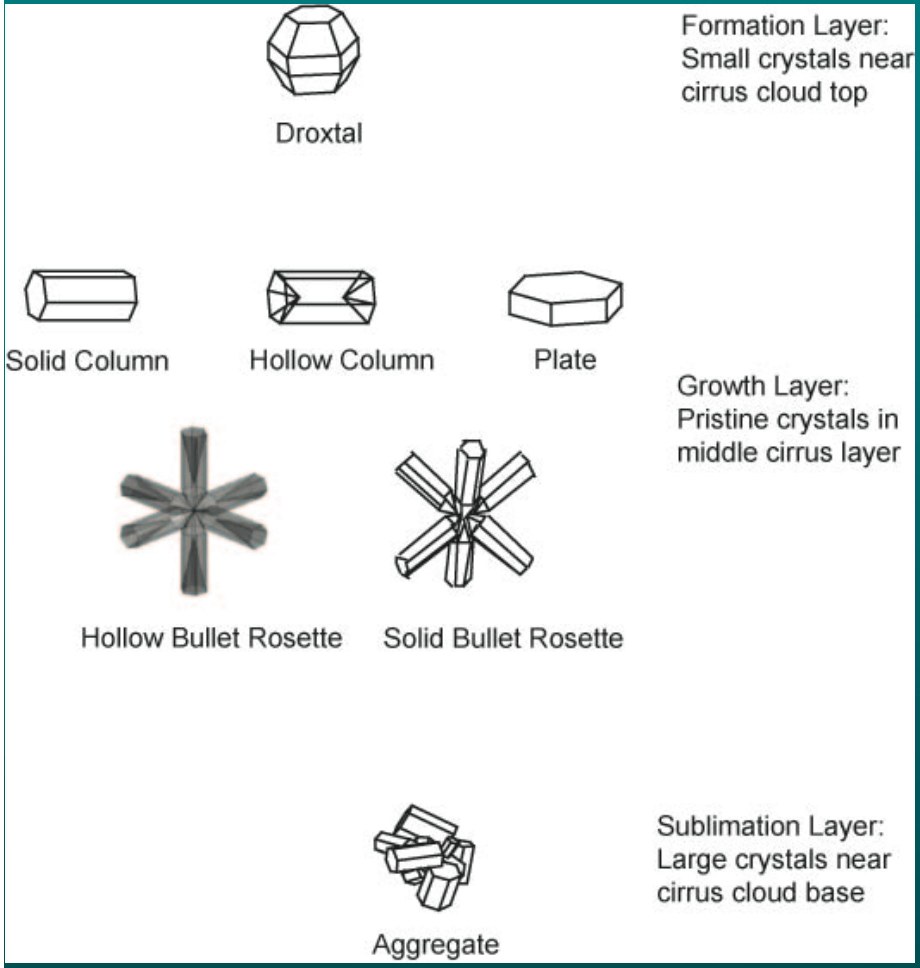
Next generation of ice models will incorporate

- 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
- more guidance on ice habits and their characteristics
- more guidance on realistic habit mixtures

Replicator Particle Habits

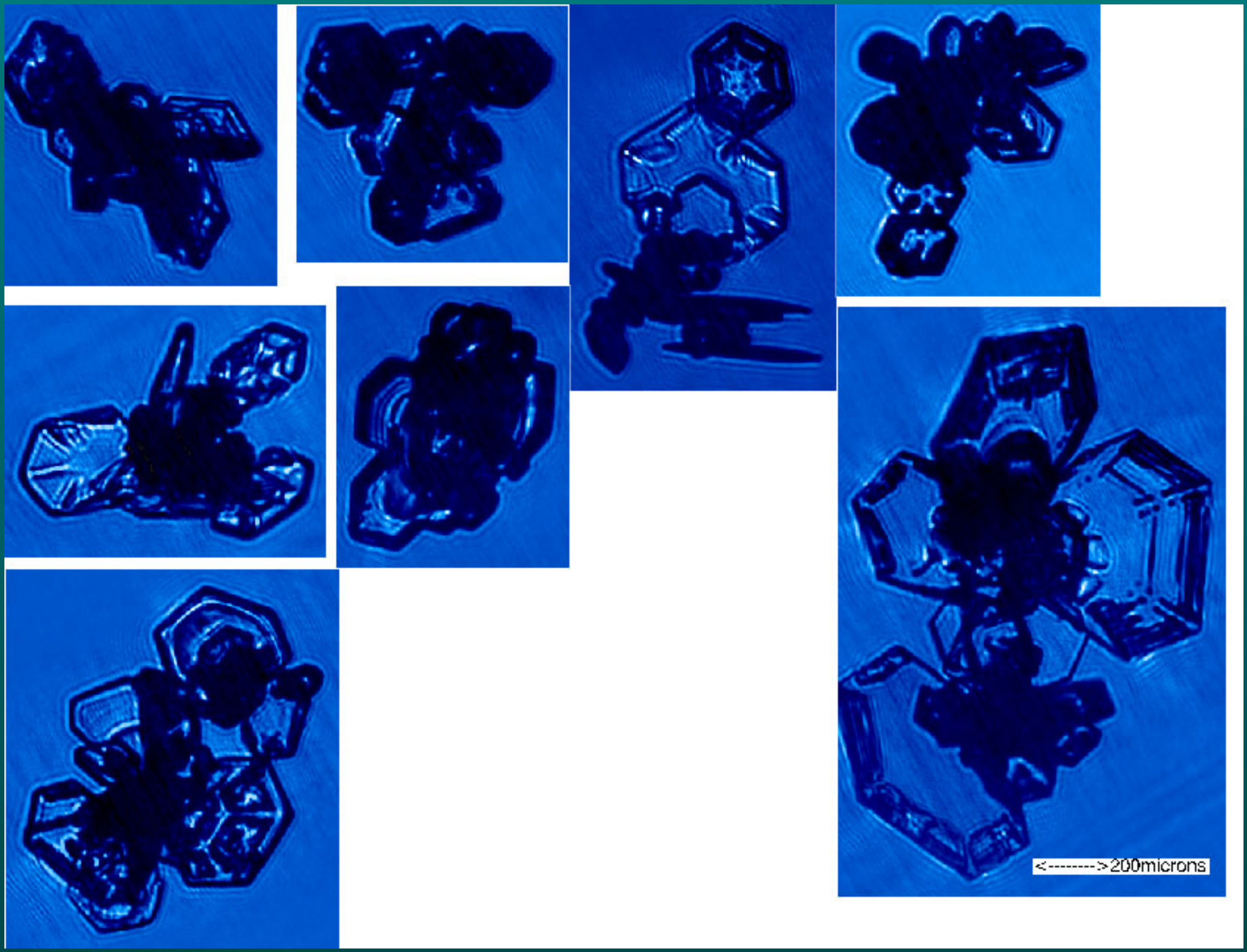
Simulated Particle Habits





Yang, P. et al. 2008: Effect of cavities on the optical properties of bullet rosettes: Implications for active and passive remove sensing of ice cloud properties. J. Appl. Meteor. Clim. 47, 2311-2330.

New Aggregate Under Development:
Plates rather than Columns



Library of IR Single Scattering Properties

100 to 3250 cm^{-1}

Current library of ice particle habits currently includes

- Solid hexagonal plates
- Solid and hollow columns
- Aggregates composed of solid columns
- Droxtals
- 3D solid bullet rosettes

45 size bins ranging from 2 to 9500 μm

Spectral range: 100 to 3250 cm^{-1} at 1 cm^{-1} resolution

Properties for each habit/size bin include volume, projected area, maximum dimension, single-scattering albedo, asymmetry factor, and extinction efficiency

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

Chosen ice particle habit mixture

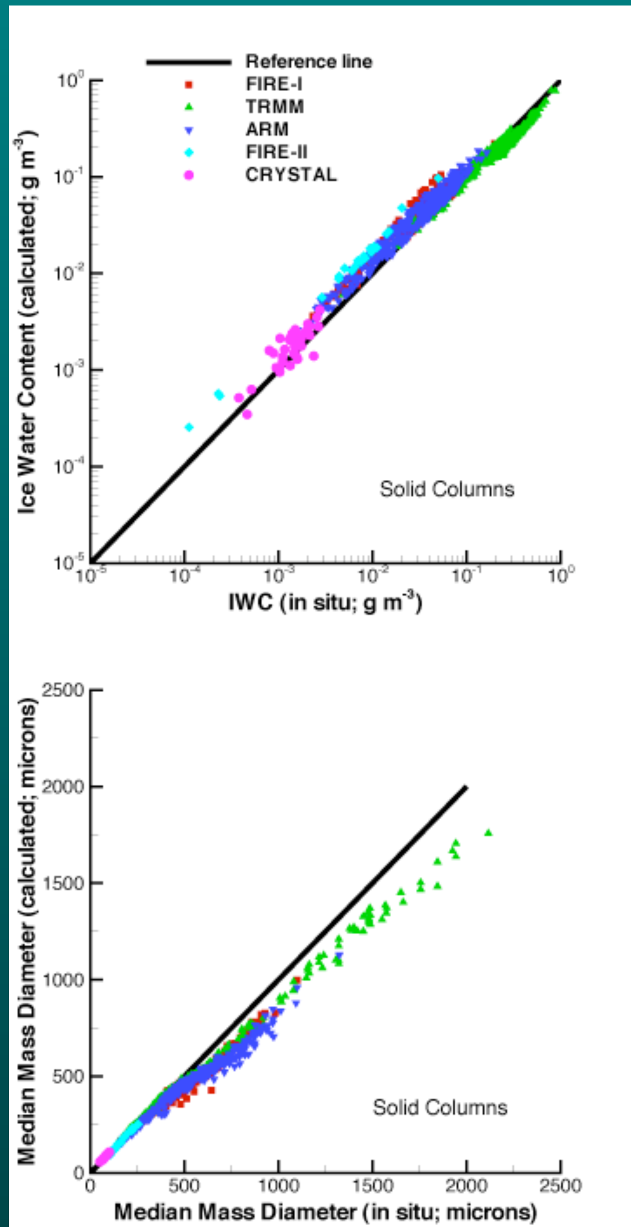
Max length < 60 μm
100% droxtals

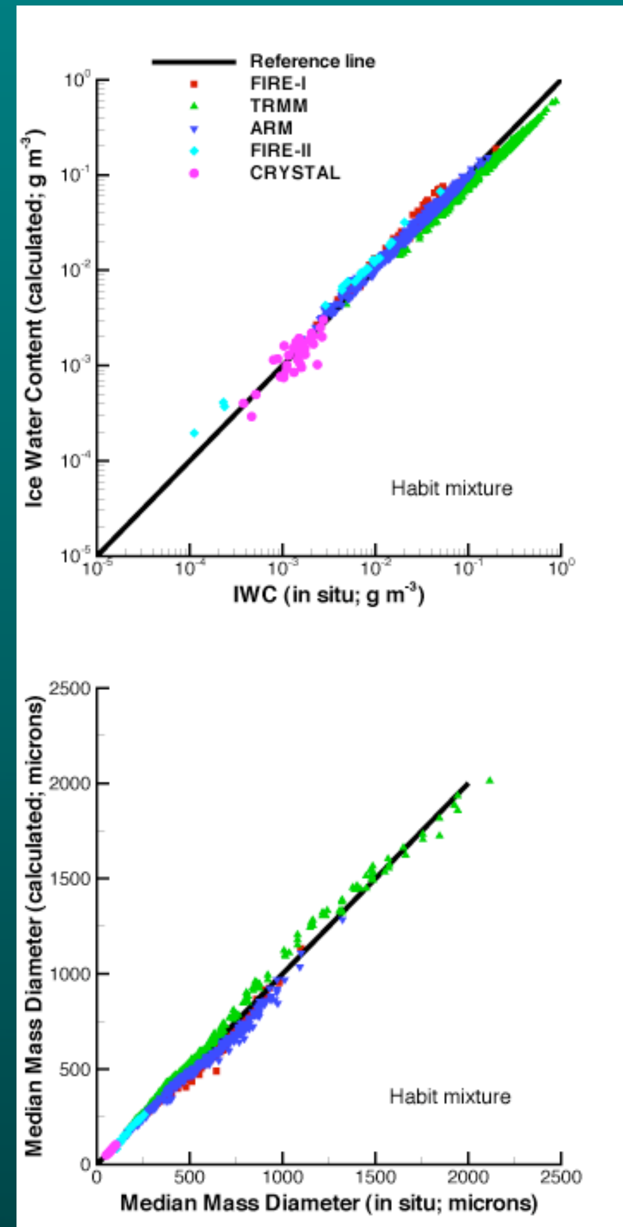
60 μm < Max length < 1000 μm
15% bullet rosettes
35% hexagonal plates
50% solid columns

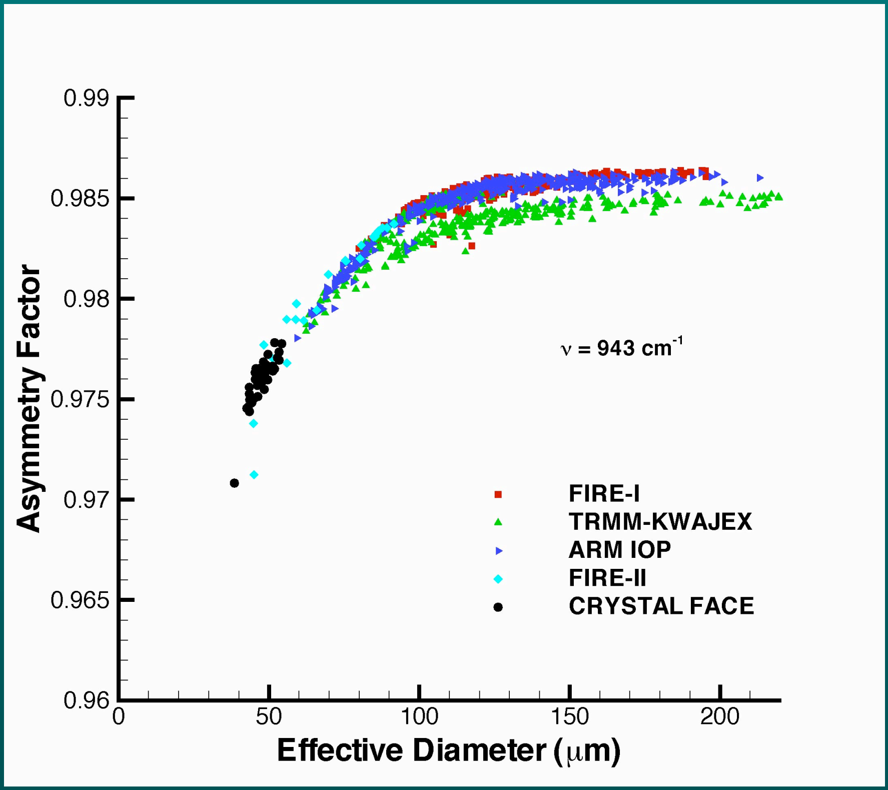
1000 μm < Max length < 2500 μm
45% solid columns
45% hollow columns
10% aggregates

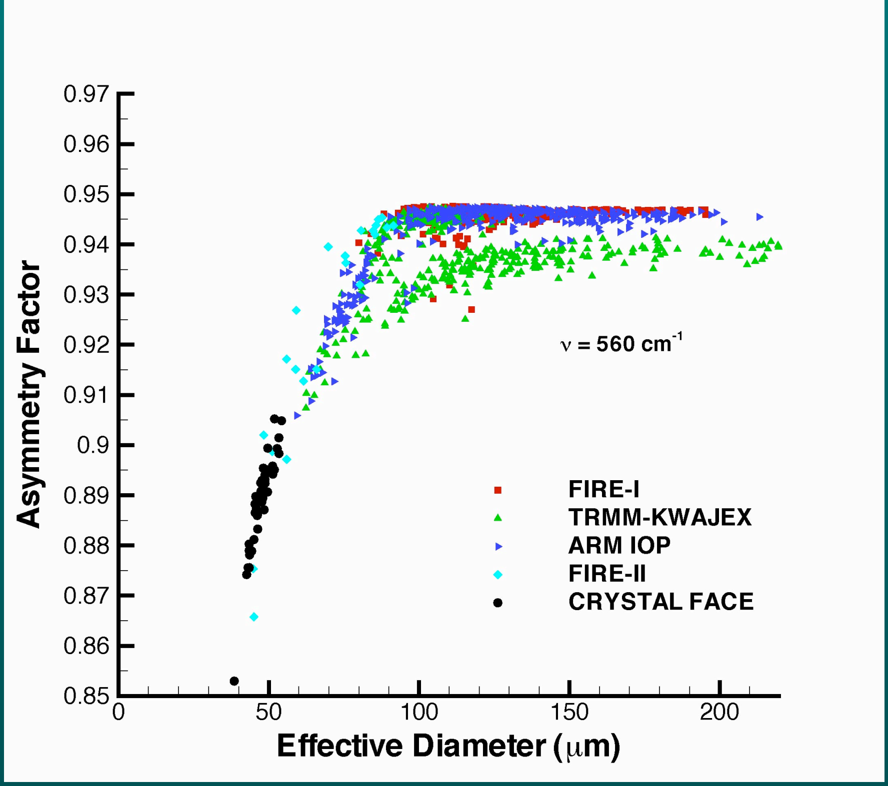
Max length > 2500 μm
97% bullet rosettes
3% aggregates

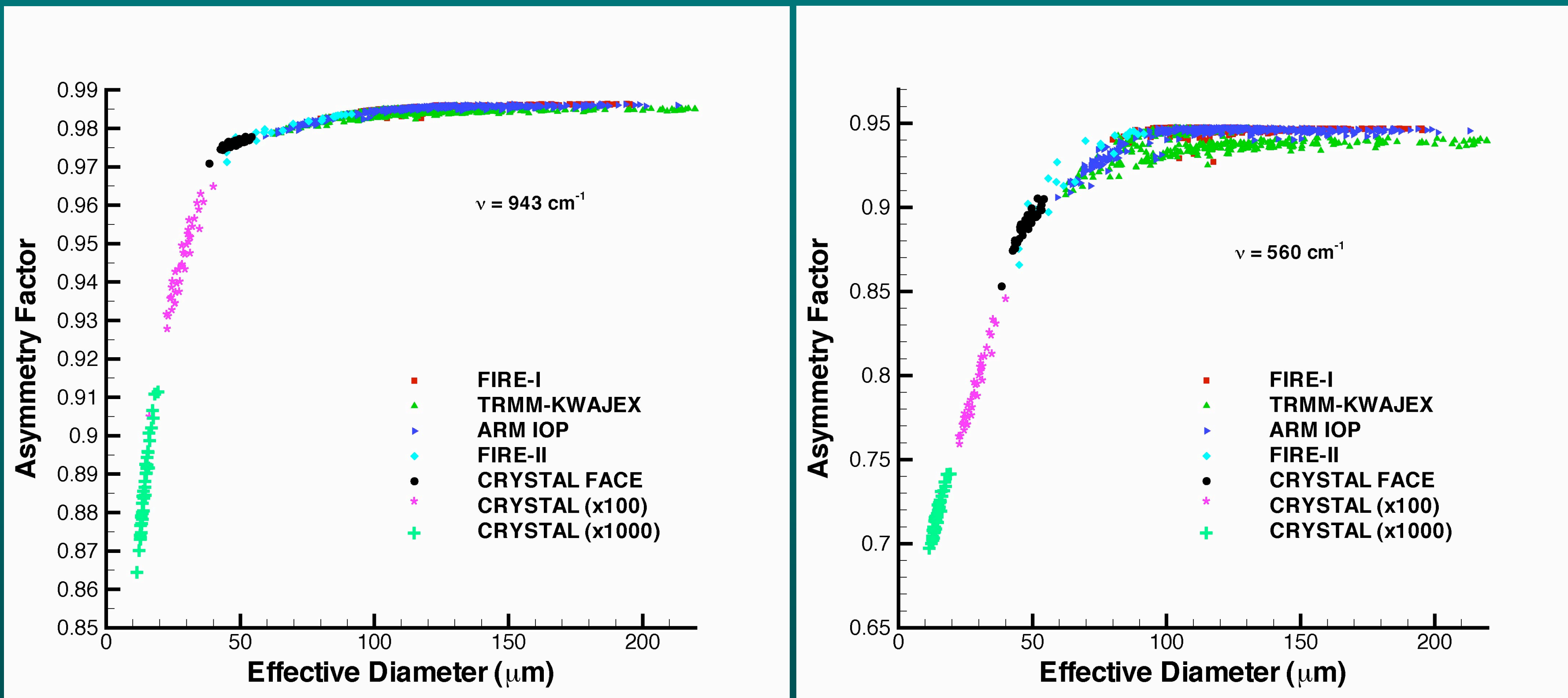
Measured vs. Simulated Ice Water Content and Median Mass Diameter



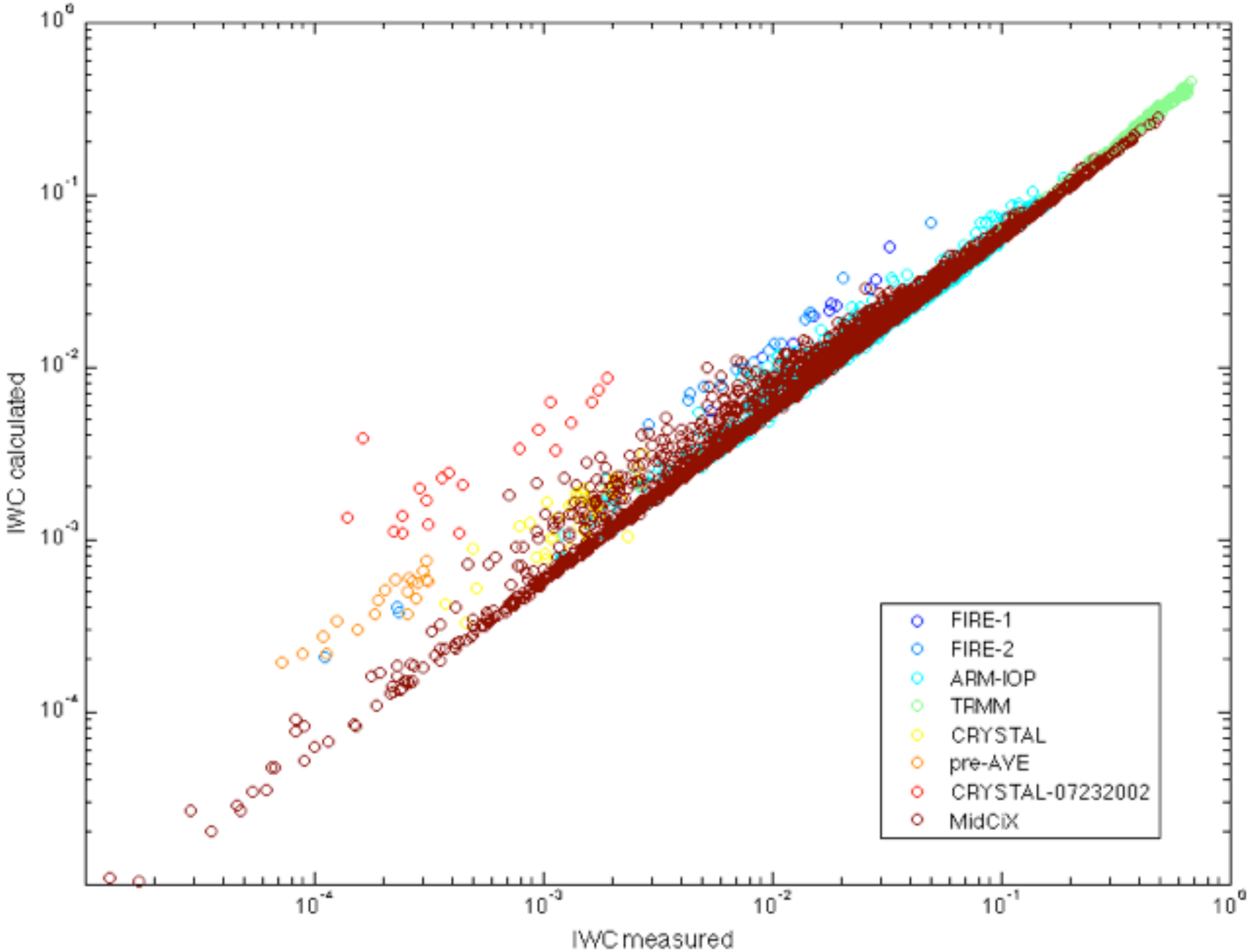



0.99
0.985
0.98
0.975
0.97
0.965
0.96
Asymmetry Factor
0
50
100
150
200
Effective Diameter (μm)
ν = 943 cm-1
FIRE-I
TRMM-KWAJEX
ARM IOP
FIRE-II
CRYSTAL FACE


0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.9
0.89
0.88
0.87
0.86
0.85
Asymmetry Factor
0
50
100
150
200
Effective Diameter (μm)
ν = 560 cm-1
FIRE-I
TRMM-KWAJEX
ARM IOP
FIRE-II
CRYSTAL FACE



ν = 943 cm-1
Asymmetry Factor
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.9
0.89
0.88
0.87
0.86
0.85
0
50
100
150
200
Effective Diameter (μm)
FIRE-I
TRMM-KWAJEX
ARM IOP
FIRE-II
CRYSTAL FACE
CRYSTAL (x100)
CRYSTAL (x1000)
ν = 560 cm-1
Asymmetry Factor
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0
50
100
150
200
Effective Diameter (μm)
FIRE-I
TRMM-KWAJEX
ARM IOP
FIRE-II
CRYSTAL FACE
CRYSTAL (x100)
CRYSTAL (x1000)



IWC calculated
IWC measured
10^0
10^-1
10^-2
10^-3
10^-4
FIRE-1
FIRE-2
ARM-IOP
TRMM
CRYSTAL
pre-AVE
CRYSTAL-07232002
MidCiX

Improvements Being Incorporated in New Scattering Models

For entire spectrum (UV to Far-IR):

Use updated optical constants of ice (Warren and Brandt, JGR, 2008)

Include hollow bullet rosettes (aggregate of plates eventually)

Improvements to scattering models

More resolution with respect to particle size

Specific to solar models:

- databases being developed for both smooth and roughened particles
- will include full phase matrix
- delta transmission included in phase function; no longer a separate parameter

Bulk Optical Models Available for Multiple Sensors

Provide microphysical and single scattering properties (mean and std. dev.) at D_{eff} from 30 μm to 180 μm for

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

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

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)

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

In Summary...

Intercomparison of ice cloud retrievals from A-Train sensors has raised some issues regarding differences between inferred cloud parameters

Resolution of these issues requires further refinement to existing bulk ice scattering models

New models will incorporate wealth of new ice cloud microphysical data, with 2D-C data reprocessed to remove (or at least mitigate) contribution of shattered ice particles

New scattering models will incorporate improvements in RT models, provide full phase matrix (solar bands), include hollow bullet rosette, and more

The new models, once built, will need thorough testing by a number of different communities