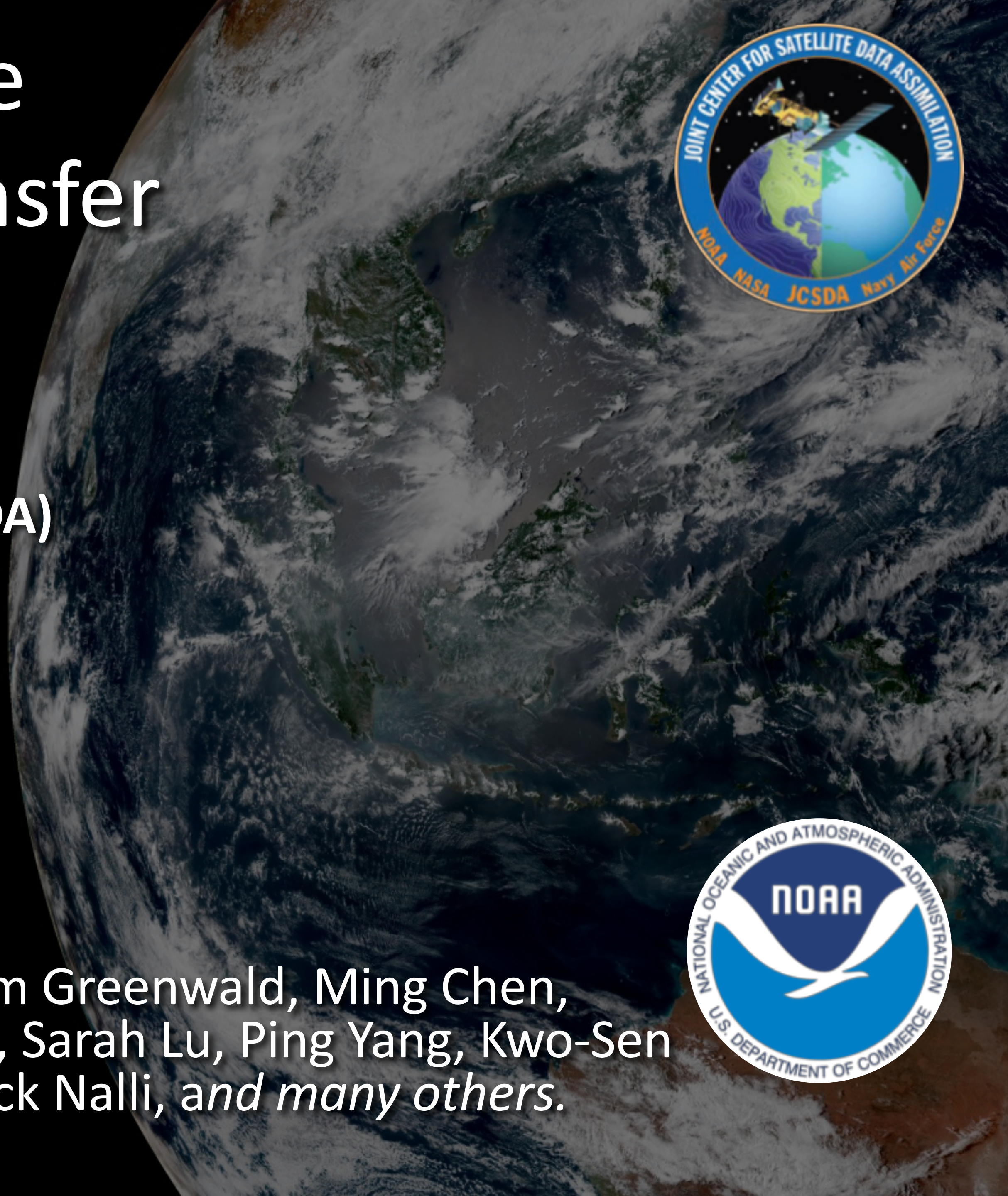
Recent Advances in the Community Radiative Transfer Model (CRTM)



CRTM Team:

Benjamin T. Johnson (Project Lead, UCAR/JCSDA)

Patrick Stegmann (UCAR / JCSDA)

Jim Rosinski (UCAR/JCSDA)

Cheng Dang (UCAR/JCSDA)

Thomas Auligné (Director, JCSDA)

With essential contributions from: Emily Liu, Tom Greenwald, Ming Chen, Barbara Scherllin-Pirscher, Quanhua ”Mark” Liu, Sarah Lu, Ping Yang, Kwo-Sen Kuo, Will McCarty, Isaac Moradi, Yanqiu Zhu, Nick Nalli, a*nd many others.*

What is the CRTM?

CRTM is the "Community Radiative Transfer Model"

Goal: Fast and accurate community radiative transfer model to enable assimilation of satellite radiances under all weather conditions, covering UV, VIS, Near-IR, IR, FarIR, subMM, MW

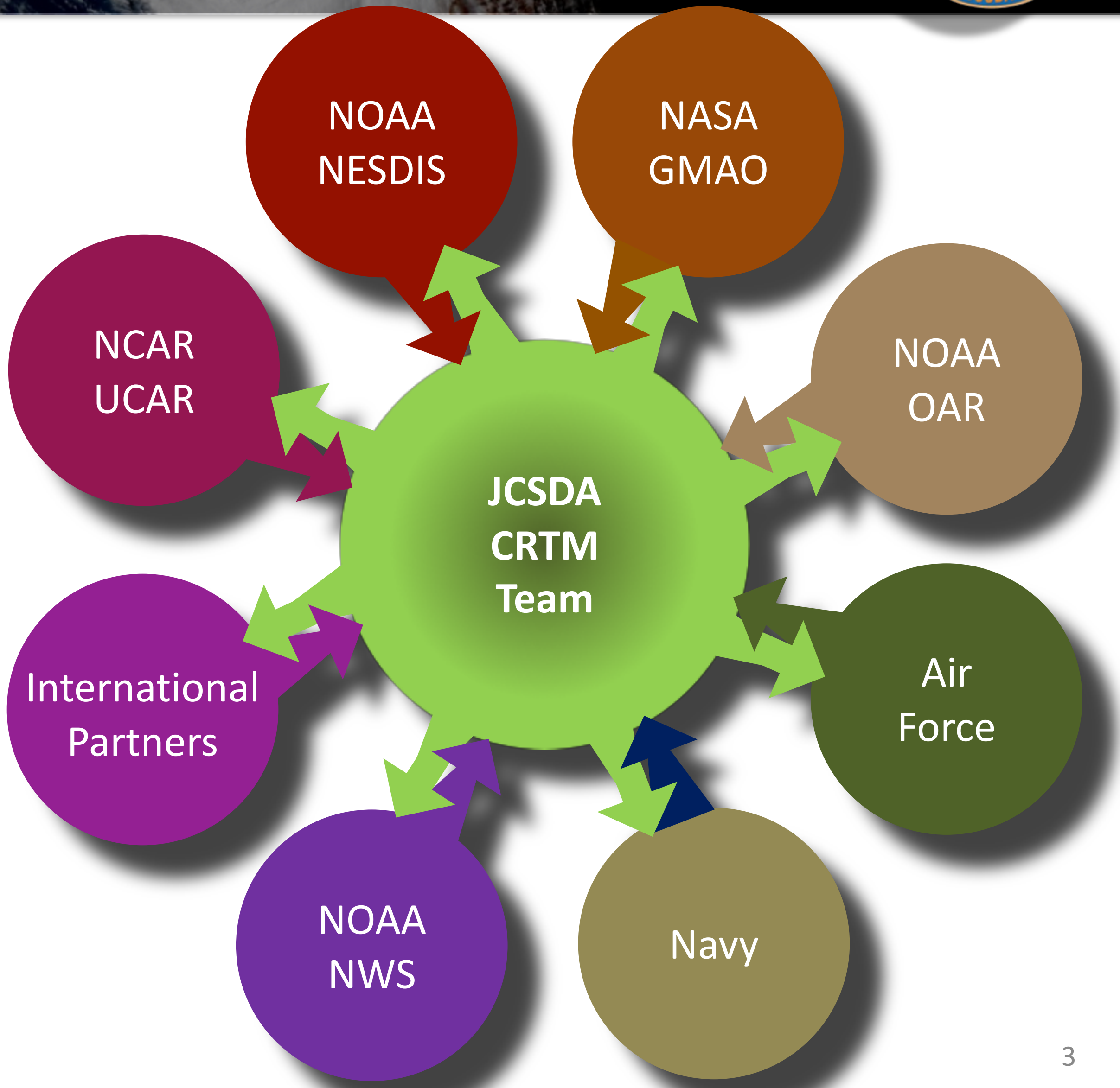
Type: 1-D, plane-parallel, multi-stream matrix operator method, advanced method of moments solver, with specular and non-specular surface reflections.

Has aerosol (GO-CART), cloud (2 species), precipitation (4 species); with unpolarized scattering and absorption (in 2.x). Computes gaseous absorption/emission for 6 gaseous species (ODPS).

History: Originally developed (as CRTM) around 2004 by Paul van Delst, Yong Han, Fuzhong Weng, Quanhua Liu, Thomas J. Kleespies, Larry M. McMillin, and many others. CRTM Combines many previously developed models into a community framework, and supports forward, tangent linear, adjoint, and k-matrix modeling of emitted/reflected radiances, with code legacy going back to the mid 1970s (e.g., OPTRAN: McMillin).

CRTM: A Community Model

- **CRTM is a Community Model**
  - Open Source and Open Access
  - Version Control (git) and peer review
  - Distributed Collaboration (GitHub, Zenhub, Confluence, Google)
  - Modern Fortran (2003+)
- **Education and Outreach**
  - CRTM User/Developer Workshop
    - Feb 28, 2020 Monterey, CA (*slots still available*)
  - JCSDA Summer Colloquium
  - Code Sprints
    - CRTM-Coef Jan 21 – 31 2020, College Park
    - CRTM-Surf March 2020, Boulder
  - Seminars / Colloquia
  - JCSDA.org website



Active Areas of Research and Development

Version 3.0.0 progress
Transmittance Coefficient Generation (CRTM-COEF)
CRTM Scattering Indicator, code optimization and solver testing
Community Hydrometeor Model (CHYM)
Community Active Sensor Module (CASM)
Community Surface Emissivity Model (CSEM)
JCSDA coordination (JEDI, NIO, SOCA) and collaboration (RTTOV)

CRTM 3.0 Goals and Work Plans

- **Cloudy Radiance** (P. Stegmann, E. Liu, Johnson)
  - ■ Backscattering coefficients for CRTM active sensor capability.
  - ■ Produce (Polarized) CRTM Scattering Coefficients from BHMIE and T-Matrix spheroids in binary and NetCDF
  - ■ Start systematic investigation of "optimal" single-scattering properties for CRTM applications
- **Surface** (M. Chen, Y. Zhu)
  - ■ Test CRTM-CSEM in GFS/GSI, focusing on the comparisons among model options.
  - ■ Analyze and document the tests of CRTM-CSEM in GFS/GSI.
  - ■ Initial implementation of MW ocean surface BRDF model.
  - ■ Ocean Surface Emissivity improvements IR (N. Nalli)
- **Full Polarization Solver Capability** (T. Greenwald, Q. Liu, B. Johnson, C. Cao)
  - ■ UV capable solver + polarization support under evaluation
  - ■ Need to touch each element of CRTM to support full polarization capabilities across all sensors
- **SW / IR improvements in CRTM**
  - ■ New hire starting January 27, 2020
- **Aerosols update** (Johnson, Stegmann, S. Lu, M. Pagowski, B. Scherllin-Pirscher, Oyola/Ruston, others).
  - ■ Update of CHYM to work with aerosol tables (Johnson, Stegmann)
  - ■ Improved aerosol indices of refraction (via D. Turner, J. Gasteiger, Stegmann)
  - ■ Update toward CMAQ specifications (Team)
  - ■ Improve Lidar backscattering and attenuation calculations (Pagowski, Scherllin-Pirscher)

CRTM 3.0 Alpha

- **Status of CRTM 3.0 Alpha**
  - Modification of CRTM 2.3.1-beta to include full polarization support, and UV support (provided by Q. Liu)
  - **Status**: Core solver work for initial implementation is completed for full stokes polarization.
    - Paper: Liu, Q. and Cao, C., 2019. *Analytic expressions of the Transmission, Reflection, and source function for the community radiative transfer model*. Journal of Quantitative Spectroscopy and Radiative Transfer, 226, pp.115-126.
  - **Numerically consistent** with CRTM 2.3.1-beta for n_stokes = 1
  - **Requires significant effort** (CRTM 3.0 Beta) toward updating and testing the science modules to support polarized RT: such as clouds, aerosols, gases, and surface properties.
  - **UV support for OMPS**: “u.omps-tc_npp”

CRTM 3.0 Alpha

Comparison of different polarized solvers:
DA = RT3, Doubling-Adding method (Evans, 1991)
VLIDORT = Linearized Vector discrete ordinate RTM (Spurr, 2005)
ADA = Adding-Doubling solver (CRTM 1.x)
AMOM = Advanced matrix operator method (CRTM 2.x)

Table 10
Comparison of CPU time usage between VLIDORT and AMOM. Phase function for an atmosphere of randomly oriented oblate spheroids and 16 streams are used. The solar flux is normalized to π, the solar zenith angle is 36.8699 (the cosine of the solar zenith angle is 0.8), and the surface albedo is 0.25. Single scattering albedo is 1.0. VLIDORT requires the single scattering is less than 1.0 and we use the single scattering albedo of 0.99999. The upwelling radiance is for a viewing (zenith) angle of 50.21°.

Layer optical depth	VLIDORT (seconds)	AMOM (seconds)
100	0.096	0.076
10	0.096	0.063
1	0.096	0.054
0.1	0.095	0.048

Table 4a
Pure Rayleigh atmosphere of optical depth of 0.1 using 4 streams

	I	Q	U	V
DA	0.215409	−0.000316	−0.020898	0.0
VLIDORT	0.215409	−0.000316	−0.020898	0.0
ADA	0.215409	−0.000316	−0.020897	0.0
AMOM	0.215409	−0.000316	−0.020897	0.0

Table 4b
Same as Table 4a, but using 16 streams.

	I	Q	U	V
DA	0.216527	−0.000214	−0.021456	0.0
VLIDORT	0.216526	−0.000214	−0.021456	0.0
ADA	0.216526	−0.000214	−0.021455	0.0
AMOM	0.216526	−0.000214	−0.021455	0.0

Table 5a
Same as Table 4a, but for an optical depth of 1.

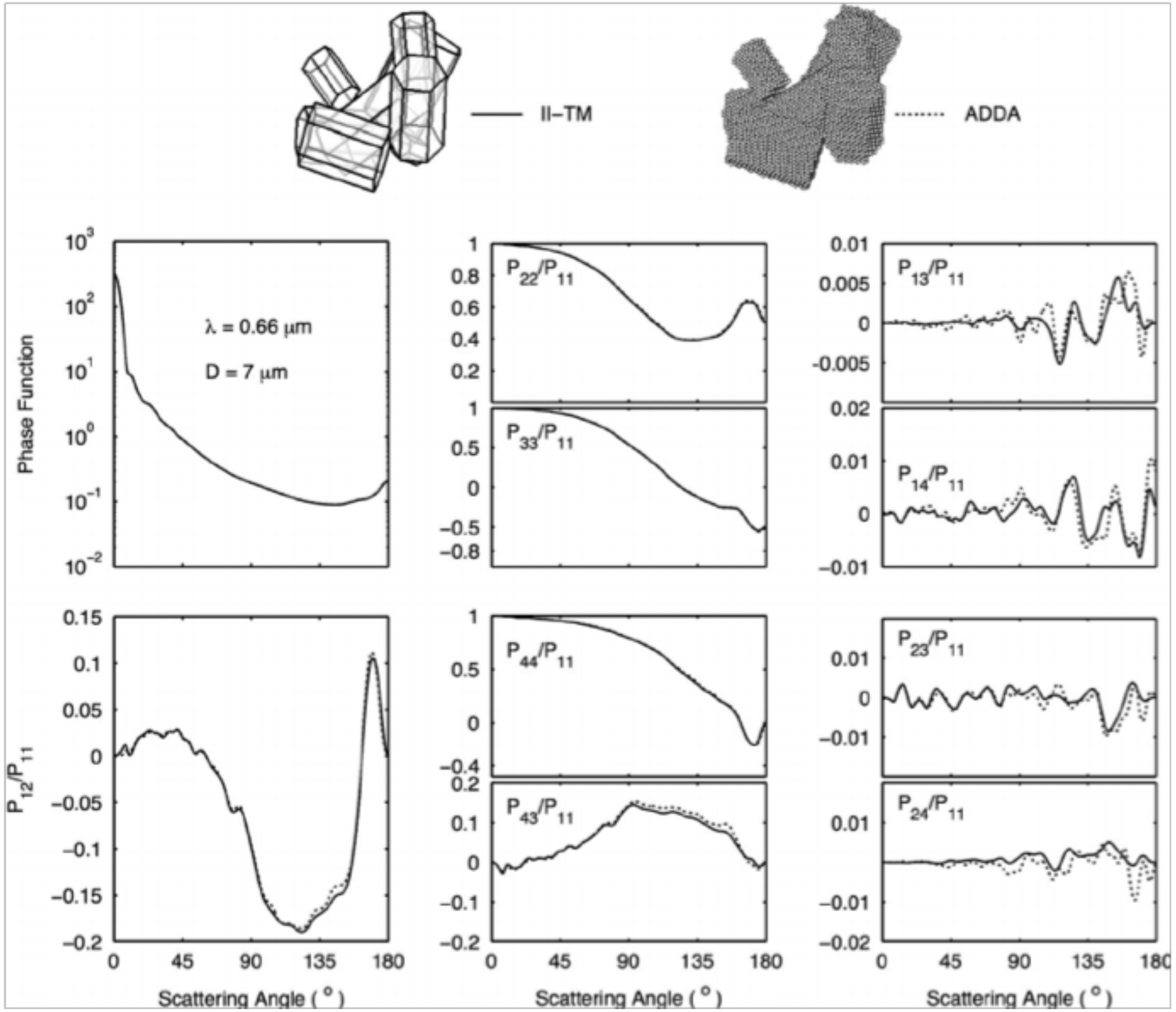
	I	Q	U	V
DA	0.374199	0.008465	−0.124870	0.0
VLIDORT	0.374189	0.008464	−0.124868	0.0
ADA	0.374197	0.008467	−0.124864	0.0
AMOM	0.374196	0.008467	−0.124864	0.0

Liu, Q. and Cao, C., 2019. *Analytic expressions of the Transmission, Reflection, and source function for the community radiative transfer model*. Journal of Quantitative Spectroscopy and Radiative Transfer, 226, pp.115-126.

CRTM 3.0 Beta Focus

Cloud-impacted radiance and physical model simulation improvements (UV, VIS, IR, MW)

- Community Hydrometeor Model (CHYM)
  - Development continuing, and creating new polarized MW, IR, and VIS integrated cloud and aerosol scattering tables that are more closely linked with model assumed microphysical properties.
  - Initial netCDF transition and conversion.
  - Updating Space-based radar support with linear polarization capabilities
- *Current focus is on tool development e.g.:*
  - https://github.com/PStegmann/INSPECT_CloudCoeff
  - https://github.com/JCSDA/CRTM_coef
- **Community Surface Emissivity Model** (Ming Chen)
  - Need extend CSEM capabilities to support fully polarized surface BRDFs for ocean and land



CRTM 3.0 Beta Cont.

Community feedback request:

(1) Clouds, Precipitation, and Aerosol single-particle physical and radiative properties including polarization and backscattering properties UV – subMM

(2) Surface radiative properties: dielectric constants, emissivities, polarized BRDFs, ocean physical models, etc.

(3) Instrument spectral response functions and antenna pattern corrections:

If you have an SRF/APC for any operational or research instrument, please send me an email to ensure that we're using the latest version.

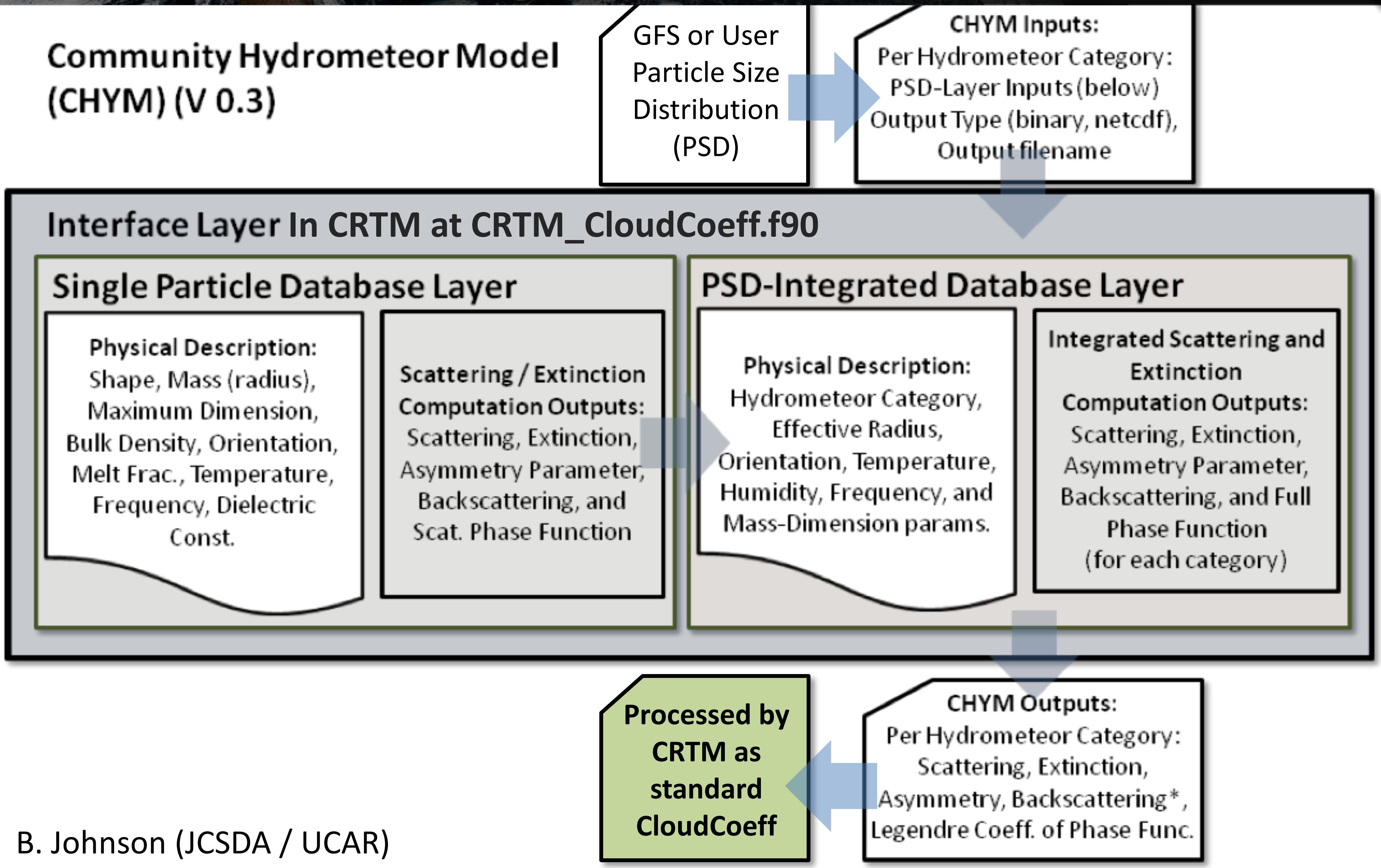
(4) Continuum absorption / emission updates beyond what's available in MT_CKD / LBLRTM

(5) NLTE corrections

(6) AI-based approaches to speeding up elements of RT.

Community Hydrometeor Model (CHYM)

Community Hydrometeor Model (CHYM) (V 0.3)

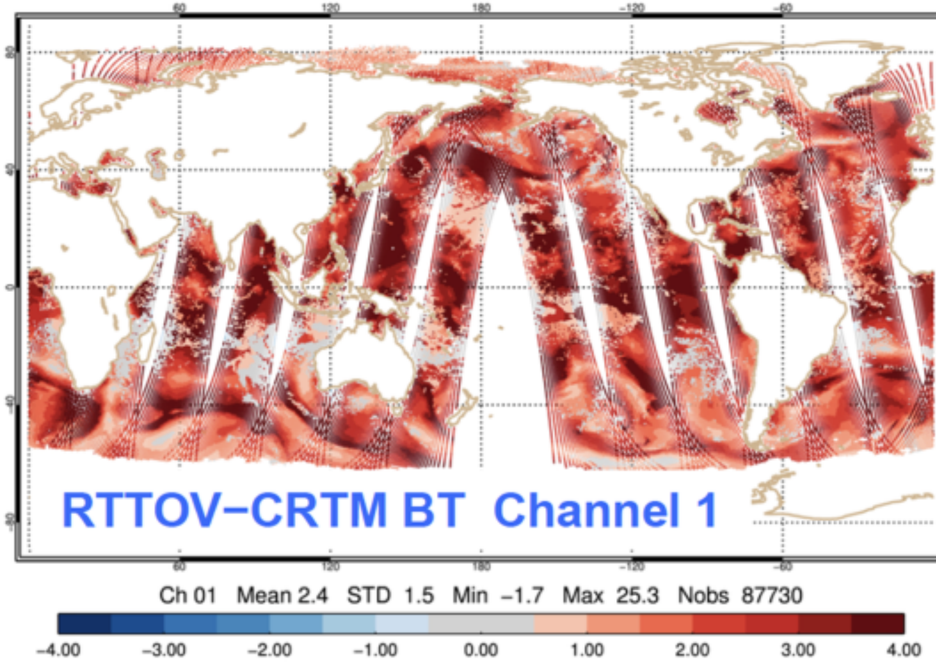


B. Johnson (JCSDA / UCAR)

Community Hydrometeor Model CHYM

- (1) **Development of the microphysical parameters of clouds and precipitation** (Lead: Emily Liu)
  - Relate to the current and planned GFS microphysical assumptions.
  - converting mixing ratios into particle size distributions (PSD) and habit distributions, consistent with the microphysics schemes
- (2) **Creating the PSD-integrated scattering properties** (Lead: Patrick Stegmann).
  - Extend and replace current CloudCoeff.bin lookup table, consistency with above microphysics
- (3) New: Addition of Aerosols to CHYM (similar to Clouds/ Precip. in structure) (Lead: Cheng Dang, UCAR)

Evaluate CRTM under Scattering Condition — Enhancement

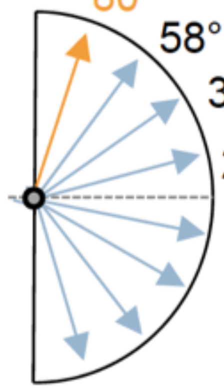


- It is found that the off-diagonal terms of the surface reflectivity matrix is zero so that there is no diffuse radiation being reflected towards the viewing direction
- A proper surface emissivity model to work with multiple scattering algorithm is necessary
- For non-scattering RT, a reflection correction is used to account for the diffuse radiation.

[Implemented by Ming Chen]

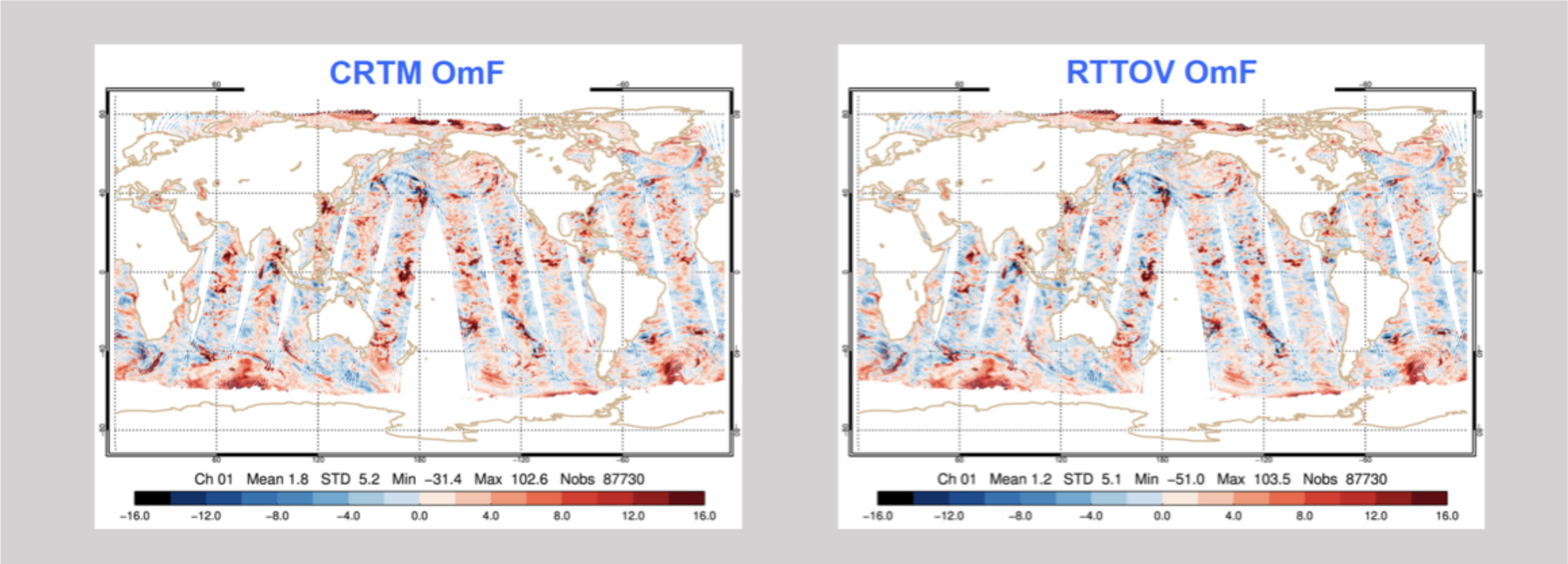
The **work-around** to reduce the biases:

- Reflection correction is included in conjunction with ADA solver and the correction is only applied to stream angles ≤ 60°
- Stream angles > 60° are taken as 60° when ADA is on.
- The bi-directional reflectance distribution function (BRDF) for MW will be developed to replace the work-around.



(Slide courtesy of Emily Liu)

Evaluate CRTM under Scattering Condition Validation w/ RTTOV



The resulting CRTM BTs with the work-around are comparable to RTTOV BTs for all channels in AMSU-A

Slide courtesy of Emily Liu

Ice Crystal Model

User Input

- Size Distribution $n(D)$
- Characteristic Diameter D_e
- Mass-Dimension Relationship $m(D) = aD^b$
- Ice Water Content $w_x = \rho_a q_x$
- Number Concentration N_t

Single Ice Crystal Microphysical and Optical Properties Data Base

- Size Distribution
- Habit Distribution
- Convolve each single particle optical property with the size and habit distribution to obtain distribution mean (bulk) ice particle optical property
- Parameterize distribution mean (bulk) ice particle optical properties as a function of characteristic diameter:

$$k_{ext}(D_e,\nu),\ k_{sca}(D_e,\nu),\ \omega_o,\ g(D_e,\nu),\ P(\Theta,D_e,\nu)$$

- Distribution Mean (Bulk) Ice Particle Optical Properties
- Ice Water Content

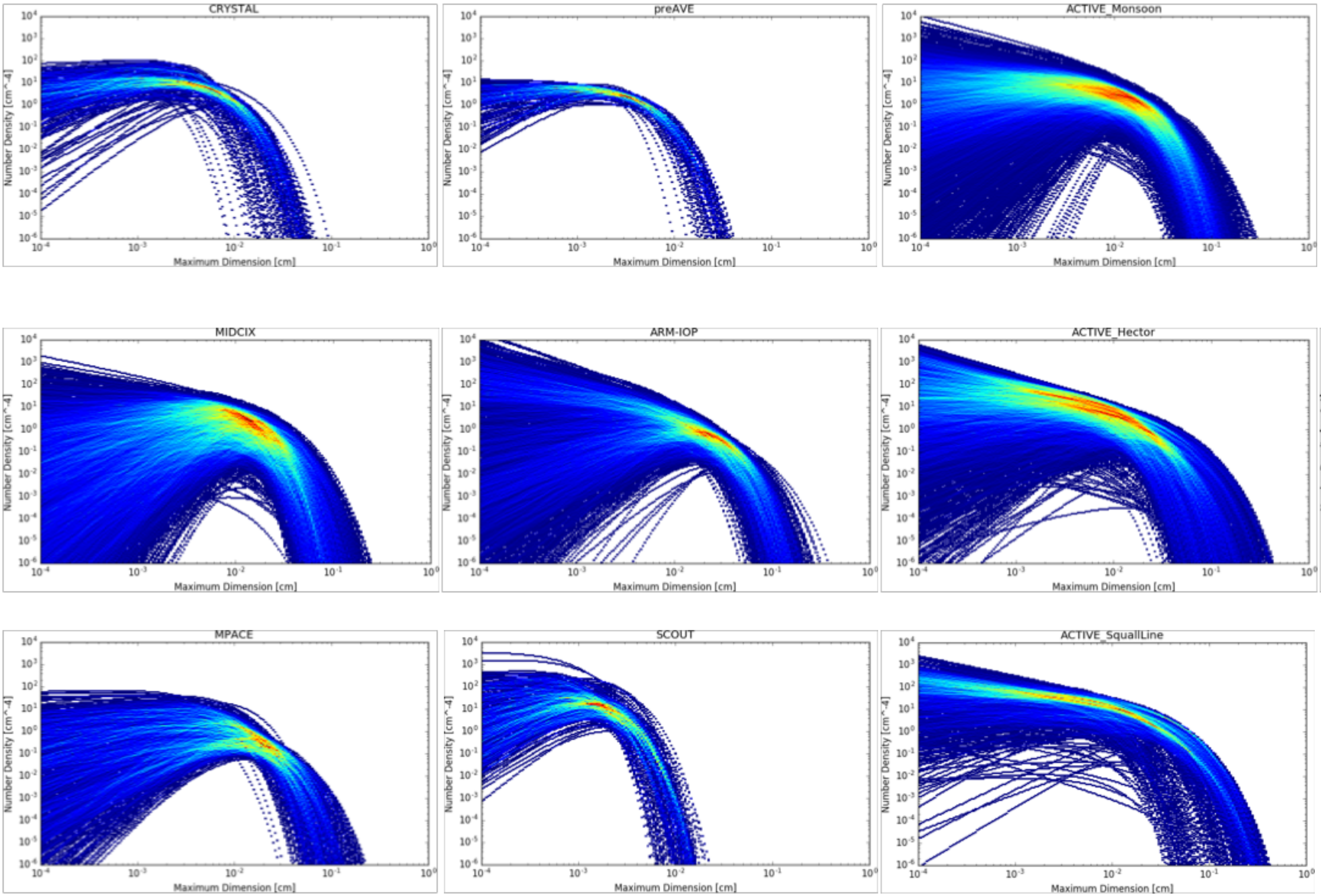
- Is the output IWC approximately equal to the input ?
- There is no doubt that mixture of habit is more realistic, but are we using the habit distribution which best represents the nature ?
- Should we parameterize the cloud optical properties using the same ice crystal database and model for the radiation model used in GFS for consistency ?

Field Campaign information

Field Campaign	Year	Location	Instruments	# PSDs
ARM-IOP	2000	Oklahoma, USA 2000	2D-C, 2D-P, CPI, CVI, FSSP	1420
TRMM-KWAJEX	1999	Kwajalein, Marshall Islands 1999	2D-C, HVPS, FSSP	201
CRYSTAL-FACE	2004	SE Florida/Caribbean 2002	CAPS (CIP, CAS), VIPS	62
SCOUT	2005	Darwin, Australia 2005	FSSP, CIP	553
ACTIVE – Monsoons	2005	Darwin, Australia 2005	CAPS (CIP, CAS)	4268
ACTIVE- Squall Lines	2005	Darwin, Australia 2005	CAPS (CIP, CAS)	740
ACTIVE-	2005	Darwin, Australia 2005	CAPS (CIP, CAS)	2583
MidCiX	2004	Oklahoma, USA 2004	CAPS (CIP, CAS), VIPS, FSSP	2968
Pre-AVE	2004	Houston,Texas, USA 2004	VIPS, CAPS	99
MPACE	2004	Alaska	2D-C	671
TC-4	2006	Costa Rica	CAPS, RIP	877

Credit: Brian Baum’s website: http://www.ssec.wisc.edu/ice_models/microphysical_data.html

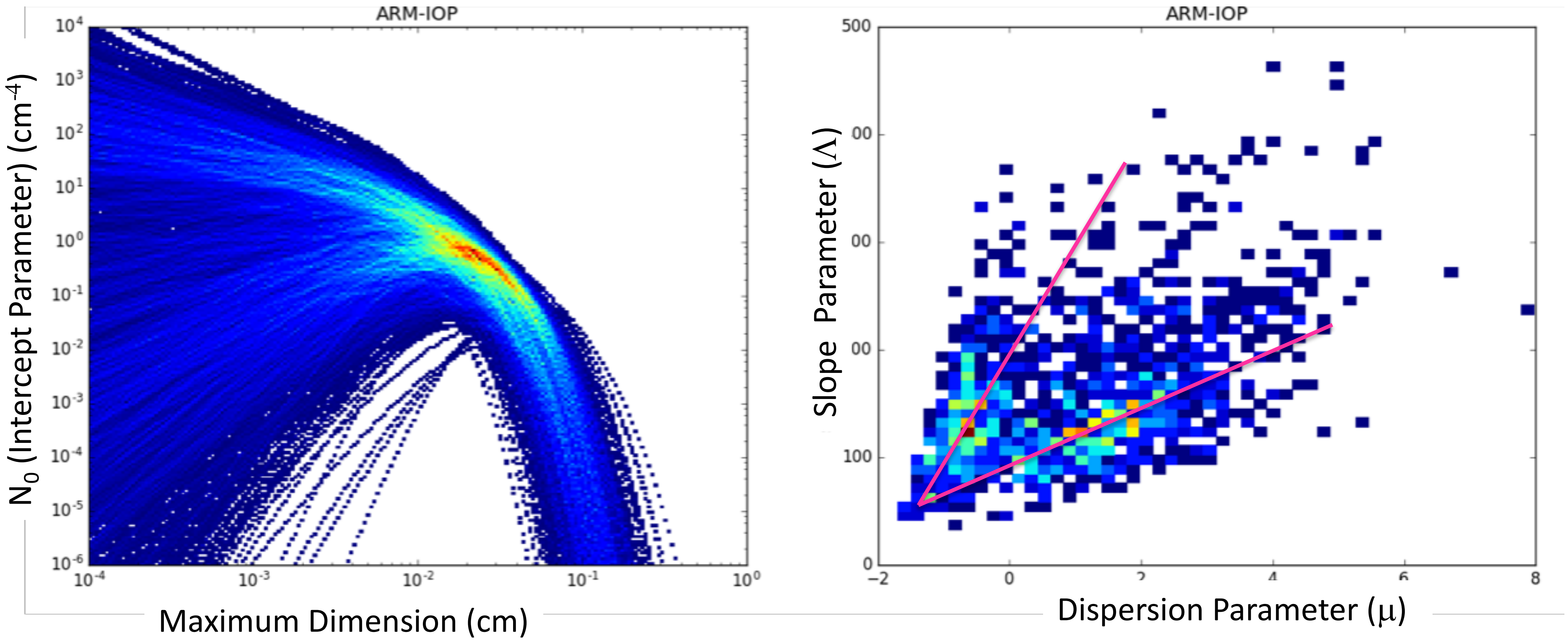
Observed Ice Particle Size Distributions



PSDs plotted using data downloaded from Brian Baum's website:
http://www.ssec.wisc.edu/ice_models/microphysical_data.htm

Cloud Physical Modeling (in CHYM)

Example: ARM Intensive Observation Program



3-parameter Gamma Distribution Function

General Gamma Function $n(D) = N_o\, D^{\mu}\, e^{-\lambda D^{\gamma}}$

3-parameter Gamma Function:

$n(D) = \mathbf{N_o}\, D^{\boldsymbol{\mu}}\, e^{-\boldsymbol{\lambda} D}$ where $\gamma = 1$; λ is the slope, μ is the dispersion, and N_o is the intercept when $\mu = 0$
D is maximum dimension

Some Useful Expressions related to Gamma Function

$$M_k = \int_0^{\infty} D^k\, n(D)\, dD = N_o \int_0^{\infty} D^{k+\mu}\, e^{-\lambda D}\, dD = N_o\, \Gamma(\mu + k + 1)\, \lambda^{-(\mu+k+1)} \;\; where\;\; \Gamma(x) = (x-1)!$$

kth Moment of 3-parameter Gamma Function

$m(D) = aD^b$ Mass and Max. Diameter Relationship

$$N_t = M_0 = \int_0^{\infty} n(D)\, dD = N_o \int_0^{\infty} D^{\mu}\, e^{-\lambda D}\, dD = N_o\, \Gamma(\mu + 1)\, \lambda^{-(\mu+1)}$$

Total Particle Number Concentration

$$w_x = \rho_a q_x = \int_0^{\infty} m(D) n(D)\, dD = a \int_0^{\infty} D^b n(D) dD = a\, M_b = a\, N_o \int_0^{\infty} D^b\, e^{-\lambda D}\, dD = a\, N_o\, \Gamma(\mu + b + 1)\, \lambda^{-(\mu+b+1)}$$

(Hydrometeor Water Content w_x = Density of Dry Air ρ_a x Hydrometeor Mixing Ratio q_x)

3-parameter Gamma Distribution Function

For **single-moment** species (hydrometeor mixing ratio q_x is prognostic) :

N_{ox} is either fixed or prescribed as a function of temperature or mixing ratio

μ is set to zero for exponential distribution (Marshall-Palmer) or prescribed

λ, the slope can be calculated from hydrometeor mixing ratio q_x as:

$$w_x = \rho_a q_x = a\, N_{ox}\, \Gamma(\mu + b + 1)\, \lambda^{-(\mu+b+1)} \longrightarrow \lambda = \left(\frac{a\, N_{ox}\, \Gamma(\mu + b + 1)}{\rho_a q_x}\right)^{\frac{1}{\mu+b+1}}$$

Mapping of single-moment model mixing ratio to PSD parameters

For **double-moment** species (both mixing ratio q_x and total number concentration N_{tx} are prognostic) :

μ is set to zero for exponential distribution (Marshell-Palmer) or prescribed

N_{0x}, the intercept can be calculated from N_{tx} as:

$$N_{tx} = N_{ox}\, \Gamma(\mu + 1)\, \lambda^{-(\mu+1)} \longrightarrow N_{ox} = \frac{N_{tx}\, \lambda^{\mu+1}}{\Gamma(\mu + 1)}$$

λ, the slope can be calculated from N_{tx} and q_x as:

$$w_x = \rho_a q_x = a\, N_{ox}\, \Gamma(\mu + b + 1)\, \lambda^{-(\mu+b+1)} \longrightarrow \lambda = \left(\frac{a\, N_{tx}\, \Gamma(\mu + b + 1)}{\Gamma(\mu + 1)\, \rho_a q_x}\right)^{\frac{1}{b}}$$

Mapping of double-moment concentration and mixing ratio to PSD parameters

Field 07 Snow Particle Size Distribution

IWC

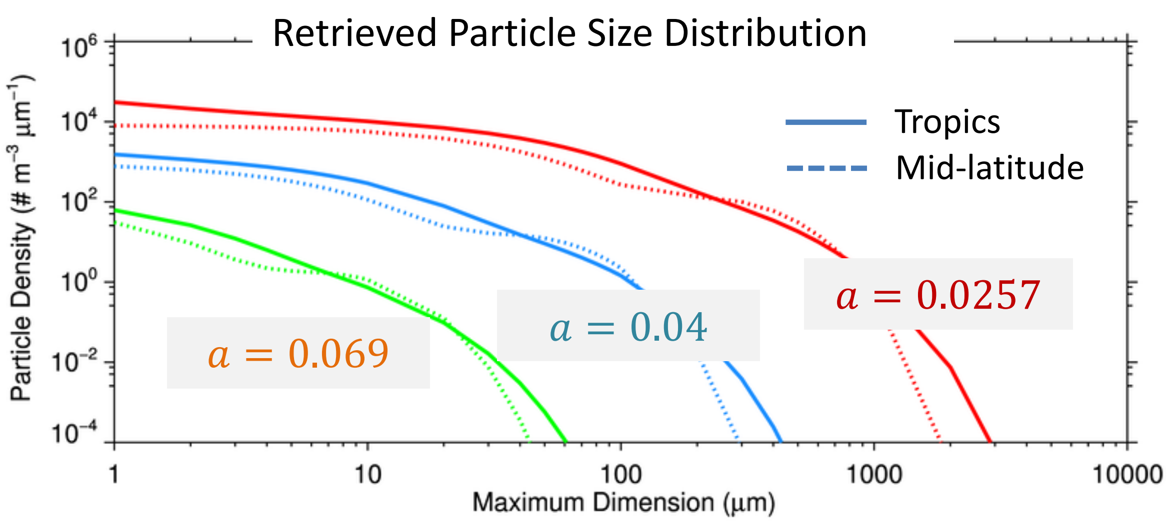
T_c

Mass-Dimensional Relationship

$$m(D) = aD^b$$

$$IWC = 0.0931\ gm^{-3}$$
$$T_c = -49.7\ °C$$

$$m(D) = aD^2$$



F07 PSD Parameterization

- Based on 10,000 in situ PSDs
- Second moment is linked to any other moment via polynomial fits to the in-cloud temperature
- Any given IWC and in-cloud temperature, the original PSD can be estimated

$$w_s = \rho_a\, q_s = a_s\, M_{b_s} \rightarrow M_{b_s} = \frac{w_s}{a_s} = \frac{\rho_a\, q_s}{a_s}$$

$$M_2 = \left(\frac{M_{b_s}}{A(b_s)\ exp[B(b_s)T_c]}\right)^{\frac{1}{C(b_s)}} \rightarrow M_n = A(n)\exp[B(n)T_c]\ M_2^{C(n)}$$

$$\begin{cases} x = D\dfrac{M_2}{M_3} \\ \Phi_{23}(x) = N(D)\dfrac{M_3^3}{M_2^4} \end{cases}$$

$$N(D) = \Phi_{23}(x)\frac{M_2^4}{M_3^3}$$

$$M_n = A(n)\exp[B(n)T_c]\ M_2^{C(n)}$$
$$A(n) = exp(13.6 - 7.76n + 0.479n^2)$$
$$B(n) = -0.0361 + 0.0151n + 0.00149n^2$$
$$C(n) = 0.807 + 0.00581n + 0.0457n^2$$

Tropical Regime:

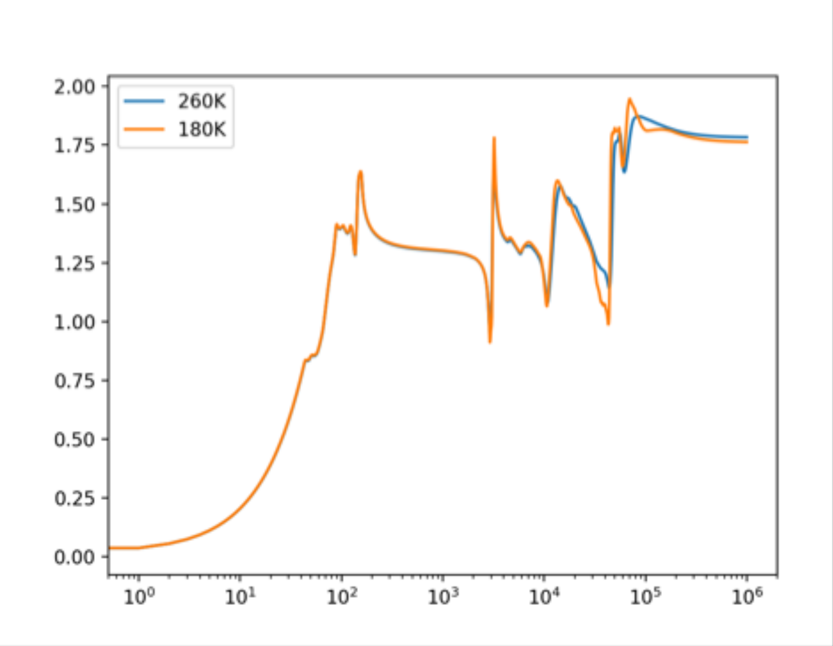
$$\Phi_{23}(x) = 152e^{-12.4x} + 3.28x^{-0.78}e^{-1.94x}$$

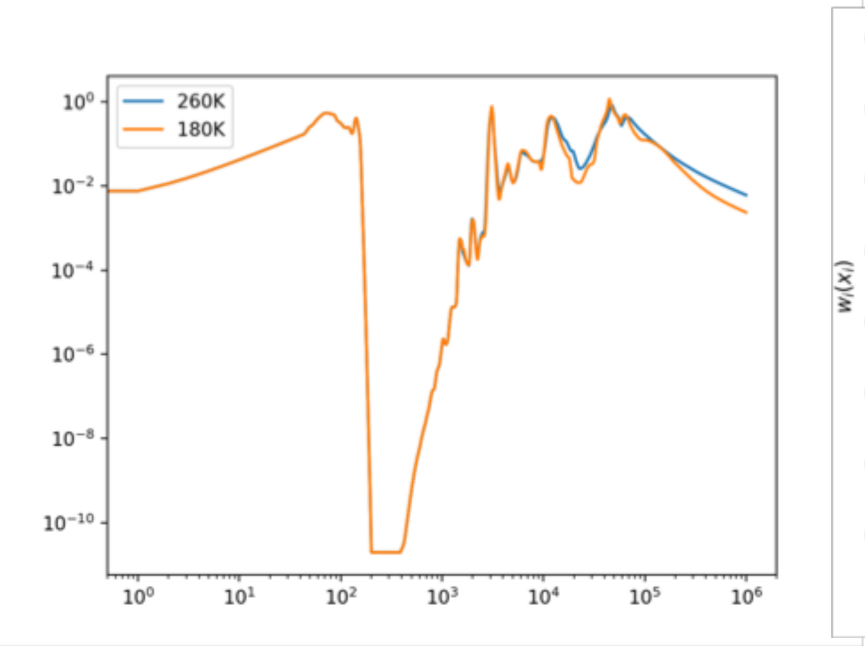
Mid-latitude Regime:

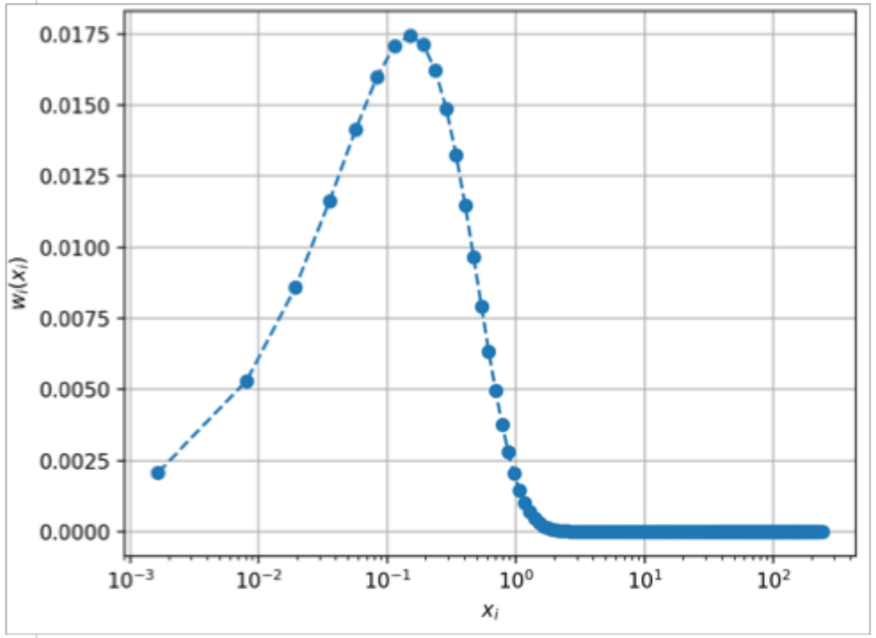
$$\Phi_{23}(x) = 141e^{-16.8x} + 102x^{2.07}e^{-4.82x}$$

CRTM Cloud / Precip. Scattering Table Work

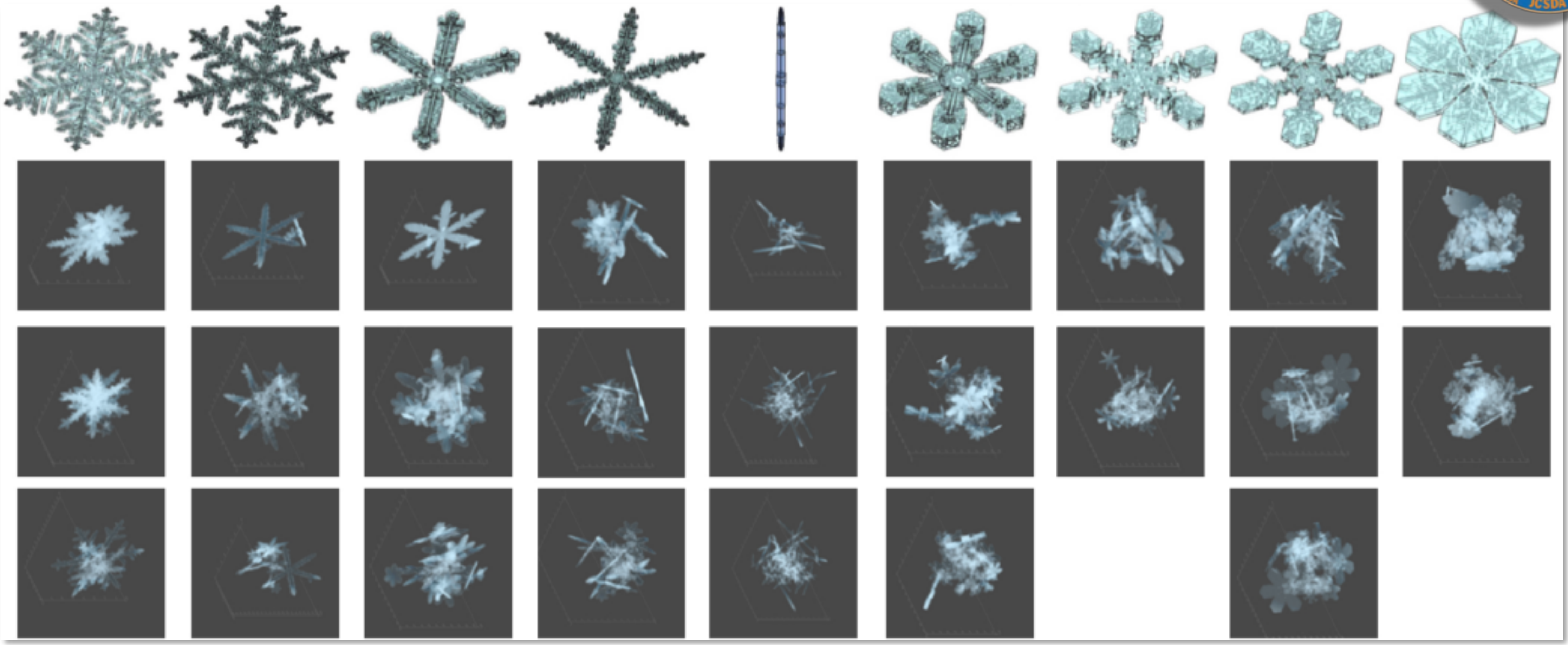
- *Rayleigh- and Henyey-Greenstein phase matrices* provide a first quick placeholder solution.
- Investigation of feasibility of using *Normalized Particle Size Distributions* for Bulk Scattering Properties (convenient alternative: MC6 PSD).
- Refractive index database of Iwabuchi and Yang (2011) included in single-scattering calculations.
- Advanced quadrature schemes show potential for decreasing computation time of single-scattering properties (Gauss-Laguerre, Sinh-Tanh, etc.)







CRTM Cloud / Precip. Scattering Table Work



The physical database contains 2126 pristine particle files, based on the above 9 base shapes, ranging from columns to plates to dendrites. Effective radius ranges from 60 to 1000 microns. The aggregate particle database, based on aggregates of the 9 base shapes above, consists of about 8100 aggregate shapes, with varying masses and constituent ice crystals. Effective radius ranges from 100 microns up to 5000 microns.

Enhancement of CRTM MODIS Collection 6 (MC6)

MODIS Collection 6

- A single habit ice model
- an ensemble of aggregates composed of eight severely roughened columns for ice cloud particles

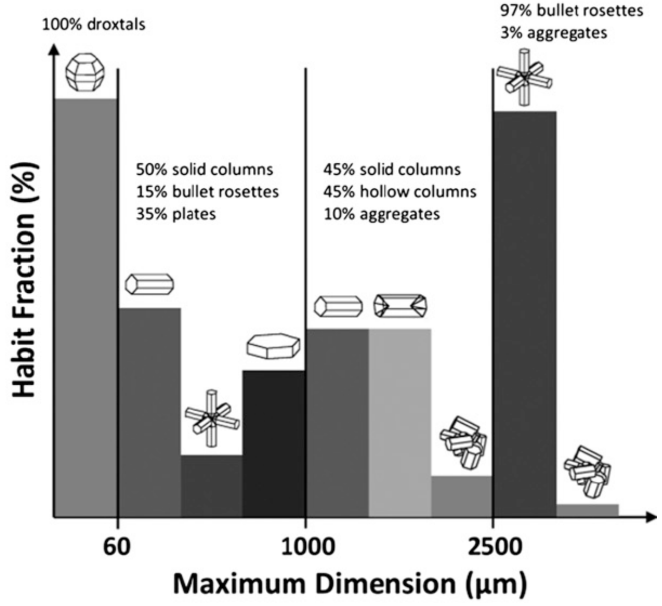
Single Particle Optical Properties

- Discrete Dipole Approximation (DDA) for small particles
- Geometric Optics (GO) Method for larger particles

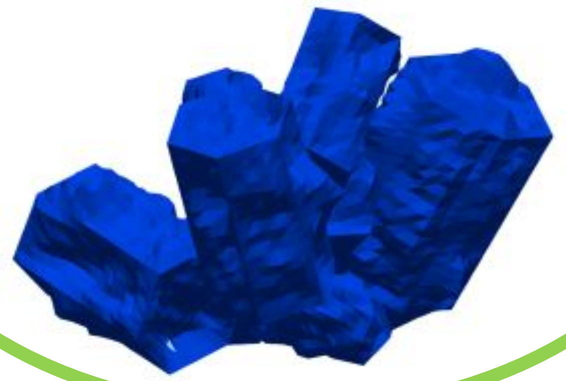
Bulk Optical Properties

- Gamma size distribution
- Temperatures at 160K and 230K

MODIS Collection 5



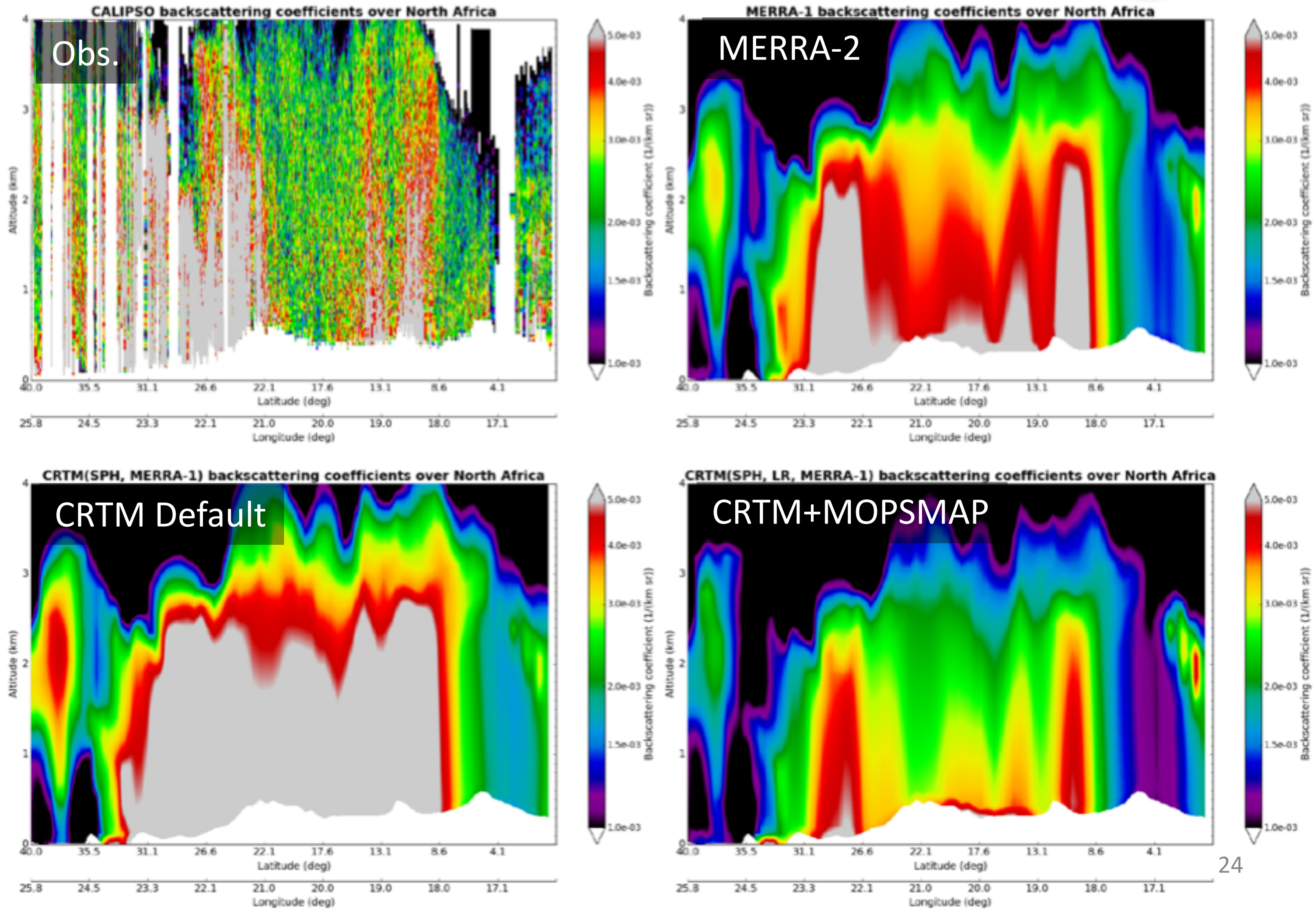
MODID Collection 6



Community Active Sensor Model :: Lidar

Dust Backscattering (532 nm) Coefficients

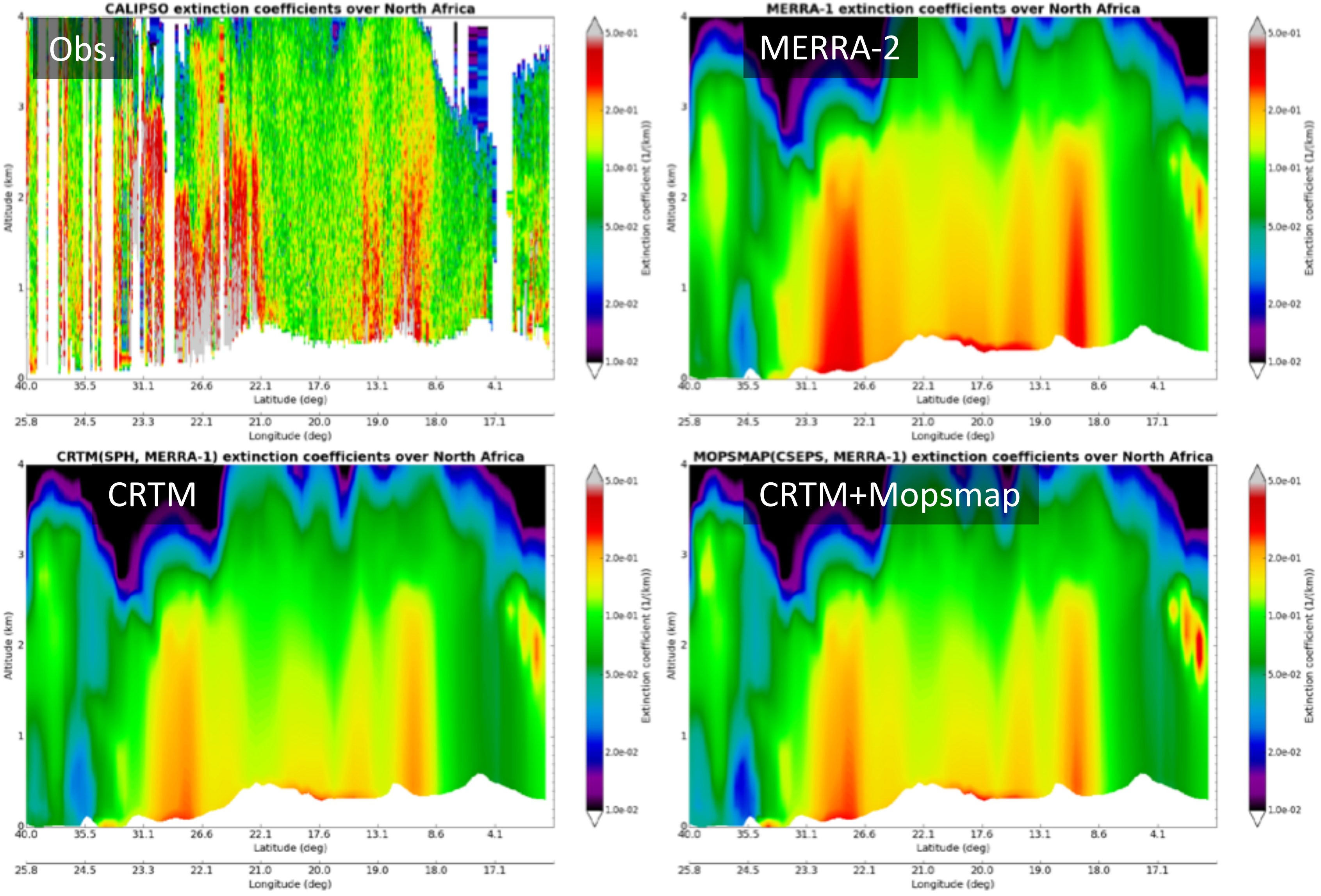
- Barbara Scherllin-Pirscher (U. Graz), Ben Johnson (JCSDA), Mariusz Pagowski (ESRL), Josef Gasteiger (U. Vienna), Patrick Stegmann (JCSDA)
- Goal: Produce an aerosol-sensitive LIDAR forward operator for use in DA, initially focusing on CALIOP
- Output: Aerosol specific AOD and LIDAR backscattering coefficient.
- CRTM backscattering compared to MERRA has similar variability, but consistently too large.



Community Active Sensor Model :: Lidar

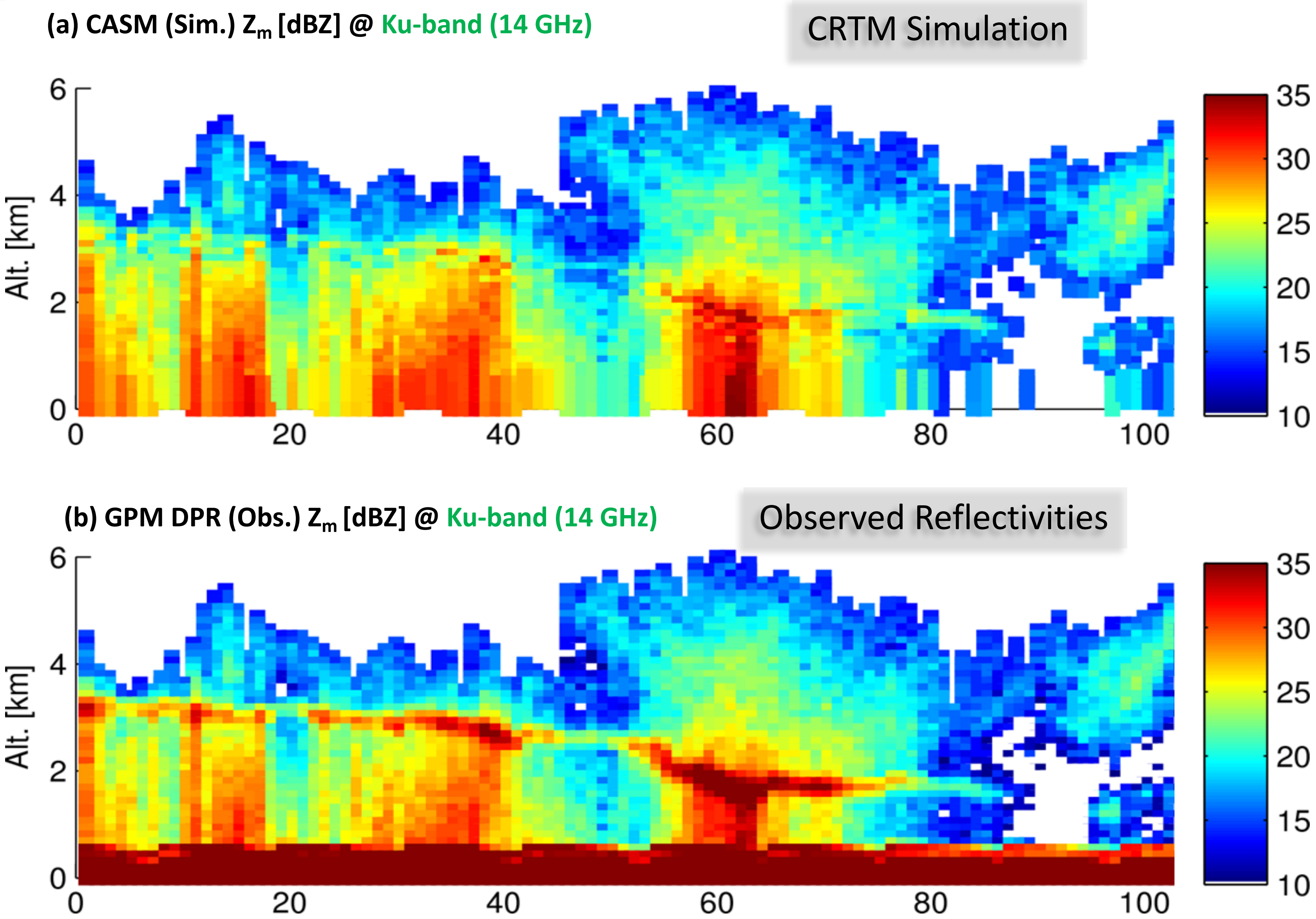
Dust Extinction (532 nm) Coefficients

- MERRA-2 extinction higher than CRTM default, but using MOPSMAP aerosol tables get us closer.
- Future: update aerosol scattering tables, test for different aerosol

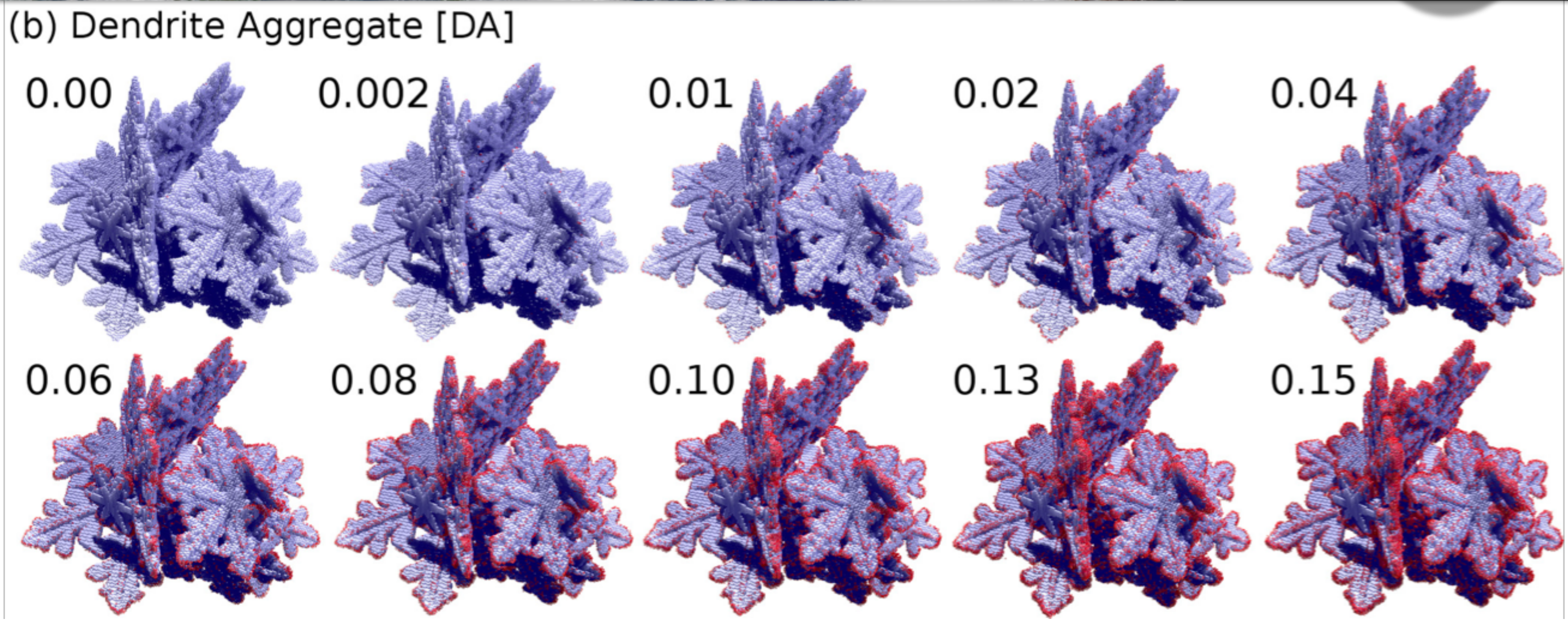


CRTM/CASM :: Space-based Radar

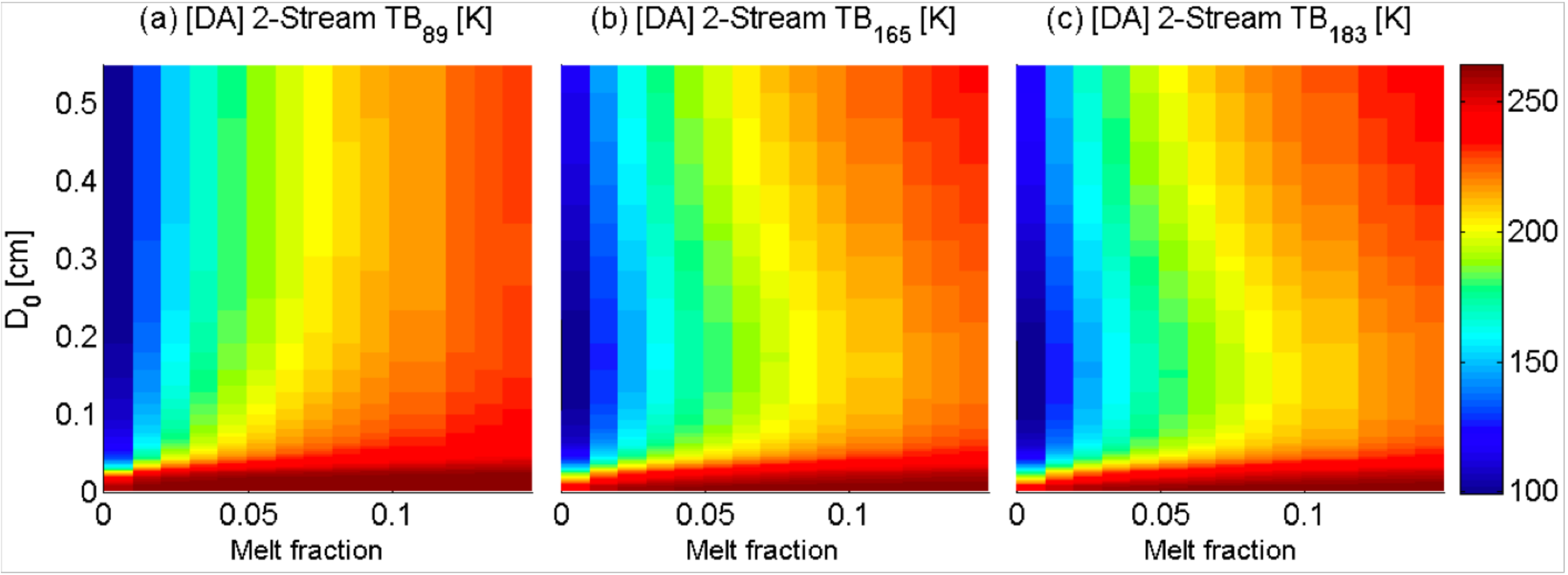
- Goal: Active Space-based Radar Simulation and Jacobians for satellite DA
- Tested for Ku, Ka, and W
- Output: Radar reflectivity and 2-way PIA
- Status: TL and AD models under testing
- Next: Melting layer model, ground-based radar, polarization



A quick note on melting particles



A quick note on melting particles



Motivation for Polarized RT

GPM GMI V-H Brightness Temperature difference at 166 GHz.

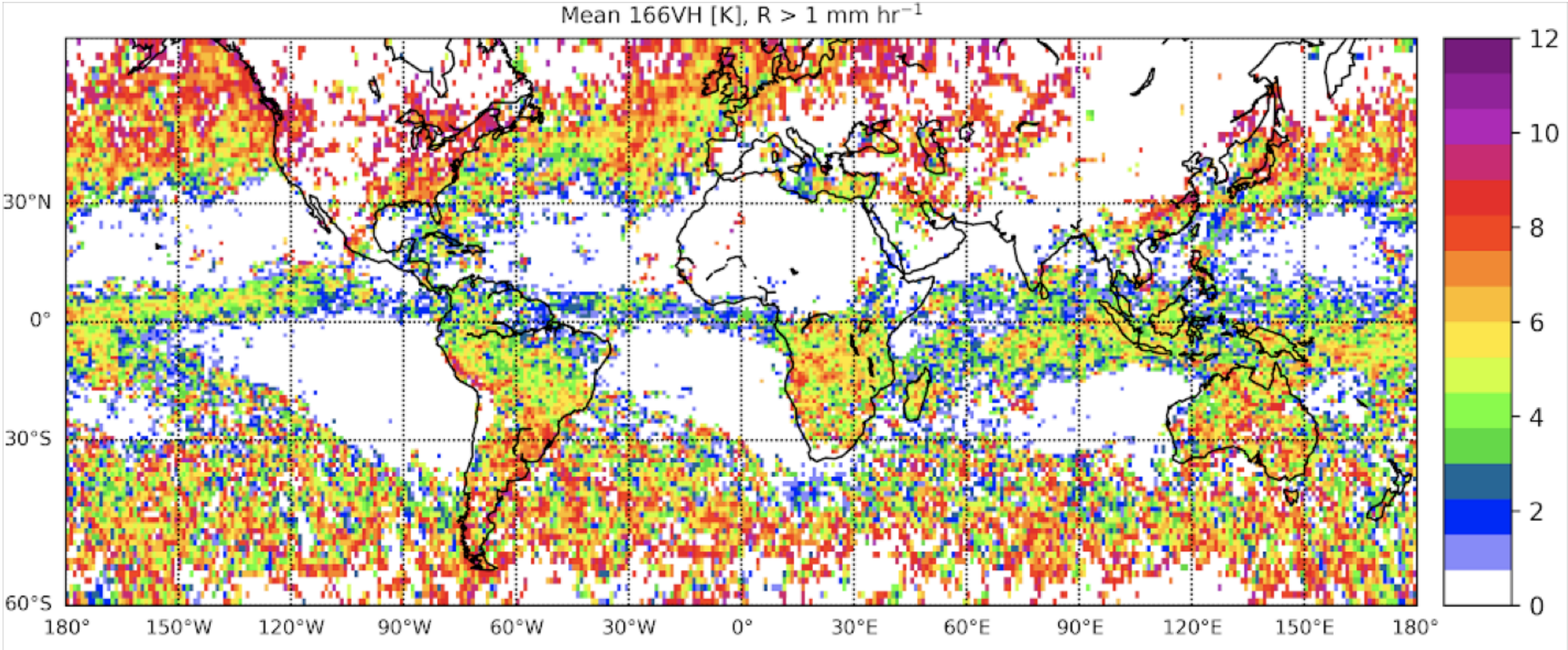


Image courtesy of V. Galligani

Motivation for Polarized RT

GPM GMI V-H Brightness Temperature difference at 166 GHz.

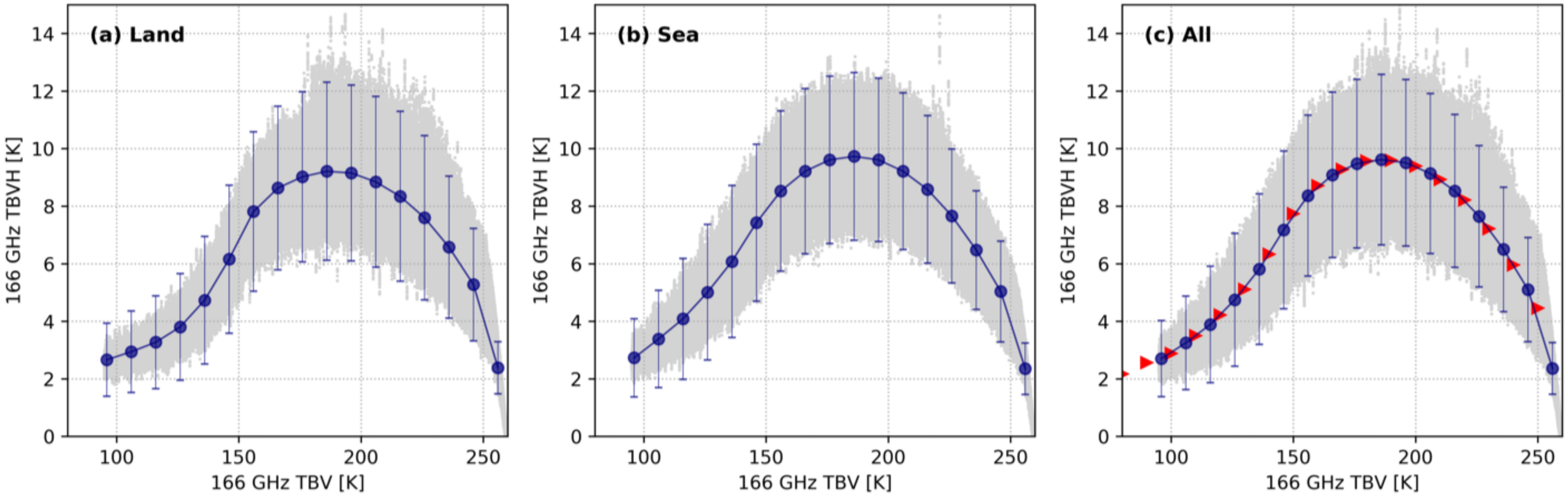


Image courtesy of V. Galligani

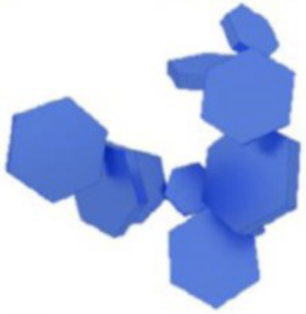
Polarized RT in CRTM progress

$$\sigma_{ext} = \int_{D_{min}}^{D_{max}} A(D)Q_{ext}(D)N(D)dD$$

$$\sigma_{sca} = \int_{D_{min}}^{D_{max}} \omega_0(D)A(D)Q_{ext}(D)N(D)dD$$

$$\omega_0 = \frac{\sigma_{sca}}{\sigma_{ext}}$$

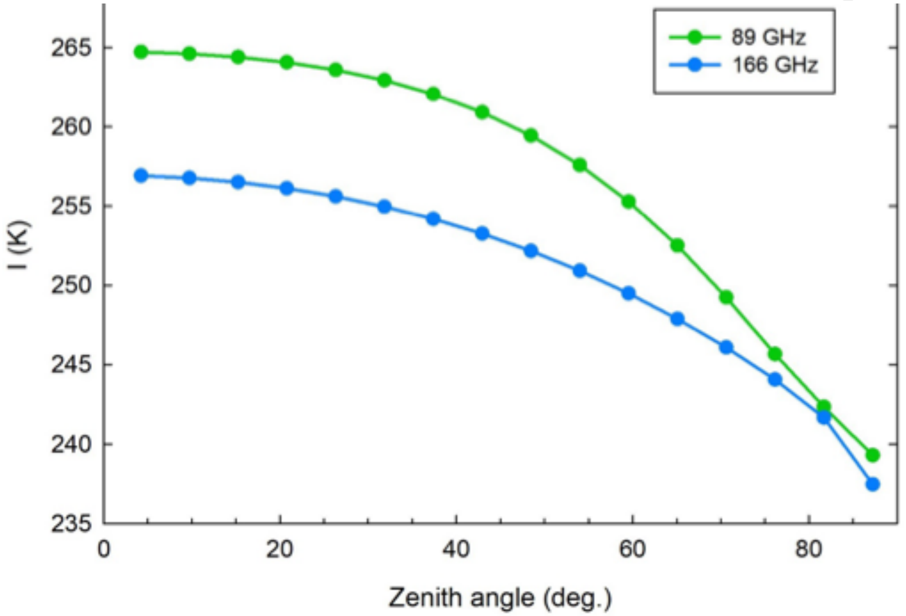
A is projected area of particle
Q_{ext} is extinction efficiency

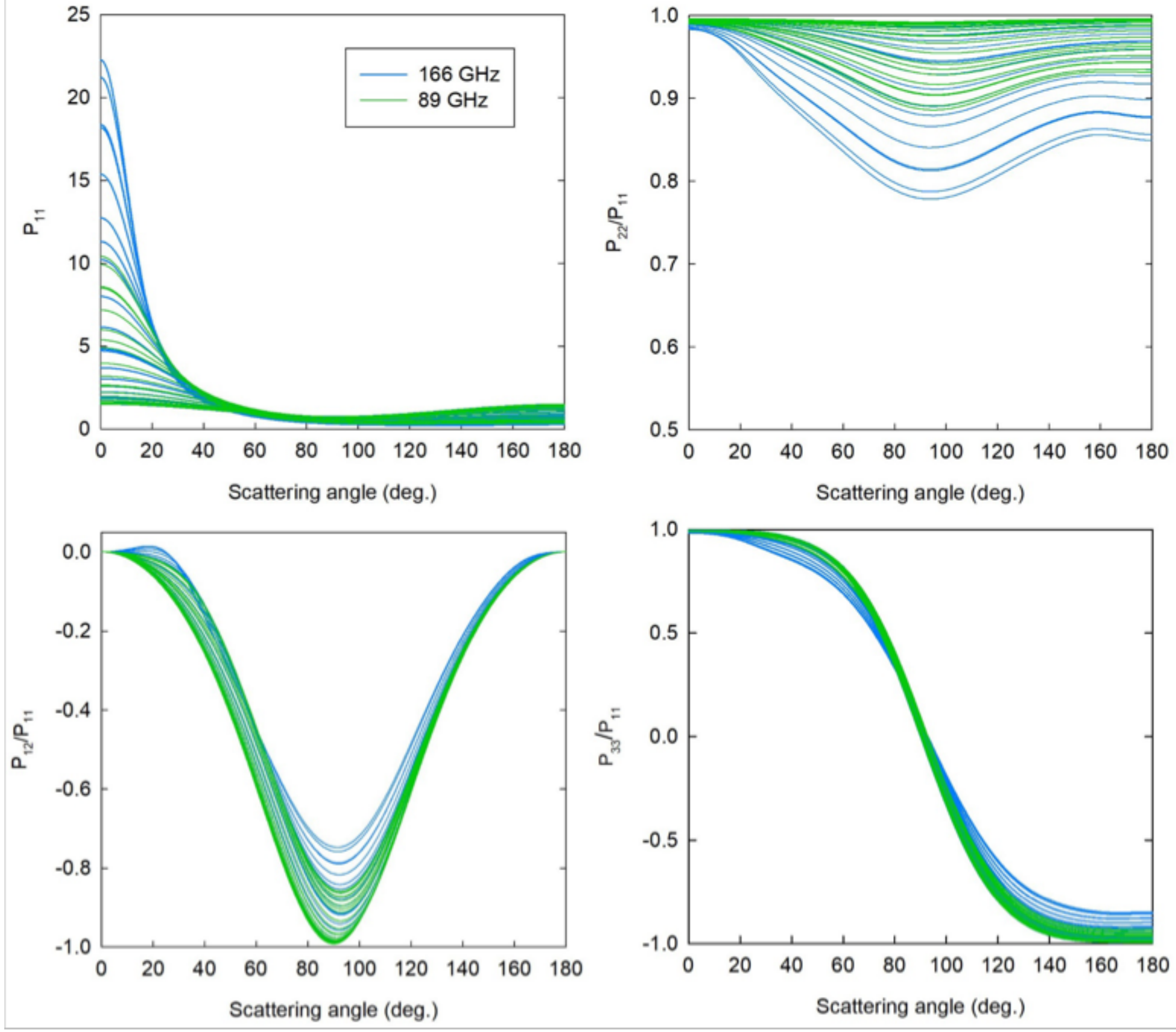


10-plate aggregate

$$\boldsymbol{P}(\Theta) = \frac{1}{\sigma_{sca}} \int_{D_{min}}^{D_{max}} \boldsymbol{P}(\Theta, D)\omega_0(D)A(D)Q_{ext}(D)N(D)dD$$

$$\boldsymbol{P}(\Theta, D) = \begin{bmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{21} & P_{22} & 0 & 0 \\ 0 & 0 & P_{33} & P_{34} \\ 0 & 0 & P_{43} & P_{44} \end{bmatrix}$$





Clouds/Precipitation -- Next Steps?

- **Technical**
  - Assemble tables for dielectric constants, shape/mass, DDA/CBFM/IITM etc.
  - Tool for creating your own cloud/aerosol coefficients
    - Python + Cloud Scat./Aerosol DB
- **Science**
  - Full Polarization support (IQUV)
    - Oriented particles, Legendre coefficients
  - Melting layer model representation
  - Extend to ICI range
  - Physical Consistency between VIS, IR, MW
- **Validation / Intercomparison**
  - Field experiment "golden cases", aircraft data
  - RTTOV intercomparison in JEDI/UFO

Questions / Comments?

Please join our CRTM google groups:

Developer Discussion:
https://groups.google.com/forum/#!forum/crtm-developers

Support:
https://groups.google.com/forum/#!forum/crtm-support

New support email:
crtm-support@googlegroups.com

This will post to the support forum, so anything you email will be available to the members of the support group.

Email: Benjamin.T.Johnson@noaa.gov for direct support, questions, and comments