Community Radiative Transfer Model (CRTM)

CRTM team:

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Patrick Stegmann (UCAR / JCSDA)

Jim Rosinski (UCAR/JCSDA)

Tom Greenwald (UW CIMSS)

Thomas Auligné (Director, JCSDA)

With essential contributions from: Ming Chen, Tong Zhu, Mark Liu, Emily Liu, Isaac Moradi, Mariusz Pagowski, Kevin Garrett, Barbara Scherllin-Pirscher, Mayra Oyola, Sarah Lu, David Turner, and many others over the past 15 years.

What is the CRTM?

CRTM is the "Community Radiative Transfer Model"

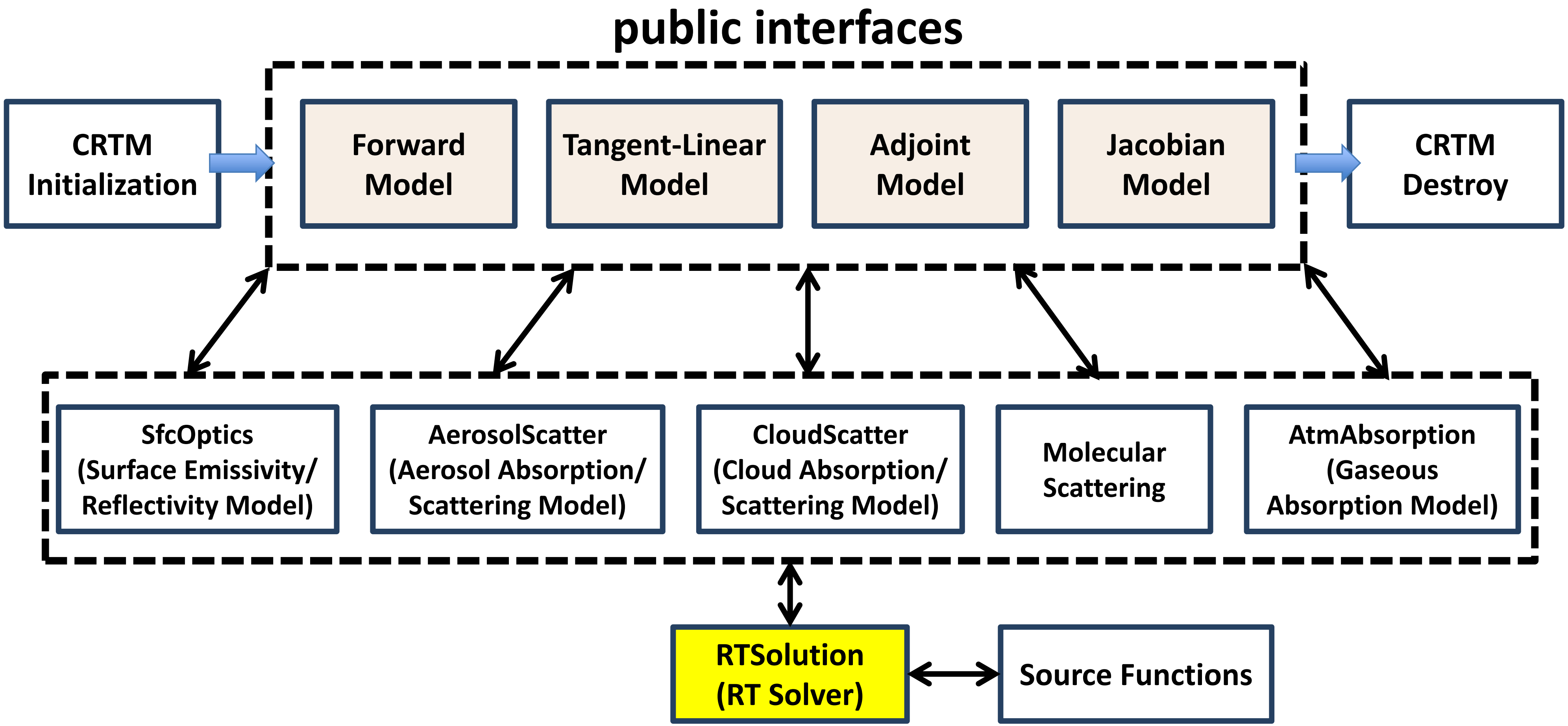
Goal: Fast and accurate community radiative transfer model to enable assimilation of satellite radiances under all weather conditions

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. 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 Structure



CRTM Overview

CRTM 1: The first task is an umbrella for all **management, external coordination/collaboration, release support, and oversight of the CRTM team activities** -- covering all versions of CRTM. This specifically includes user-support, documentation, education, and outreach elements.

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CRTM 2: The second task is primarily a **software engineering**-driven task aimed specifically at improving the computational aspects of CRTM.

CRTM 3: The third and final task aims at **scientific development and testing**. CRTM users require fast computations of radiances with the highest degree of accuracy and sensitivity possible, while still maintaining the operational computational resource requirements.

CRTM Design Philosophy

Science

- State-of-the Art
- Physical consistency across components
- Full consideration of instrument characteristics (e.g., SRF, cal/val)
- Requirements driven development

Code

- Clean, generic interfaces
- Consistent self-describing code and variable names
- Internal documentation for each module / subroutine
- Modular and Object-Oriented
- Optimized for memory and HPC requirements
- Hand-crafted TL / AD

CRTM Design

- Modularity and Standards
  - All structures and their procedures are defined in their respective definition modules,

    CRTM_*structure*_**Define**
  - Currently, I/O procedures are defined in a separate module,

    CRTM_*structure*_**IO**

    but will eventually be moved to the definition module.
- Procedures are named following the convention

  CRTM_*structure*_*action*

Implemented default procedures

Action	Type	Description
`Associated`	Elemental function	Tests if the structure components have been allocated.
`Destroy`	Elemental subroutine	Deallocates any allocated structure components.
`Create`	Elemental subroutine	Allocates any allocatable structure components.
`Inspect`	Subroutine	Displays structure contents.
`OPERATOR(==)`	Elemental function	Tests the equality of two structure.

Example default procedures

```
MODULE CRTM_Atmosphere_Define
  …etc…
  PUBLIC :: OPERATOR(==)
 …etc…
  PUBLIC :: CRTM_Atmosphere_Associated
  PUBLIC :: CRTM_Atmosphere_Destroy
  PUBLIC :: CRTM_Atmosphere_Create
  PUBLIC :: CRTM_Atmosphere_Inspect
  …etc…
END MODULE CRTM_Atmosphere_Define
```

Example default procedures

```
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  PUBLIC :: CRTM_Atmosphere_Create
  PUBLIC :: CRTM_Atmosphere_Inspect
  …etc…
END MODULE CRTM_Atmosphere_Define
```

```
TYPE(CRTM_Atmosphere_type) :: atm(100)  ! Many profiles
INTEGER :: scalar_n_layers, rank1_n_layers(100)

…etc…

! All profiles have same layering
scalar_n_layers = 64
CALL CRTM_Atmosphere_Create( atm, scalar_n_layers, …etc…
)

…etc…

! All profiles can have different layering
Rank1_n_layers = [28,64,91,…,75]
CALL CRTM_Atmosphere_Create( atm, rank1_n_layers, …etc… )
```

Code Optimization and Solver Developments

Original CRTM Performance Optimizations for GSI

- Thread loop over channels in CRTM_K_Matrix_module.f90 using OpenMP
  - ~5X speedup using 6 OMP threads
  - ~8X speedup using 12 OMP threads
- Numerous code changes were required to enable OpenMP threading, e.g.
  - From NESDIS_ATMS_SnowEM_Module.f90:

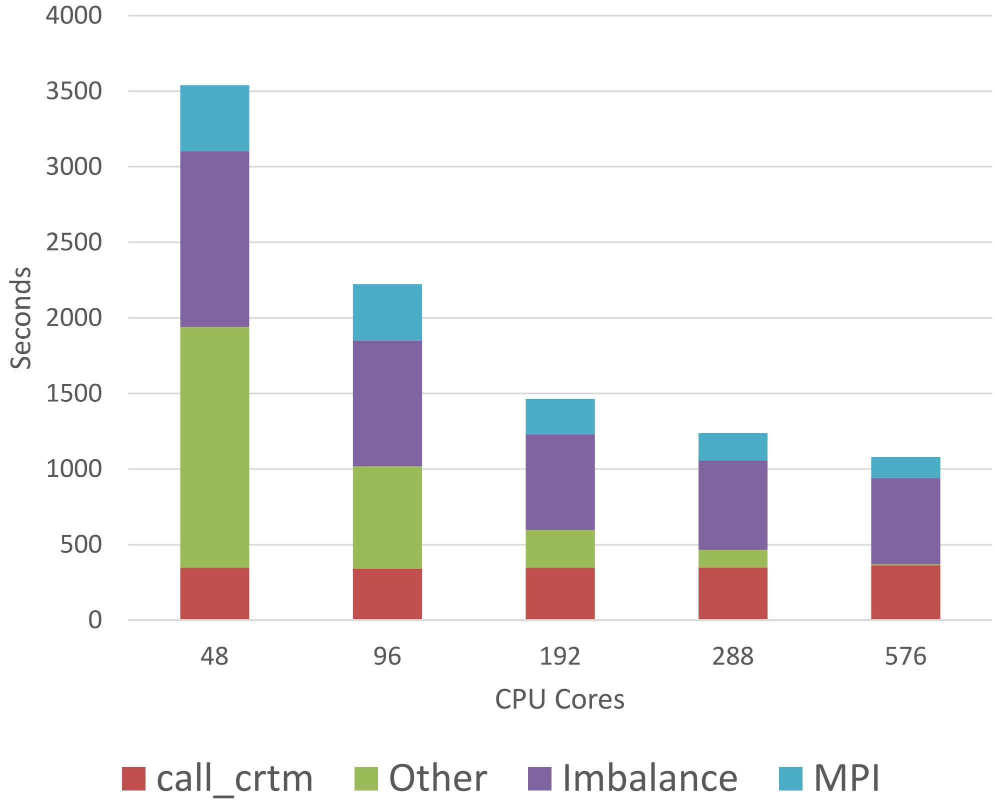
```
REAL(fp) :: Ts = 273.15
INTEGER :: Snow_Type = 4
```

  - Must be changed to:

```
REAL(fp) :: Ts
INTEGER :: Snow_Type
Ts = 273.15
Snow_Type = 4
```

CRTM Optimization (J. Rosinski, JCSDA)

T670 DA time: 48 MPI, various thread counts (1,2,4,6,12) node counts=(2,4,8,12,24) Note: "Other" is a residual calculation from max values, thus an underestimate



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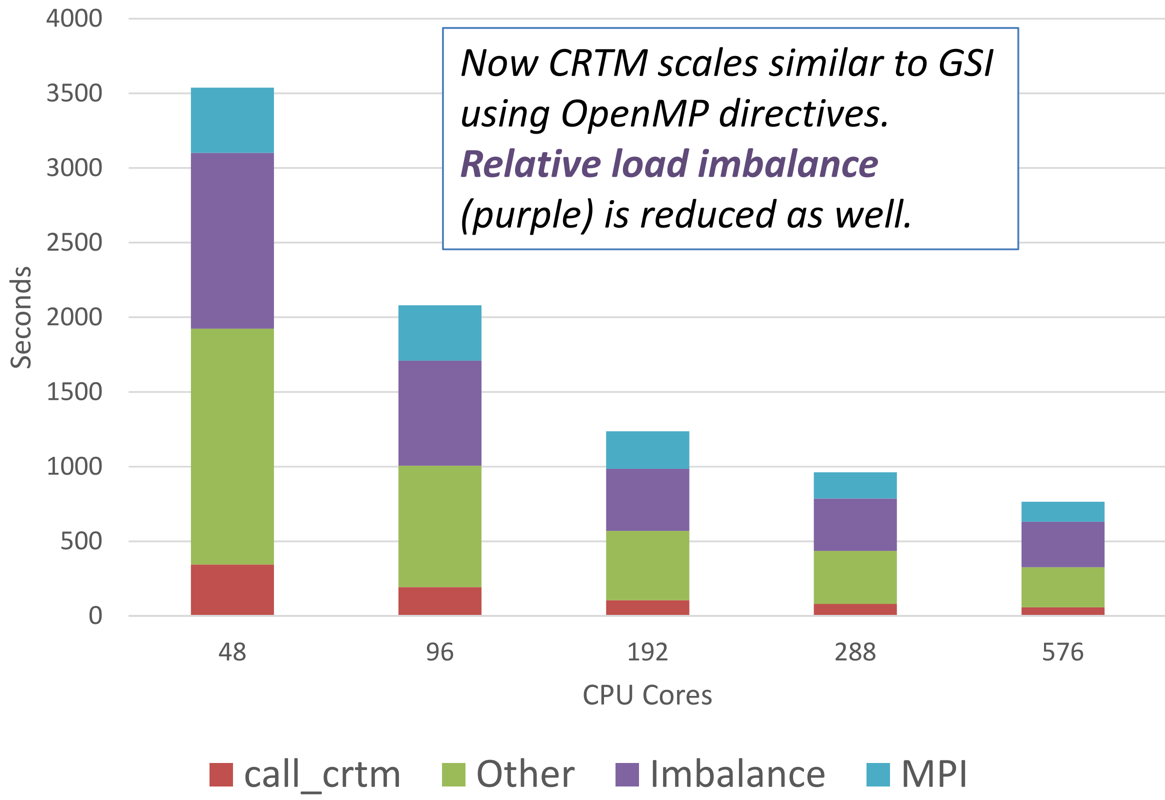
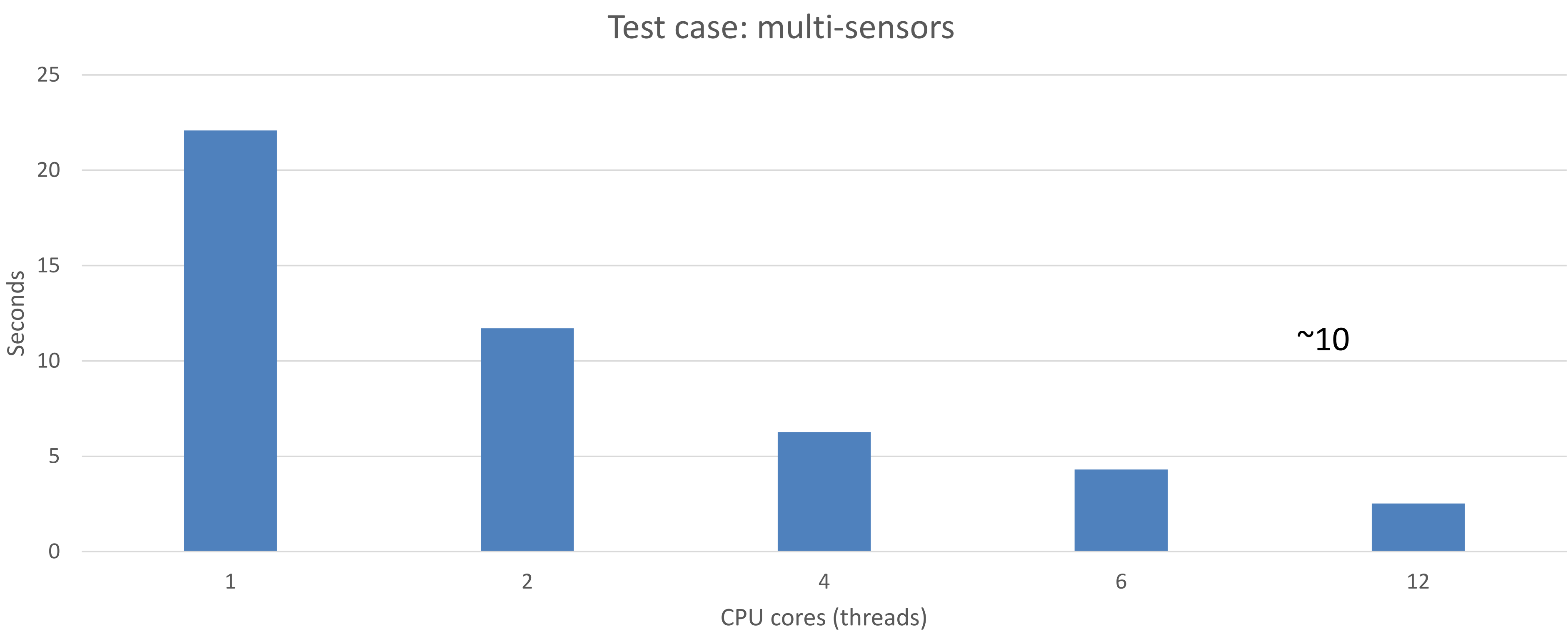
Now CRTM scales similar to GSI using OpenMP directives. ***Relative load imbalance*** *(purple) is reduced as well.*



Recent CRTM Performance Optimizations for JEDI

- Implemented OpenMP threading over n_Profiles rather than n_Channels in CRTM_K_Matrix.f90
  - Better speedup opportunity due to vast number of profiles that can be processed in parallel. In contrast, some sensors have only one or a few channels so this limited the opportunity for parallelism in the previous approach.
- Applied same threading approach (over n_Profiles) to CRTM_Forward.f90
  - Like CRTM_K_Matrix.f90, results in threaded mode are bitwise identical to original code
- Thus far, optimization work for JEDI has only been tested underneath ufo-bundle. So no MPI or large application use of CRTM yet.

CRTM_Forward OpenMP Scaling on a single (12-core) socket of NOAA machine theia



Example: Improving loop-level performance

- Original code from ODPS_AtmAbsorption.f90:

```
DO k = n_Layers, 1, -1
  DO j = 1, n_orders
    Predictor_AD%Ap(k, j) = Predictor_AD%Ap(k, j) + coeff(j)*b_AD(k,i)
  END DO
  b_AD(k,i) = ZERO
END DO
```

- Modified code (note swapping of j,k loops):

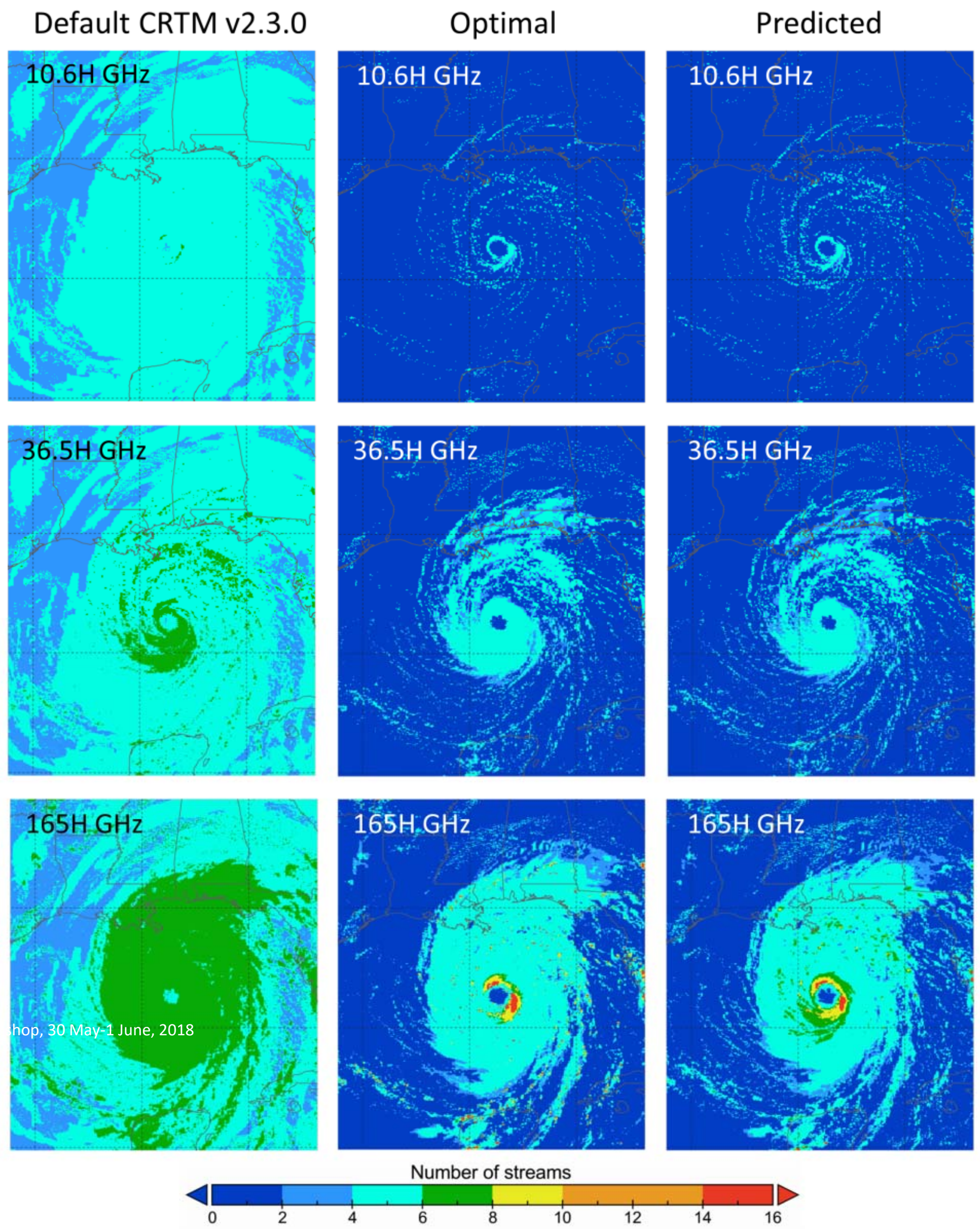
```
DO j = 1, n_orders
  DO k = 1, n_Layers
    Predictor_AD%Ap(k, j) = Predictor_AD%Ap(k, j) + coeff(j)*b_AD(k,i)
  END DO
END DO
b_AD(1:n_Layers,i) = ZERO
```

RT Model Optimization (Tom Greenwald)

- Predicting the fewest number of streams needed to achieve a desired accuracy (i.e., optimal number of streams, ONOS) or whether scattering even needs to be accounted for
- A **scattering indicator based on successive order of scattering was developed to predict the ONOS** for microwave frequencies
  - Integrated into CRTM v2.3.0 (2018)
  - DA experiments show the optimized CRTM reduced runtime by 19% as compared to the original CRTM (2018)
- Currently developing a method to predict the ONOS for IR wavelengths

Optimization of Multi-stream Solvers

- Benchmark tests used high-resolution (1.5 km) WRF model simulation of Hurricane Katrina (1800 UTC 28 Aug 2005)
- For GMI channels, method correctly predicts optimal number of streams 94% of the time (assuming 0.5 K accuracy) and is 2.5x faster than CRTM v2.3.0
- Coordinated effort with Min-Jeong Kim (NASA GMAO)



Slides courtesy of Tom Greenwald

Vector RT Models (Tom Greenwald)

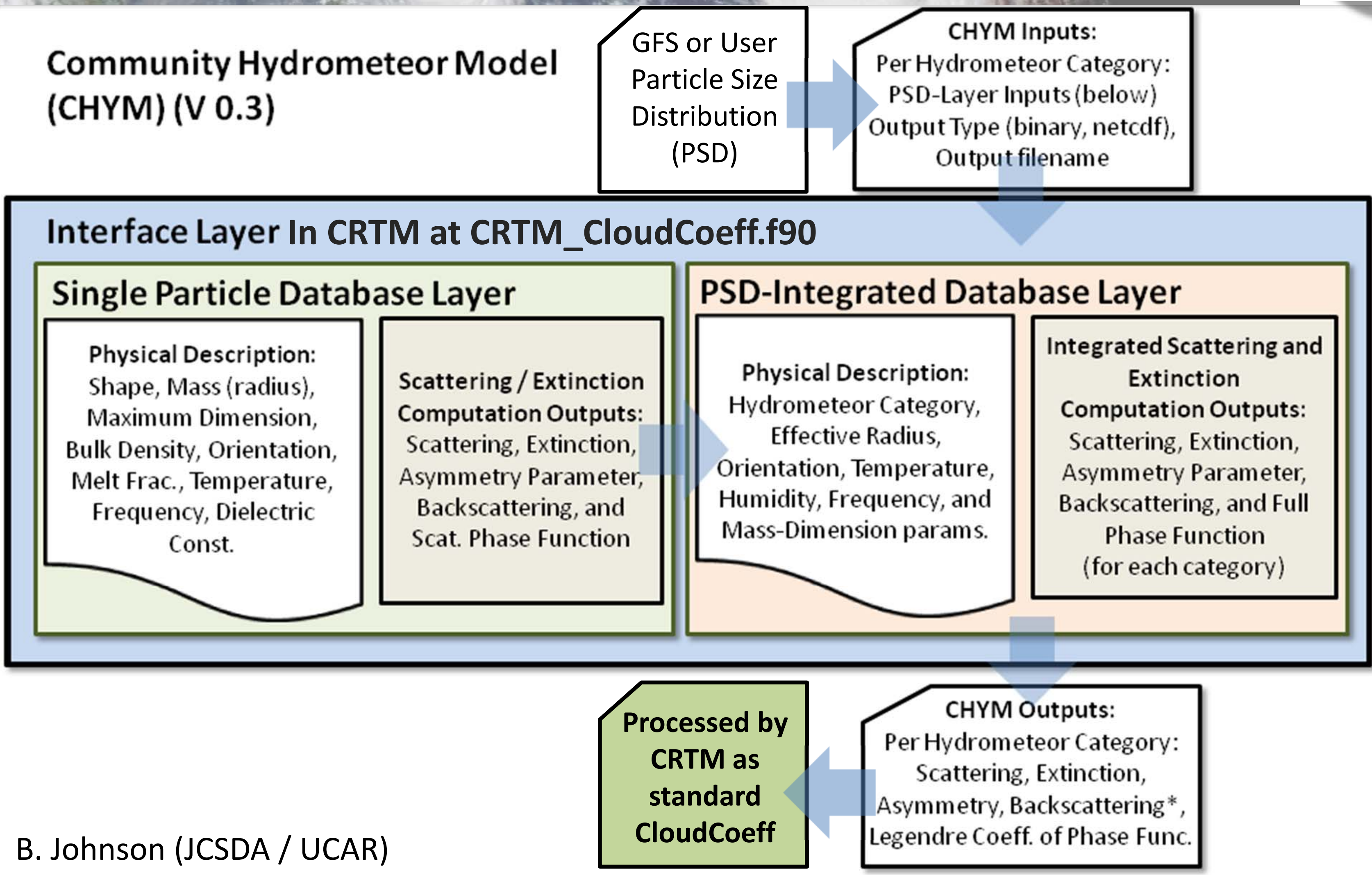
- There is a need for the CRTM to be fully polarized
  - Necessary to account for polarization generated by large horizontally oriented non-spherical ice particles at microwave frequencies (Galligani et al. 2013)
  - Polarization effects on cloud property (τ, r_e) retrievals can be significant (up to 15%) (Yi et al. 2014)
  - Allow for use of WindSat measurements (I,Q,U,V) in radiance data assimilation
- Investigated a vector 2n-stream adding-doubling (VAD) model for potential use in the CRTM

Science

- Community Hydrometeor Model (CHYM)
  - Aerosols, Clouds, Precipitation
- Community Active Sensor Module (CASM)
  - Space-based lidar, radar
  - Ground-based active sensors (future)
- Community Surface Emissivity Model (CSEM)
  - Improved surface emissivity characterization
  - Framework for modular emissivity algorithms (IR/MW)

Community Hydrometeor Model (CHYM)

Community Hydrometeor Model (CHYM) (V 0.3)

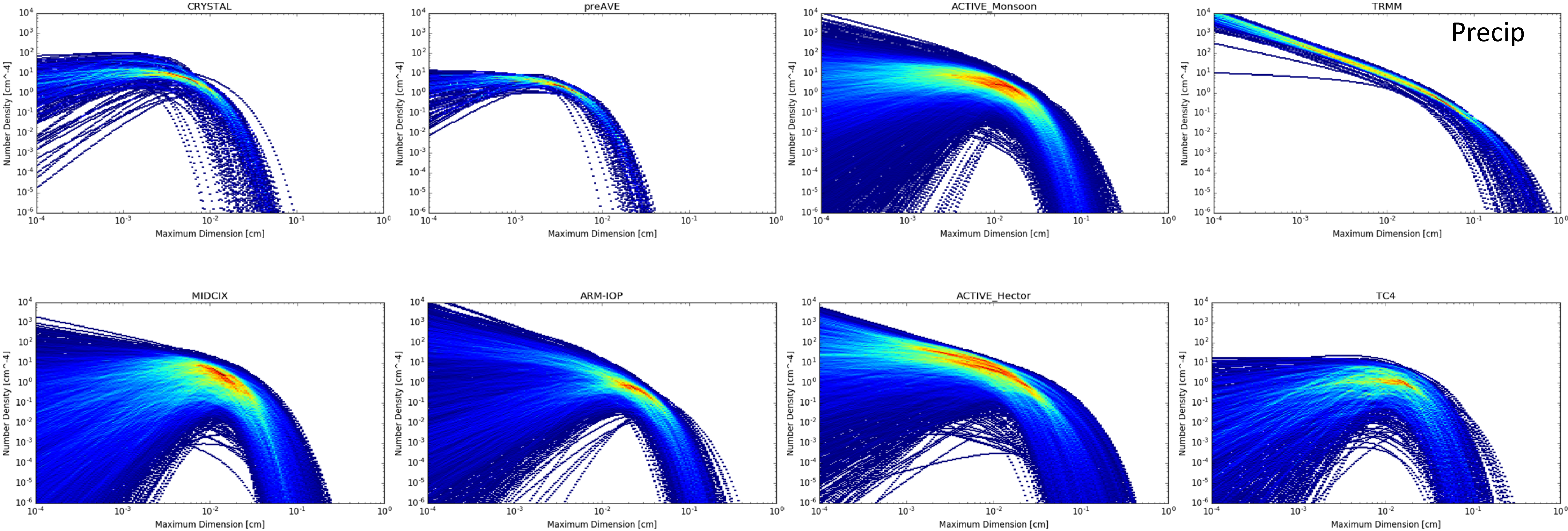


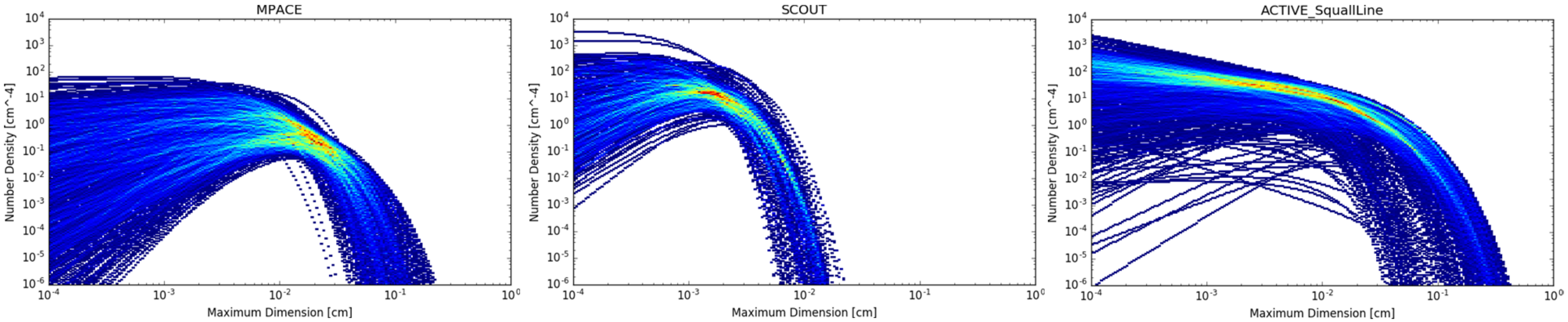
B. Johnson (JCSDA / UCAR)

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: Ben Johnson).
  - 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)

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

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:

Single Moment

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

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:

Double Moment

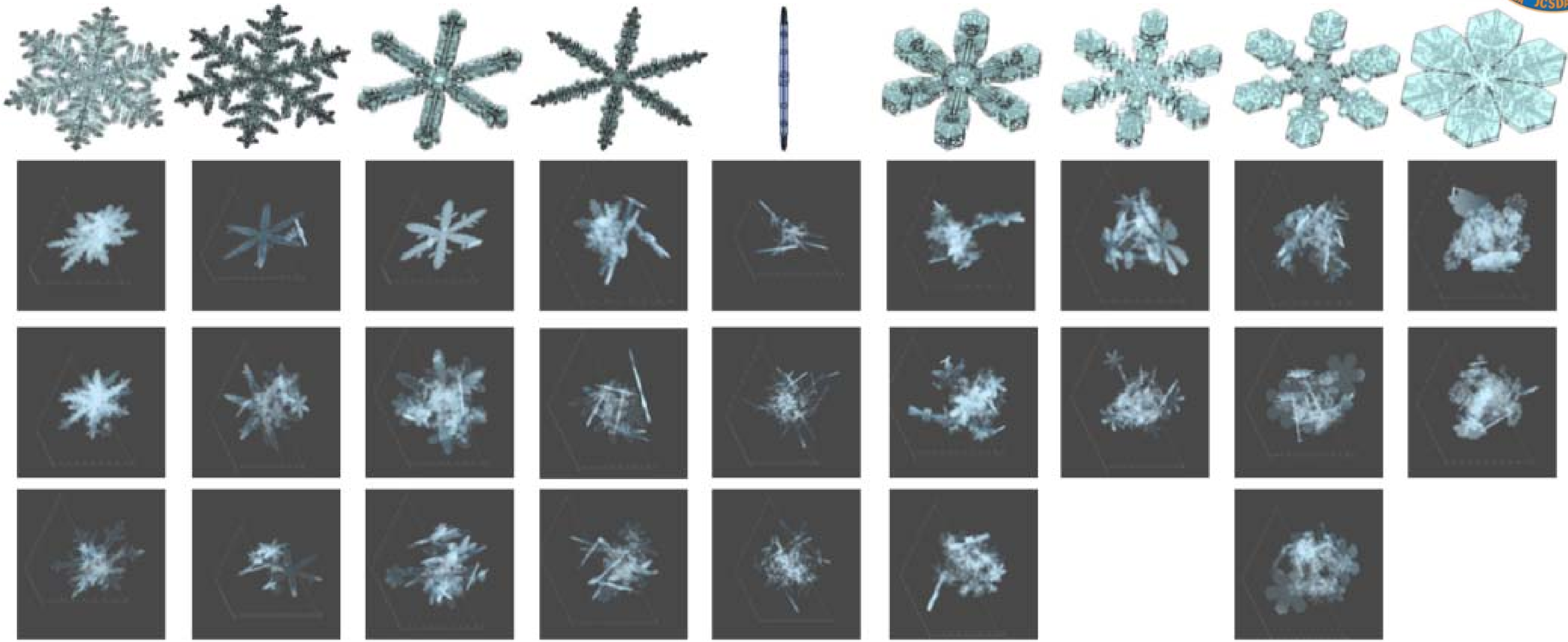
$$N_{tx} = N_{ox}\, \Gamma(\mu + 1)\, \lambda^{-(\mu+1)} \longrightarrow \boxed{N_{ox} = \frac{N_{tx}\, \lambda^{\mu+1}}{\Gamma(\mu + 1)}}$$

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

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

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

CHYM:: Cloud / Precip. Scattering Table Work

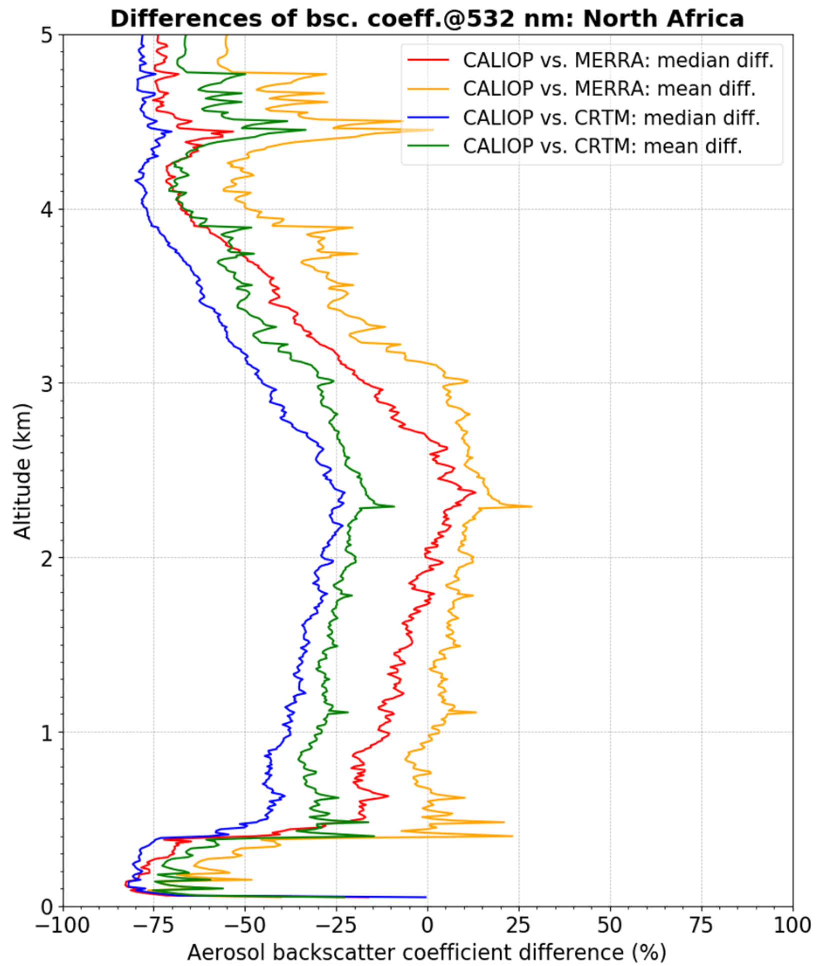


The physical database contains 2126 pristine particle files, based on the above 9 base shapes, ranging from columns to plates to dendrites. Effective radius ranges from 60 to 1000 microns. The aggregate particle database, based on aggregates of the 9 base shapes above, consists of about 8100 aggregate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

CASM :: Aerosol + Lidar Work

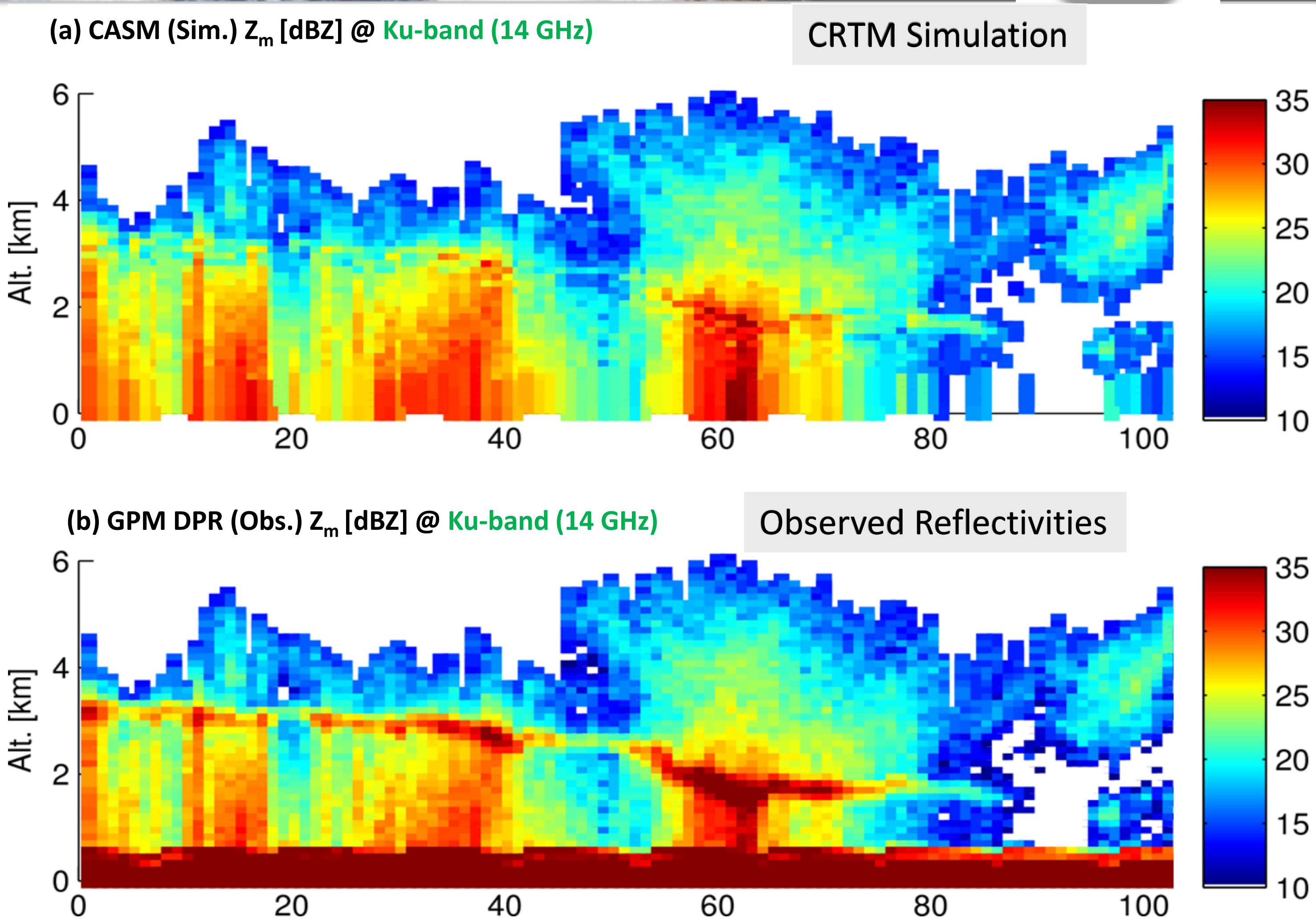
- Goal: Produce an aerosol-sensitive LIDAR forward operator for use in DA, initially focusing on CALIOP
- Output: Aerosol specific AOD and LIDAR backscattering coefficient.
- Status: Preliminary results (see fig.)
- CRTM backscattering compared to MERRA has similar variability, but is consistently too large.
- Future: update aerosol scattering tables, find source of difference.

Aerosol Backscattering Coefficient differences at 532 nm



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



CSEM :: Surface Emissivity (M. Chen)

<u>Highlights</u>:

1) CSEM top-down interfaces were refined to support upper-level vectorised RT solvers.

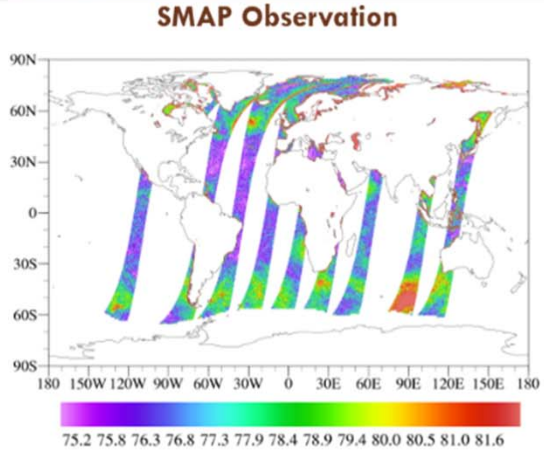
2) Integrated CRTM-CSEM version was successfully implemented in ProdGSI

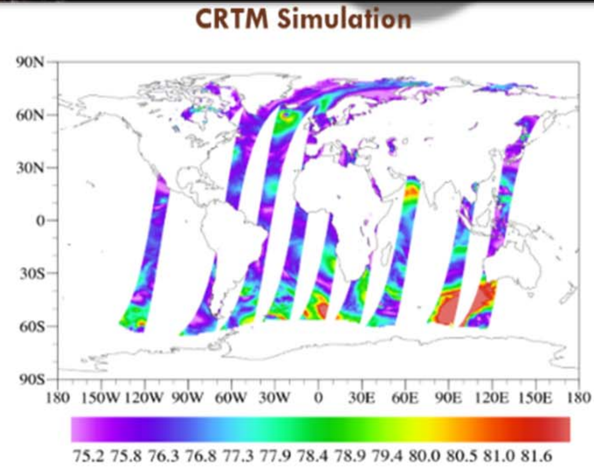
3) The tangent linear and adjoint modules of the physical MW land model implemented.

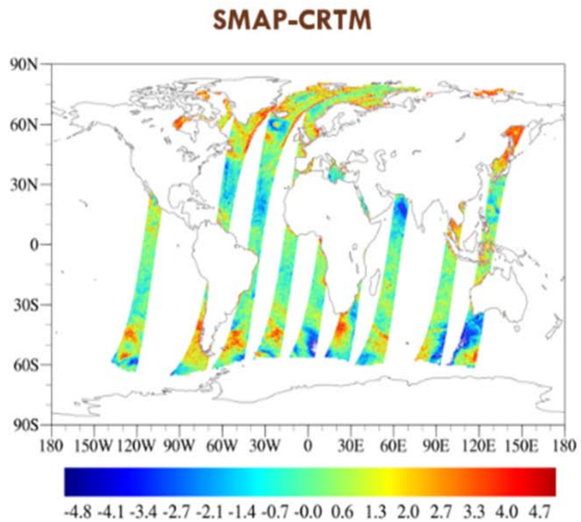
4) Implementation of L-band in CRTM has been tested with the integrated CRTM-CSEM.

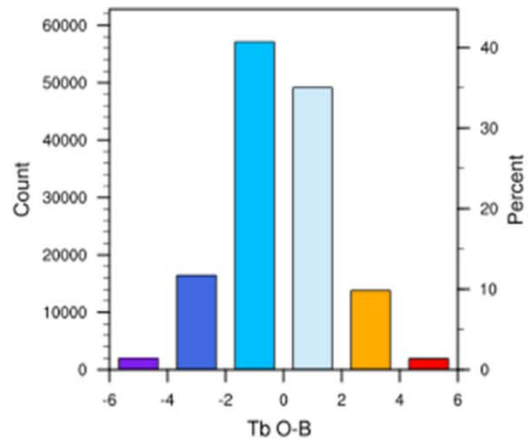
5) The testing of CRTM-CSEM in FV3 GFS/GSI is in progress.

6) Implementation of the JPL SMAP Level-3 monthly sea surface salinity (SSS) atlas into CSEM to account for the impact of SSS on the forward Tbs simulation and to improve the first guess accuracy in DA, especially for the L-band Tb.









Ongoing and Future Development

- CRTM 3.x
- JEDI / UFO implementation

Ongoing tasks toward CRTM 3.0

- **Cloudy Radiance** (P. Stegmann, E. Liu, Johnson)
  - Adding 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.
  - Continued testing of CSEM in GSI
- **Full Polarization Solver Capability** (T. Greenwald, Q. Liu, B. Johnson, C. Cao)
  - UV capable solver + polarization support under development
  - Need to touch each element of CRTM to support UV capabilities – still establishing scope of effort required.

Ongoing tasks toward CRTM 3.0

- **NLTE corrections** (Z. Li)
- **SW / IR improvements in CRTM**
  - IR Sea surface emissivity improvement (N. Nalli, M. Chen)
  - Aerosol + solar impacted IR (expert needed!)
- **Aerosols update** (Johnson, Stegmann, S. Lu, M. Pagowski, B. Scherllin-Pirscher, A. Naeger, NRL, GMAO, others).
  - Update of CHYM to work with aerosol tables (Johnson, Stegmann)
  - Improved aerosol indices of refraction (via D. Turner and J. Gasteiger)
  - Update toward CMAQ specifications (Team)
  - Improve Lidar backscattering and attenuation calculations (Pagowski, Scherllin-Pirscher)
- **Fast coefficient generation** (Johnson, Stegmann, Moradi, Q. Liu)
  - Modernized physically-based approach
  - AI / Machine Learning-based approach

Final Thoughts

- Need traceable requirements derived from observation and model
  - Science, model, computational efficiency
- Requirements drive development goals
  - Critical path planning for well-defined goals
- Coordinate effort toward primary NWP requirements
  - Reduce duplication of effort
  - Build consensus for requirements
- Establish maturity levels of RT model development
- Action: Report from this workshop to ITSC-22 (Oct. 2019), JCSDA/ECMWF Joint Workshop (Feb. 2020)
- Action: Initiate Whitepaper on Reference RT model requirements, to be presented at ITSC-22

Questions / Comments?

Please join our new CRTM google groups:

Announcements:
https://groups.google.com/forum/#!forum/crtm

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

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

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

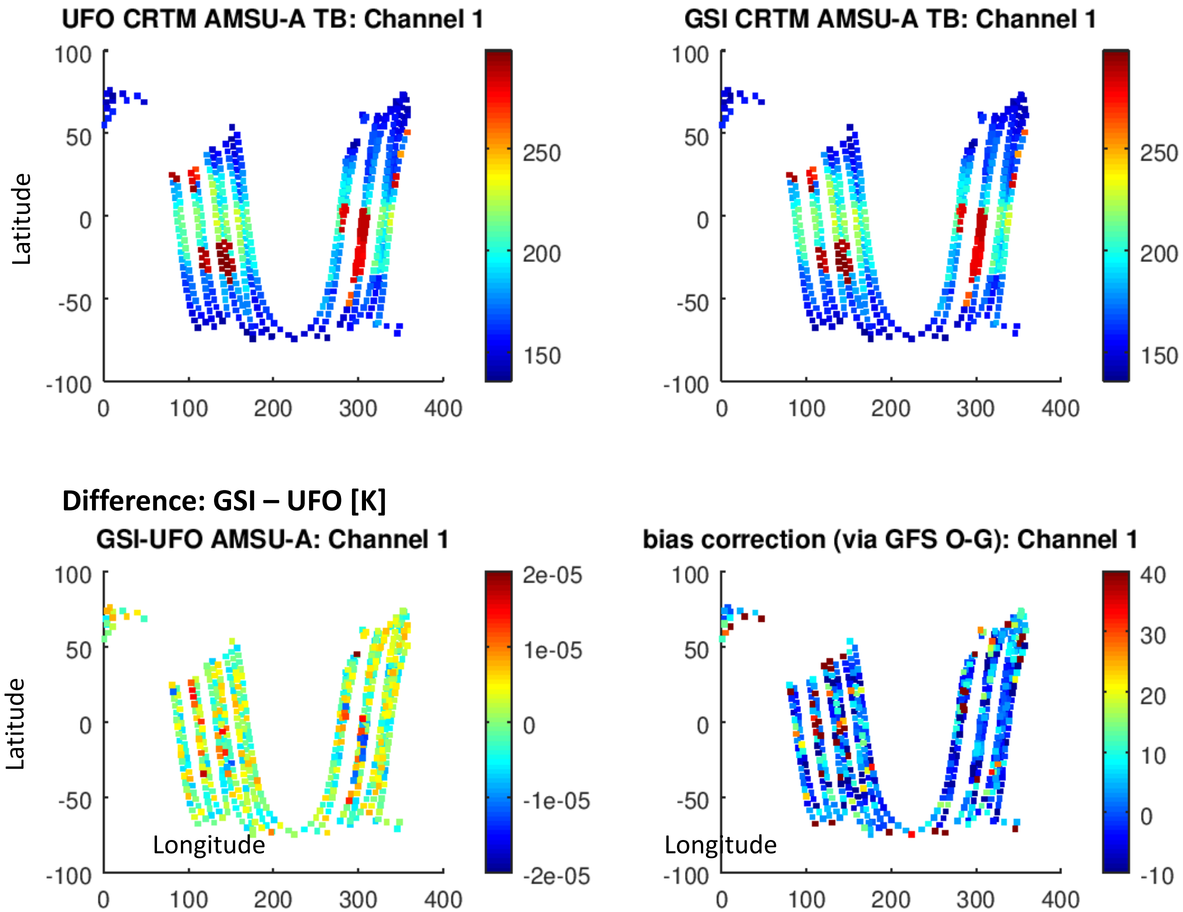
These groups replace the legacy listserv groups.

Joint Effort for Data Assimilation Initiative (JEDI)

Unified Forward Operator (UFO)

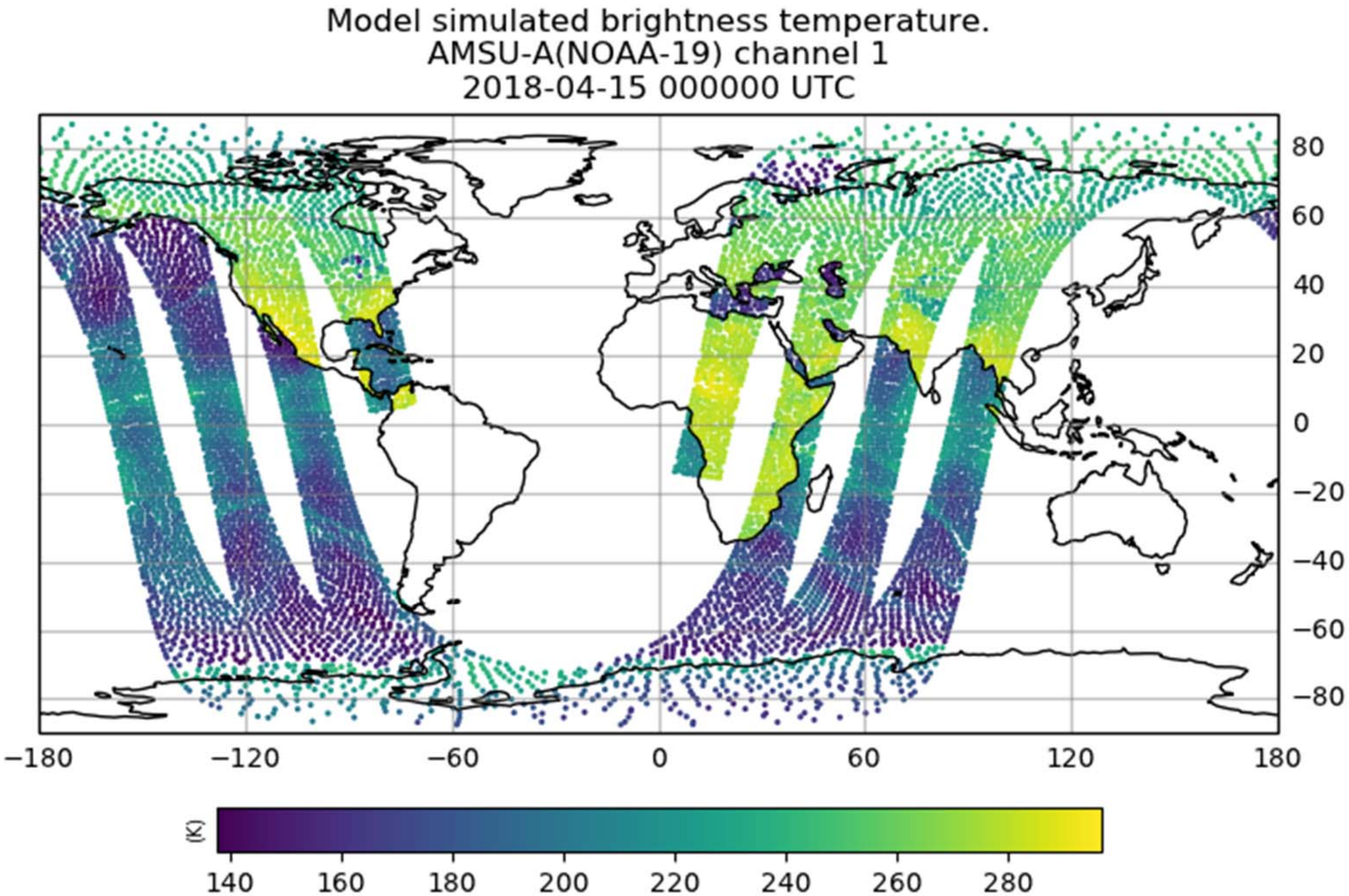
CRTM-JEDI Interface Forward Operator

- Goal: reproduce GSI-CRTM TBs via UFO interface
- 806 profiles taken from GSI
- Differences approximately 1e-5 K
- GSI bias correction provided for reference.
- **Key point**: UFO CRTM accurately reproduces GSI CRTM for the same physical profiles.
- FV3-JEDI interface mostly completed.
- Next: adding additional sensors according to priority.



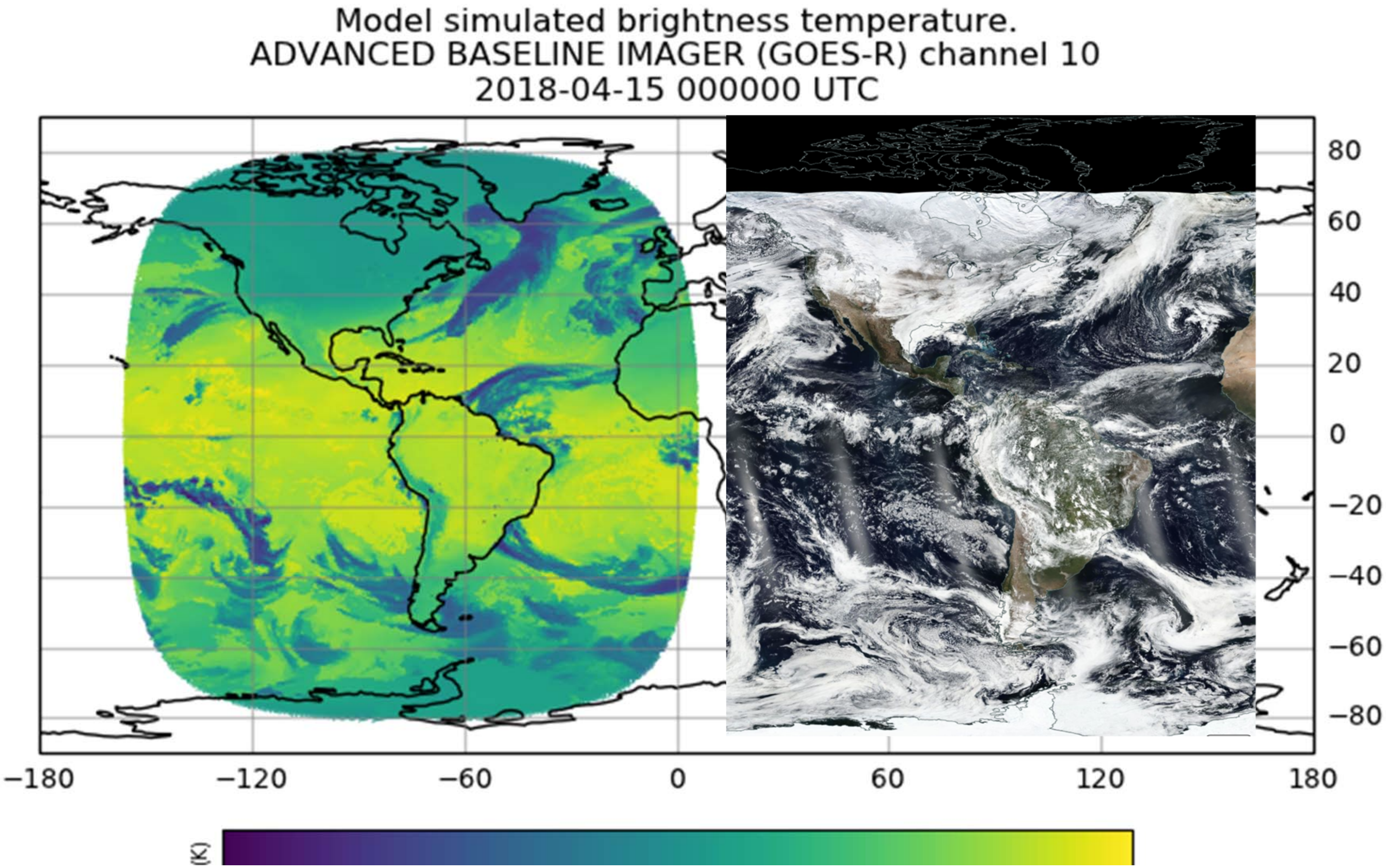
CRTM-JEDI Interface Forward Operator

- JEDI FV3-GFS model fields -> CRTM simulated **AMSU-A** radiances



CRTM-JEDI Interface Forward Operator

- JEDI FV3-GFS model fields -> CRTM simulated **GOES-16 ABI** radiance



Field 07 Snow Particle Size Distribution

IWC

T_c

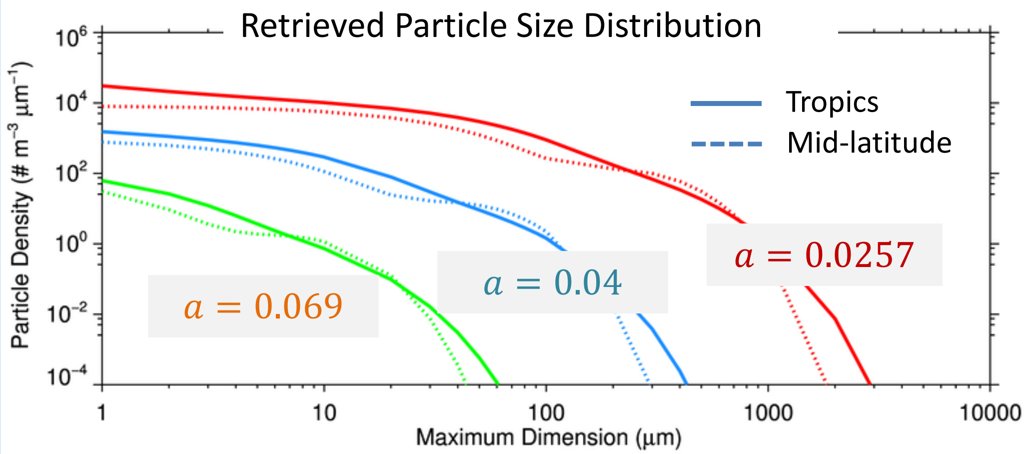
Mass-Dimensional Relationship

$m(D) = aD^b$

$IWC = 0.0931\ gm^{-3}$

$T_c = -49.7\ °C$

$m(D) = aD^2$



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

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

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

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

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

$$M_n = A(n)\exp[B(n)T_c]\, M_2^{C(n)}$$

$$A(n) = exp(13.6 - 7.76n + 0.479n^2)$$

$$\mathrm{B}(n) = -0.0361 + 0.0151n + 0.00149n^2$$

$$C(n) = 0.807 + 0.00581n + 0.0457n^2$$

Tropical Regime:

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

Mid-latitude Regime:

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

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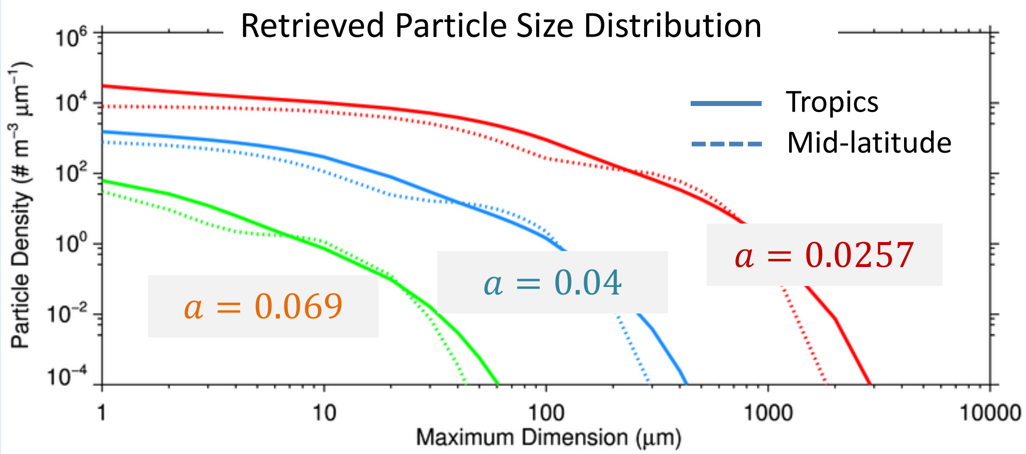

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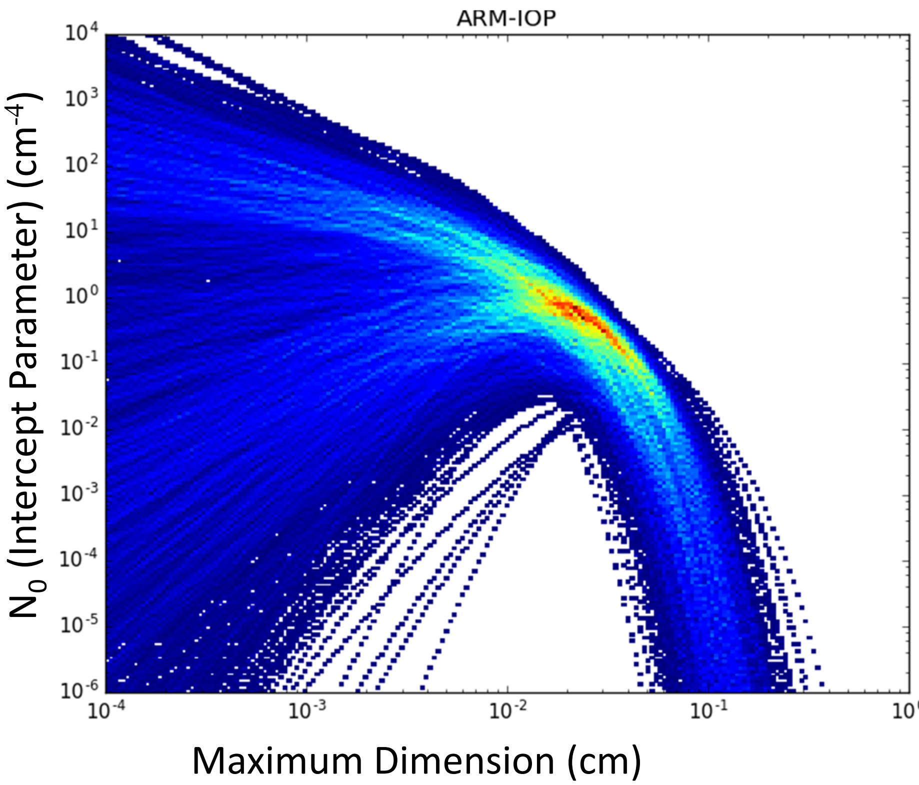
Field Campaign information

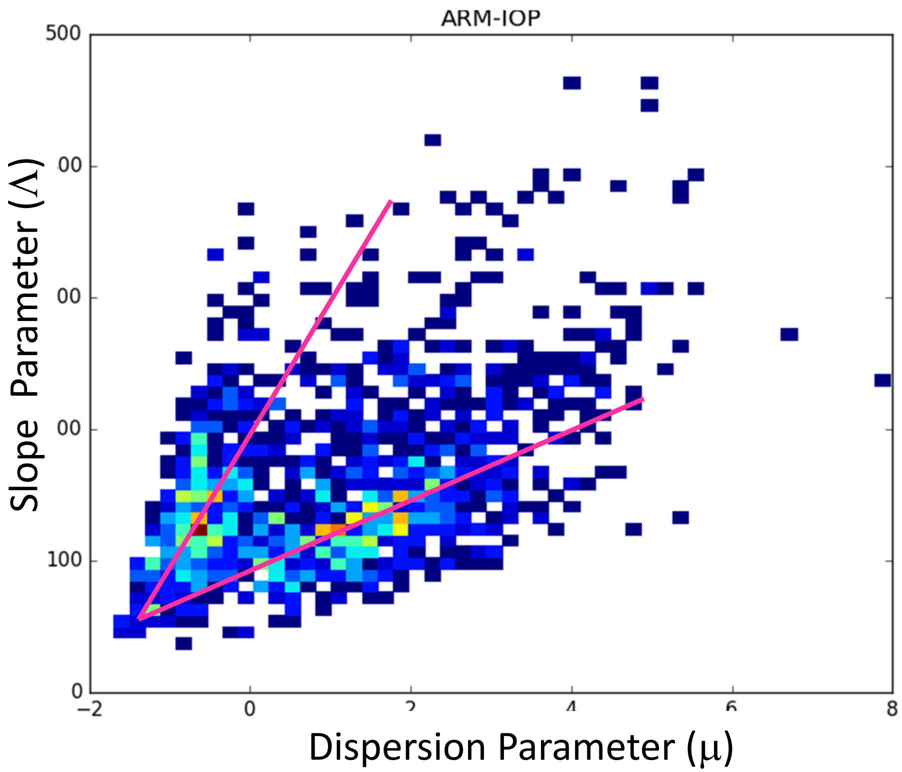
Field Campaign	Year	Location	Instruments	# PSDs
ARM-IOP	2000	Oklahoma, USA 2000	2D-C, 2D-P, CPI, CVI, FSSP	1420
TRMM-KWAJEX	1999	Kwajalein, Marshall Islands 1999	2D-C, HVPS, FSSP	201
CRYSTAL-FACE	2004	SE Florida/Caribbean 2002	CAPS (CIP, CAS), VIPS	62
SCOUT	2005	Darwin, Australia 2005	FSSP, CIP	553
ACTIVE – 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

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:

$\boxed{n(D) = \boldsymbol{N_o}\, D^{\boldsymbol{\mu}}\, e^{-\boldsymbol{\lambda} D}}$ 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

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

k[th] 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)

WRF with modification from Ruiyu Sun

THOMPSON CLOUD SCHEME

Liquid Hydrometeors

Variable	Habit	Density ρ	Mass-Diameter $m-D$	Size Distribution $N(D)$	Distribution Parameters	Effective (Characteristic) Diameter D_e
Cloud Water q_c $w_c = \rho_a q_c$	Spherical	1.00	$a_c D^{b_c} = \frac{\pi}{6}\rho_c D^3$	Gamma $N_{oc}\, D^{\mu_c}\, e^{-\lambda_c D}$	$N_{tc} = 10^8\ m^{-3}$ (maritime) Prescribed $\mu_c = min\left(15, \frac{10^9}{N_{tc}} + 2\right);\ 2 < \mu_c <= 15$ $\lambda_c = \left(\frac{a_c\, N_{tc}\, \Gamma(\mu_c + b_c + 1)}{\rho_a\, q_c\, \Gamma(\mu_c + 1)}\right)^{\frac{1}{b_c}}$ $N_{oc} = \frac{N_{tc}\, \lambda_c^{\mu_c+1}}{\Gamma(\mu_c + 1)}$	$D_{ec} = \frac{M_3}{M_2}$ $= \frac{\int_0^\infty D^3 N(D) dD}{\int_0^\infty D^2 N(D) dD}$ $= \frac{\Gamma(\mu_c + 4)\lambda^{-(\mu_c+4)}}{\Gamma(\mu_c + 3)\lambda^{-(\mu_c+3)}}$ $= \frac{\mu_c + 3}{\lambda_c}$
Rain q_r N_{tr} $w_r = \rho_a q_r$	Spherical	1.00	$a_r D^{b_r} = \frac{\pi}{6}\rho_r D^3$	Exponential $N_{or}\, D^{\mu_r}\, e^{-\lambda_r D}$	$\mu_r = 0$ $\lambda_r = \left(\frac{a_r\, N_{tr}\, \Gamma(\mu_r + b_r + 1)}{\rho_a\, q_r\, \Gamma(\mu_r + 1)}\right)^{\frac{1}{b_r}}$ $N_{or} = \frac{N_{tr}\, \lambda_r^{\mu+1}}{\Gamma(\mu_r + 1)}$	$D_{er} = \frac{M_3}{M_2}$ $= \frac{\int_0^\infty D^3 N(D) dD}{\int_0^\infty D^2 N(D) dD}$ $= \frac{\Gamma(\mu_r + 4)\, \lambda^{-(\mu_r+4)}}{\Gamma(\mu_r + 3)\, \lambda^{-(\mu_r+3)}}$ $= \frac{3}{\lambda_r}$

All units are defined in SI units unless noted

Solid Hydrometeors

Variable	Habit	Density ρ	Mass-Diameter $m - D$	Size Distribution $N(D)$	Distribution Parameters	Effective (Characteristic) Diameter D_e
Cloud Ice $\mathbf{q_i}$ $\mathbf{N_{ti}}$ $\mathbf{w_i = \rho_a q_i}$	Spherical	0.89	$a_i D^{b_i} = \frac{\pi}{6}\rho_i D^3$	Exponential $N_{oi}\, D^{\mu_i}\, e^{-\lambda_i D}$	$\mu_i = 0$ $\lambda_i = \left(\frac{a_i\, N_{ti}\, \Gamma(\mu_i + b_i + 1)}{\rho_a\, q_i\, \Gamma(\mu_i + 1)}\right)^{\frac{1}{b_i}}$ $N_{oi} = \frac{N_{ti}\, \lambda_i^{\,\mu+1}}{\Gamma(\mu_i + 1)}$	$D_{ei} = \frac{M_3}{M_2}$ $= \frac{\int_0^\infty D^3 N(D) dD}{\int_0^\infty D^2 N(D) dD}$ $= \frac{\Gamma(\mu_i+4)\lambda^{-(\mu_i+4)}}{\Gamma(\mu_i+3)\lambda^{-(\mu_i+3)}}$ $= \frac{3}{\lambda_i}$

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Solid Hydrometeors

Variable	Habit	Density ρ	Mass-Diameter $m - D$	Size Distribution $N(D)$	Distribution Parameters	Effective (Characteristic) Diameter D_e
Graupel q_g $w_g = \rho_a q_g$	Spherical	0.50	$a_g D^{b_g} = \frac{\pi}{6}\rho_g D^3$	Exponential $N_{og}\, D^{\mu_g}\, e^{-\lambda_g D}$	$N_{o,min} = 10^{-4}$ $N_{o.max} = 3 \times 10^6$ $x = \begin{cases} 4.01 + \log_{10}(D_{med,r}) & T < 270.56 \text{ and } D_{med,r} < 10^{-4} \\ 0.01 & Otherwise \end{cases}$ $Where\ \ D_{med,r} = \frac{3+\mu_{0,}+0.672}{\lambda_r}$ $is\ the\ median\ mass\ diameter\ for\ rain$ $y = 4.31 + \log_{10}(\max(5 \times 10^{-5}, \rho_a q_r))$ $z = 3.1 + \frac{100}{\left[\frac{300xy}{\left(\frac{10}{x} + 1 + 0.25y\right)} + 30 + 10y\right]}$ $N_{o,exp} = 10^z$ $N_{o,exp} = max\left(N_{o,min}, min\left(N_{o,exp}, N_{o,max}\right)\right)$ $N_{o,min} = min\left(N_{o,exp}, N_{o,min}\right)$ $N_{o,exp} = N_{o,min}$ $\lambda_{exp} = N_{o,exp}\left(\frac{a_g\Gamma(b_g+1)}{\rho_a q_g}\right)^{\frac{1}{b_g+1}}$ $\lambda_g = \lambda_{exp}\left(\frac{\Gamma(b_g+\mu_g+1)}{(b_g+\mu_g+1)(\mu_g+1)}\right)^{\frac{1}{b_g}}$ $N_{og} = \frac{N_{o,exp}}{(\Gamma(\mu_g+1)\lambda_{exp})}\lambda_g^{\mu_g+1}$	$D_{eg} = \frac{M_3}{M_2}$ $= \frac{\int_0^\infty D^3 N(D)dD}{\int_0^\infty D^2 N(D)dD}$ $= \frac{\Gamma(\mu_g+4)\lambda^{-(\mu_g+4)}}{\Gamma(\mu_g+3)\lambda^{-(\mu_g+3)}}$ $= \frac{3}{\lambda_g}$

All units are defined in SI units unless noted

Solid Hydrometeors (Field 2007)

Variable	Habit	Density ρ	Mass-Diameter $m-D$	Size Distribution $N(D)$	Distribution Parameters	Effective Diameter D_e
Snow q_s $w_s = \rho_a q_s$	Non-spherical Fractal-like aggregated crystals (Cox,1988)	Variable (?)	$a_s D^{b_s} = 0.069D^2$	Field (2007) $\begin{cases} x = D\frac{M_2}{M_3} \\ \Phi_{23}(x) = N(D)\frac{M_3^3}{M_2^4} \end{cases}$ $N(D) = \Phi_{23}(x)\frac{M_2^4}{M_3^3}$	$M_n = A(n)\exp[B(n)T_c]\, M_2^{C(n)}$ $A(n) = exp(13.6 - 7.76n + 0.479n^2)$ $\mathrm{B}(n) = -0.0361 + 0.0151n + 0.00149n^2$ $C(n) = 0.807 + 0.00581n + 0.0457n^2$ $w_s = \rho_a q_s = a_s M_{b_s} \rightarrow M_{b_s} = \frac{w_s}{a_s} = \frac{\rho_a q_s}{a_s}$ $M_2 = \left(\frac{M_{b_s}}{A(b_s)\, exp[B(b_s)T_c]}\right)^{\frac{1}{C(b_s)}} \rightarrow M_n = A(n)\exp[B(n)T_c]\, M_2^{C(n)}$ Tropical Regime: $\Phi_{23}(x) = 152e^{-12.4x} + 3.28x^{-0.78}e^{-1.94x}$ Mid-latitude Regime: $\Phi_{23}(x) = 141e^{-16.8x} + 102x^{2.07}e^{-4.82x}$	$D_{es} = \frac{M_3}{M_2} = \frac{\int_0^\infty D^3 N(D)dD}{\int_0^\infty D^2 N(D)dD}$

The effective ice-particle density is parameterized through a mass-dimension relationship

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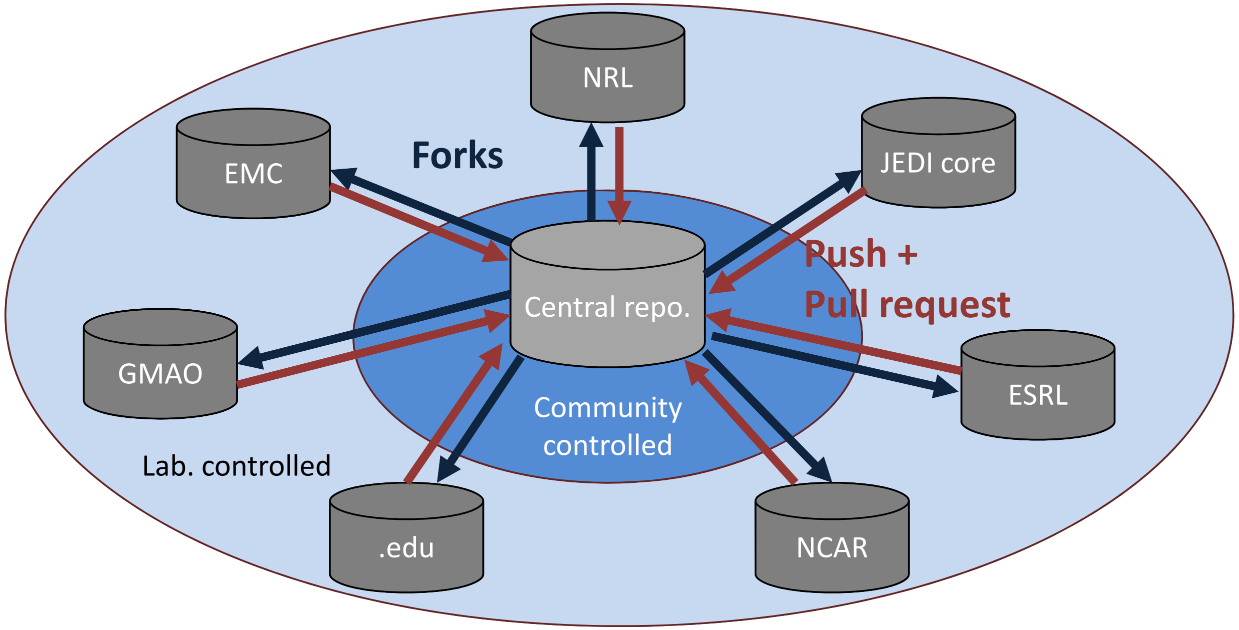
Collaboration, Education, and Outreach

A “new” way of collaborating



- Strong community engagement @coding level (not ‘working groups’)
- Transparent and inclusive process
- Continuous online discussions + testing
- Fast-paced code development + reviews

- Community repositories on github.com/JCSDA + flexible build system + ‘graduate student test’
- Improved collaborative environment (Zenhub issue tracking, Sphinx/ReadTheDocs/Doxygen, Singularity containers)
- Enforce software quality (correctness, coding norms, efficiency)
- Initial work toward continuous integration

Education / Training / Outreach

The CRTM team successfully held the CRTM User/Developer's workshop on May 16, 2017 in conjunction with the CRTM Scientific and Technical workshop (May 17 – May 19). The workshop consisted of a series of tutorials on CRTM operation and development. A particular focus was on covering the adjoint and tangent-linear programming. Also covered was spectral and transmittance coefficient generation, and regression / unit testing. There were 7 instructors more than 40 participants -- with about 16 in-person and more than 25 online.

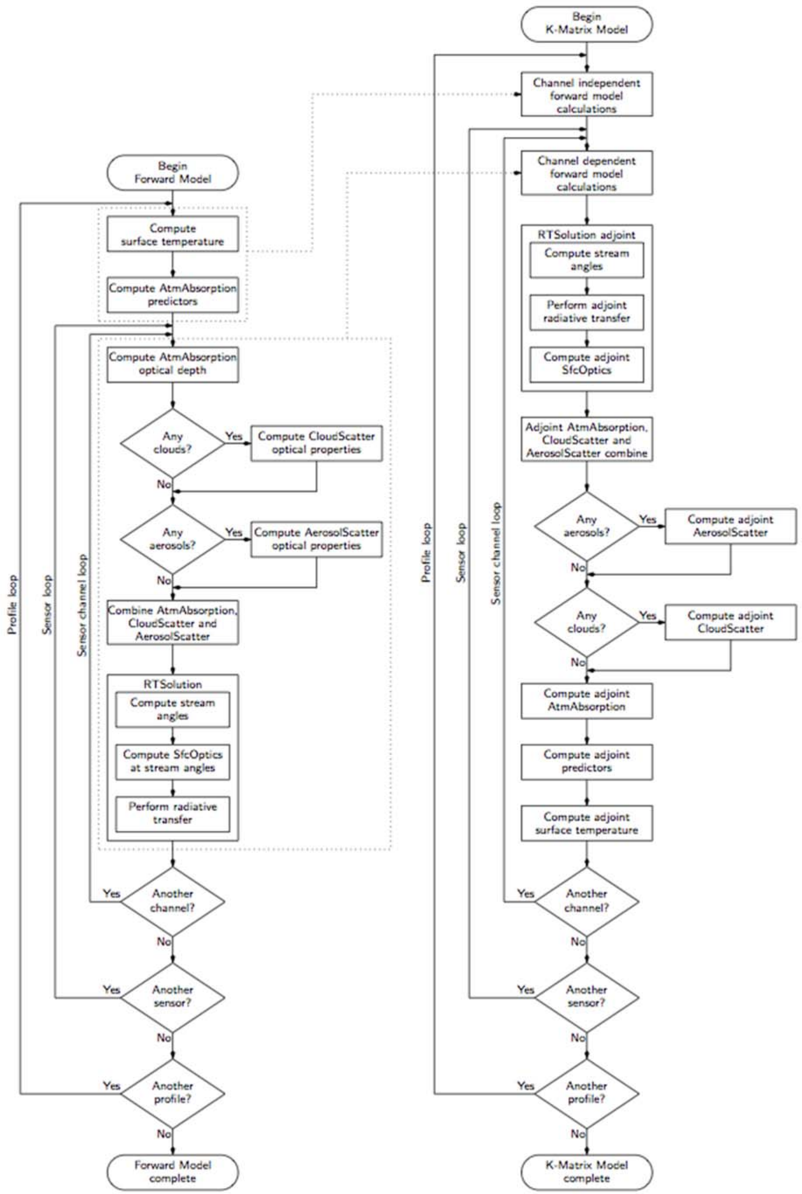
Participant feedback was overwhelmingly positive.

NOTE: A new workshop will be held in 2019, date / time / location TBD

JCSDA Summer Colloquium on Satellite Data Assimilation

Bozeman, Montana July 22 – August 3, 2018

- **Objective:** Foster the education of the next generation of data assimilation scientists.
- **Colloquium Topics:**
  - Data assimilation fundamentals including variational and ensemble techniques
  - Satellite data observation techniques, including infrared and microwave
  - Satellite data assimilation techniques
  - Overview of atmospheric, ocean, land, sea-ice, wave and aerosol data assimilation
  - Overview of the global observing system.
- **Summary Article:**
  - https://repository.library.noaa.gov/view/noaa/19248



(a) Forward Model (b) K-Matrix Model

Overview

- CRTM uses regression transmittance models
- Cloud and aerosol optical properties are read from a LUT
- Surface emissivity models are split into four “gross” surface types (land, water, snow, and ice) and three spectral regions (microwave, infrared, and visible). There is a great variety of model implementations, e.g. surface categories, emissivity atlases, empirical models, physical models.
- Radiative transfer is a simple emission model for clear sky; ADA, or SOI, for scattering.
- Inputs and outputs to the CRTM are packaged in their own structures.
- Tangent-linear, adjoint, and K-matrix functions are all constructed “line-by-line” from the forward model. Each are stand-alone, i.e., the forward model calls are incorporated in each.