[1.02] The Community Radiative Transfer Model: A Community Model for Operational Contributions

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Isaac Moradi (NASA/GMAO)
And *many, many, others over the years.*

Aerosol Model Collaborators:

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Peng Xian, Jeff Reid *(NRL)*
James Hocking *(Met Office)*
Shih-Wei Wei, Cheng-Hsuan (Sarah) Lu *(JCSDA/UCAR, University at Albany, SUNY)*

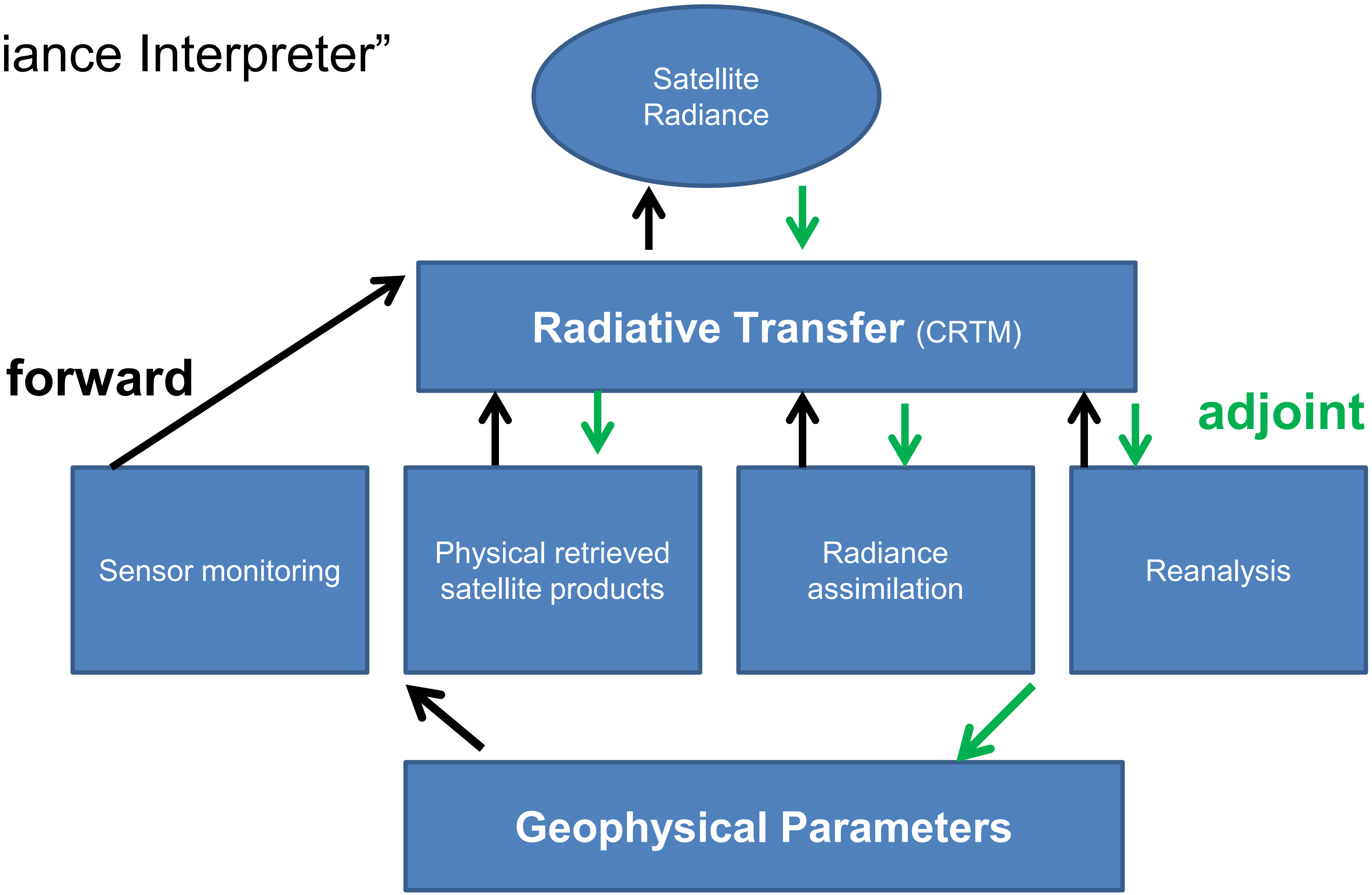
Community Radiative Transfer Model (CRTM)

The *Community Radiative Transfer Model (CRTM)* is a fast, 1-D radiative transfer model used in numerical weather prediction, calibration, and validation across multiple federal agencies and universities.

- **Goal**: fast and accurate community radiative transfer model to enable assimilation and satellite observations under all weather conditions.
- **Type**: 1-D plane parallel, multi-stream radiative transfer algorithms.
- **Key Components**: aerosol, cloud, precipitation, gas, atmosphere and surface. Includes NLTE and Zeeman simulations. Written in modern Fortran (2003+)
- **History**: originally developed (as CRTM) around 2004 by Paul van Delst (U. Wisc), 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).

What does the CRTM do?

It's a "Radiance Interpreter"



CRTM enables use of satellite observations

- Satellites are Costly
  - Design, Construction, Launch, Operations, De-orbit
  - Short lifetimes (< 10 years)
  - GOES-T: $11.7B
  - JPSS: $6.8B (J2 - J4)
- Most observation data goes unused in data assimilation
  - What we do use provides up to 20% of short-range forecast skill improvements (e.g., Geer et al., 2017)
  - Typically up to 80% of available mid-tropospheric observations in cloud-affected scenes are discarded (Geer et al., 2018)

Sources (from left to right): alexyz3d, ABCDstock, 3dsculptor, Framestock, Paul Fleet/stock.adobe.com.

CRTM supports a wide variety of platforms

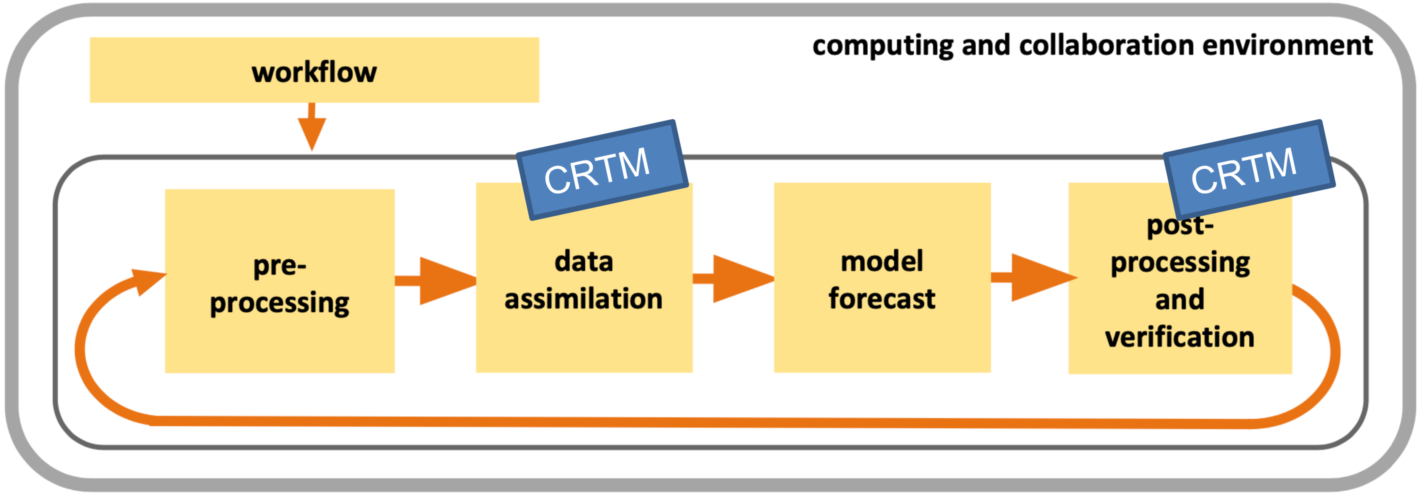
- **Space- and Aircraft-based sensors**
  - GEO/LEO/ISS
  - UV, Visible, Infrared, Microwave
  - 200+ sensors, ~50 actively used
  - Support for primary operational sensors
    - NOAA, NASA, DoD, Europe, Asia, South America, Australia
    - GOES, JPSS, PMM/AOS, METOP, MeteoSat, DMSP, etc.
- **New sensors**
  - Concept, design, evaluation
  - SmallSat / Constellation planning (TROPICS, GEMS, tomorrow.io, etc.)
- **Calibration / Validation**
  - Ensuring sensor accuracy

CRTM: the critical enabling component

- Enables DA in US systems
  - NOAA: UFS, GFS, RRFS, UPP, etc.
  - UCAR: JEDI
  - NASA: GEOS, MERRA
  - DoD: Navy / Air Force

UFS
UNIFIED FORECAST SYSTEM

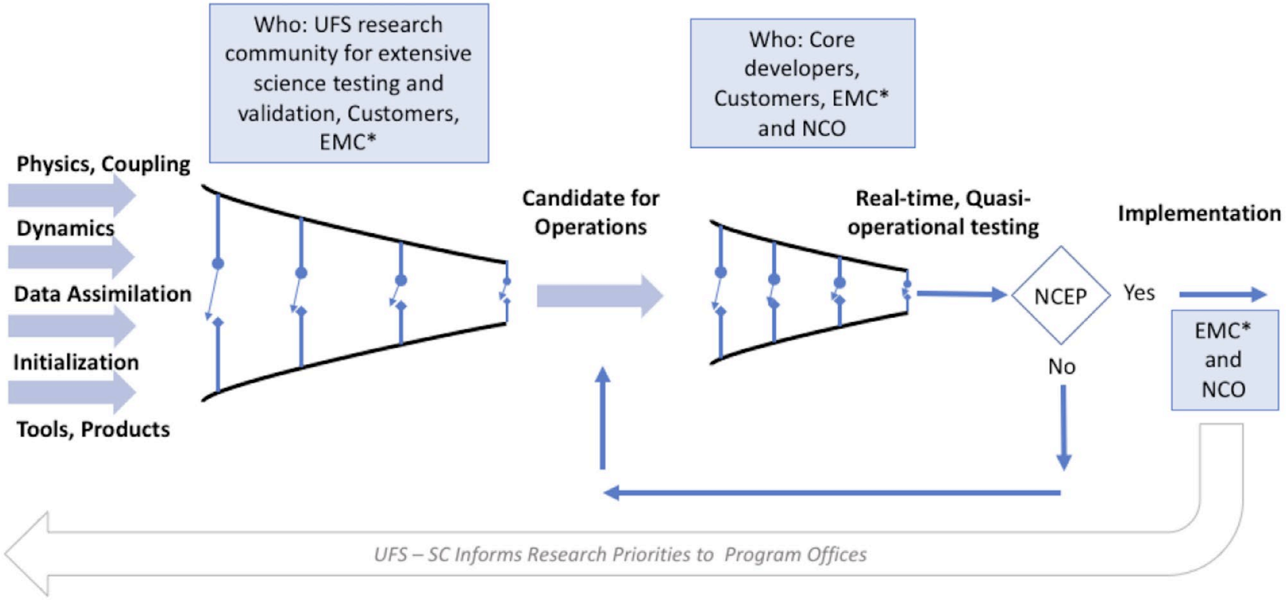
Parts of a UFS Application



Pre-processing and data assimilation	• Stages inputs, performs observation processing, and prepares an analysis
Model forecast	• Integrates the model or ensemble of models forward
Post-processing and verification	• Assesses skill and diagnoses deficiencies in the model by comparing to observations
Workflow	• Executes a specified sequence of jobs
Computing and collaboration environment	• May be different for research (experiment focus) and operations (forecast focus) • Provides actual or virtualized hardware, databases, and support

CRTM: A Research to Operations (R2O) Pipeline

- Rapid Transition of Research to Operations
  - Modern/Agile Software Development
  - Modern Repository management: GitHub / Zenhub
  - Community Driven development
  - Interdependent project coordination
  - Deep engagement in key scientific communities
  - Public Domain license
- Full cooperation with operational centers
- Direct collaboration with satellite sensor science teams / data product teams (public / private)



* EMC or any NOAA entity responsibility for the application (e.g. GSD, MDL, NOS etc.)

CRTM

key technical capabilities

Support for Polarized **UV, VIS/near-IR, IR, sub-MM, MW** – future: far IR.

Instrument specific (center frequency, bandwidth, side bands, viewing geometry, polarization basis, spectral response)

Clouds: multi-species / habits supporting clouds / precipitation from VIS -> MW, microphysics-model specific LUTs (Thompson, GFDL, WSM-6)

Aerosols (detailed later)

Gaseous species available in CRTM: H_2O, CO_2, O_3, N_2O, CO, CH_4, O_2, NO, SO_2, NO_2, HNO_3, N_2, OCS, and CFCs – *many others available from LBLRTM, not yet used in CRTM.*

Surface properties: land (soil moisture, vegetated), ocean (wind, foam,), sea-ice, snow cover (land, sea-ice, depth) --- primarily tested in IR/MW.

Active sensor development: space-based radar / lidar (backscat, extinct.)

Non-LTE (daytime) and Zeeman effects; Aircraft-based simulation

CRTM v3.0 (under heavy development)

https://github.com/JCSDA/CRTMv3

Status: Code merged with v2.4.1, v3.0.0 release expected Dec. 30, 2022

- Full Polarization Solver Capability
  - ▣ UV capable solver + polarization support under evaluation (CRTM v3.0-beta) [Thanks Q. Liu]
- Aerosols
  - ▣ Improved aerosol indices of refraction (P. Yang/TAMU, P. Stegmann, D. Turner, J. Gasteiger, C. Dang)
  - ▣ Update of CRTM using initial CMAQ specifications (C. Dang, Y. Ma)
  - ▣ Improve Lidar backscattering and attenuation calculations (Pagowski, Scherllin-Pirscher)
- Cloud / Precipitation
  - ▣ Backscattering coefficients for CRTM active sensor capability (Moradi, Johnson, Stegmann)
  - ▣ 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
  - ▣ Update of CHYM for microphysical consistency with NWP (B. Johnson, G. Thompson, Y. Lu, E. Clothiaux)
- Surface
  - ▣ Test CRTM-CSEM in GFS/GSI, focusing on the comparisons among model options. (M. Chen)
  - ▣ Initial implementation of MW ocean surface BRDF model
  - ▣ Ocean Surface Emissivity improvements IR (IRSSE, N. Nalli), and Microwave (Team)
  - ▣ Improved snow cover / ice emissivity in IR (Nall), and Microwave (Team)
- SW / IR improvements in CRTM
  - ▣ Cloud, surface, and aerosol impacts on visible channels (C. Dang)

Motivation for Polarized RT :: CRTM v3

Observed GPM GMI V-H Brightness Temperature difference at 166 GHz for precipitating pixels

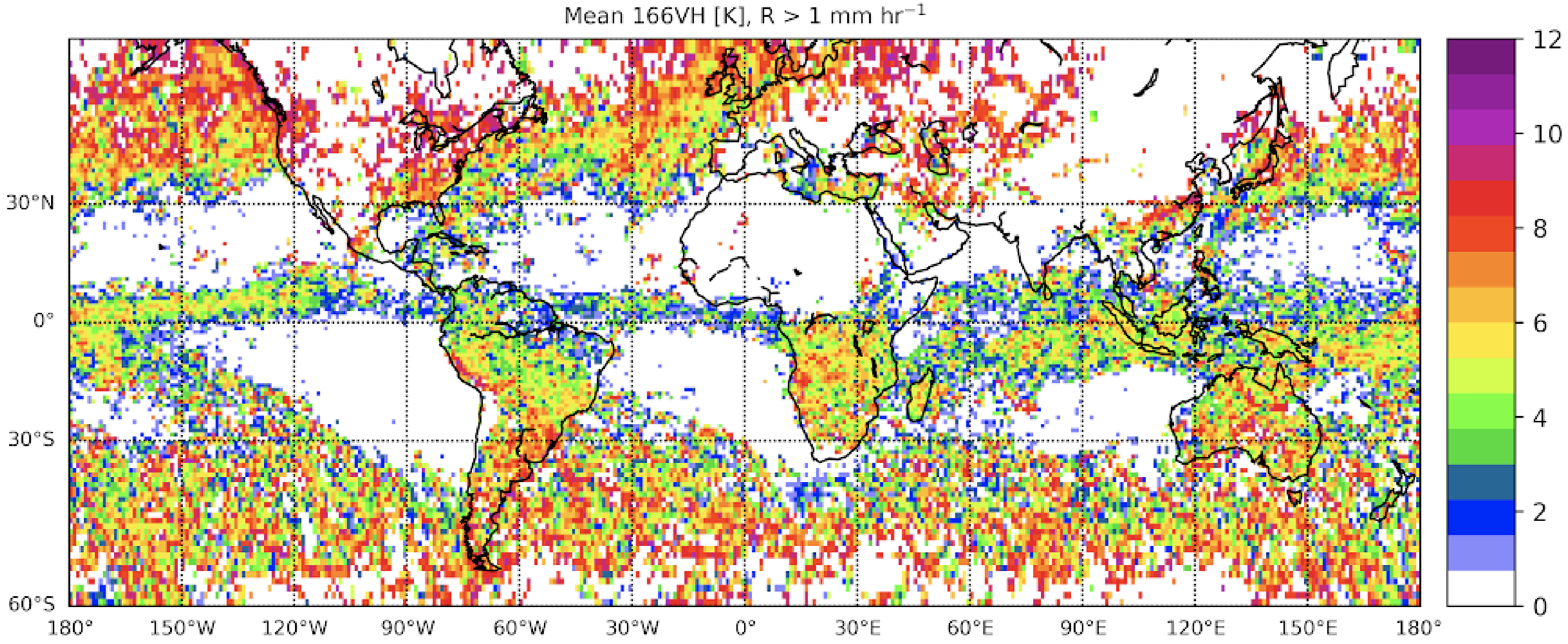
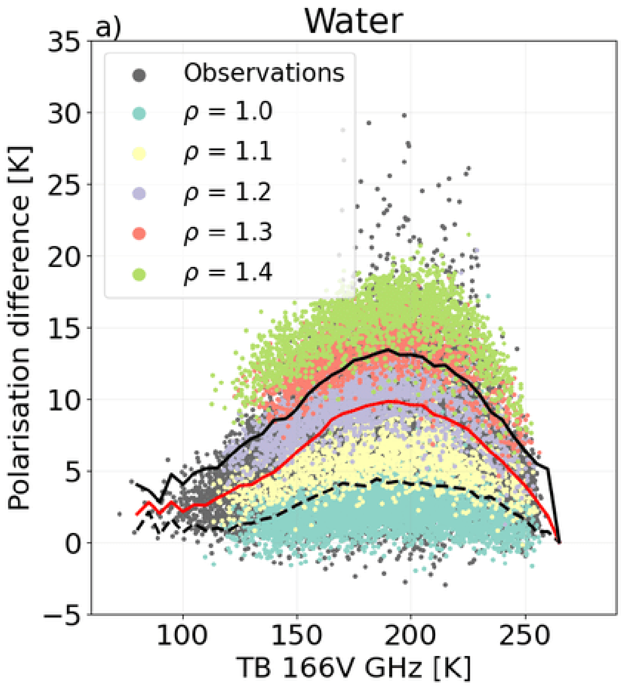


Image courtesy of V. Galligani

The polarization differences (166V − 166H) as a function of brightness temperatures at 166V GHz (PD-TB V relationship) over water. The GMI observations are shown in dark grey, while the other colors represent the simulations for different values of ρ. The three overlaid lines represent the 5th, 50th and 95th percentiles of the observed polarization differences for each TB interval. The simulations were based on large plate aggregate. The data affected by the surface were filtered out



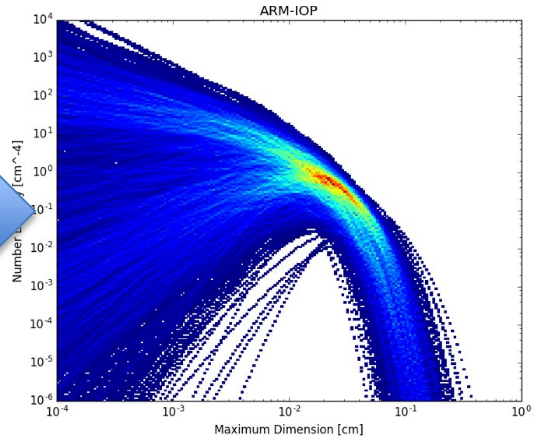
Kaur, I., Eriksson, P., Barlakas, V., Pfreundschuh, S. and Fox, S., 2022. Fast Radiative Transfer Approximating Ice Hydrometeor Orientation and Its Implication on IWP Retrievals. Remote Sensing, 14(7), p.1594.

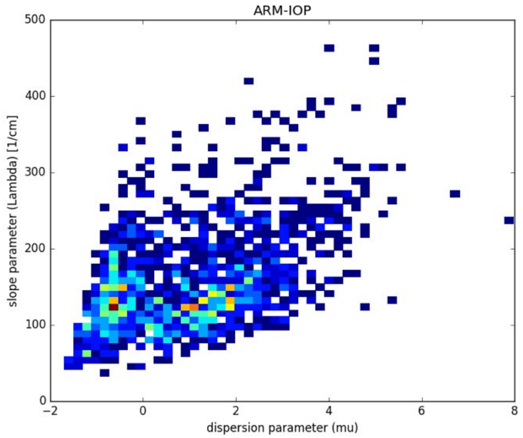
CRTM Community Hydrometeor Model (CHYM)

Purpose: An interface between CRTM and library of community generated cloud and precipitation particle physical and radiative properties.

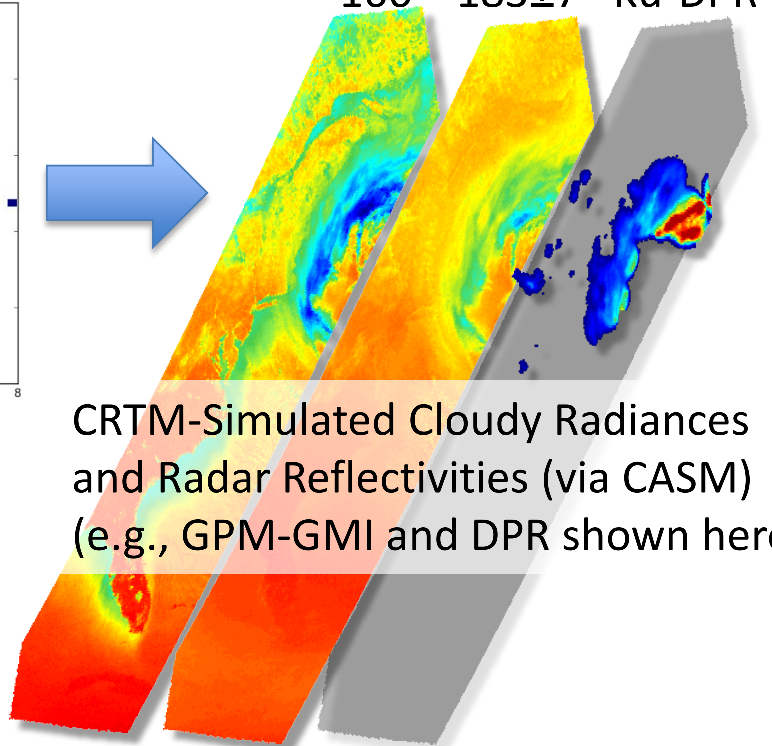
Impact: Provides physical consistency between NWP microphysical assumptions, CRTM microphysical assumptions – enabling accurate cloudy radiance simulation in support of all current and future sensor platforms. Significant improvement over current fixed LUT. Key sensors of interest: AIRS, IASI, MODIS, ABI, GPM-GMI, AMSU-A/B, MHS, SSMI/S, ICI, AOS, etc.

Single-Particle properties



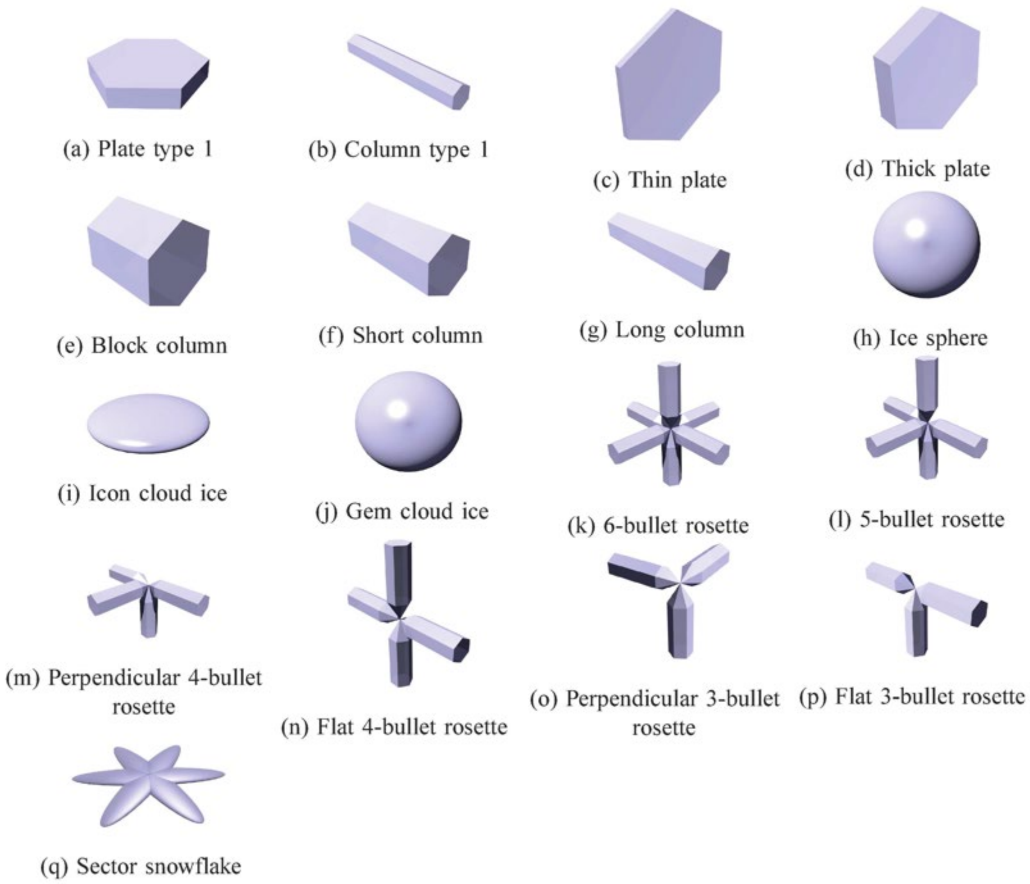


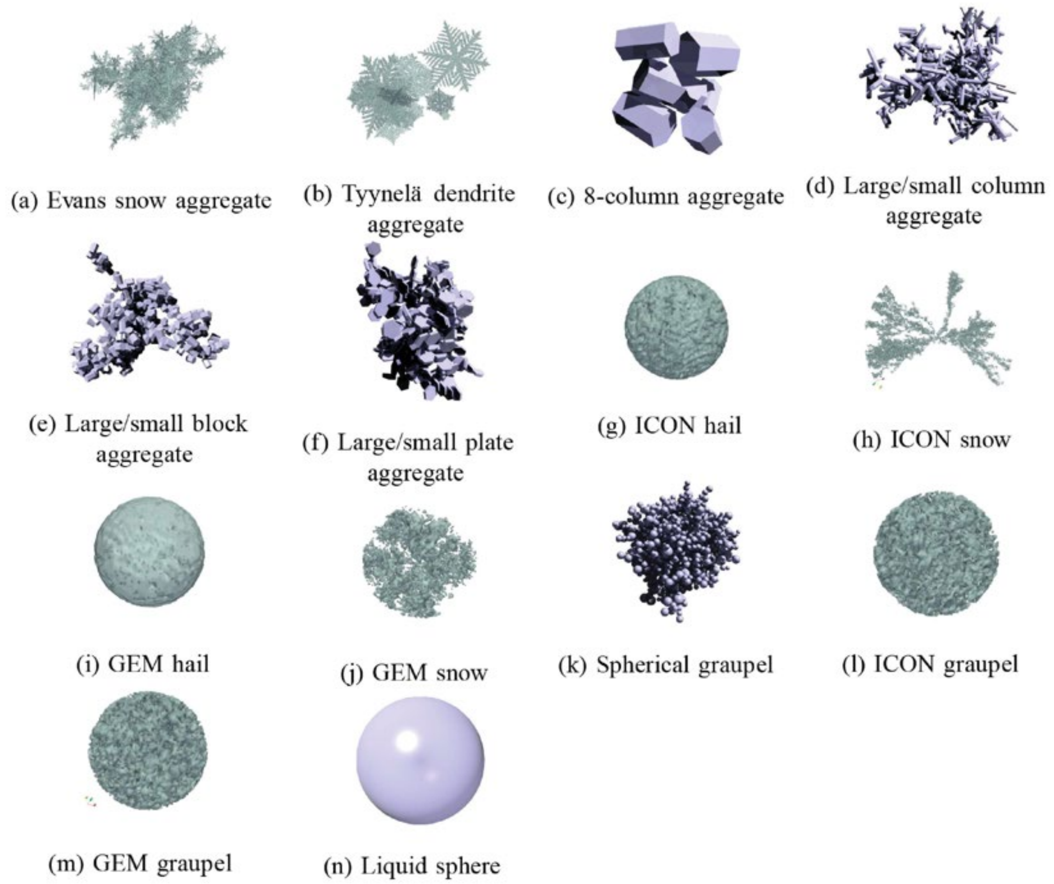
Size-distribution properties from multiple field observations



CRTM-Simulated Cloudy Radiances and Radar Reflectivities (via CASM) (e.g., GPM-GMI and DPR shown here)

Cloud Scattering Table Updates (I. Moradi, GMAO)





(a) Single crystal

(b) Aggregates and liquid habits

Figure 4: Single crystal, aggregate, and liquid habits included in the database generated by Eriksson et al. (2018). Note that although habits "h" and "j" may look identical in the image, they have different aspect ratio.

But first, we need two things: observational support of model choices, and a model to simulate ice melting

Calculate λ from model outputs

- Assume m-D relationship and Gamma distribution

$$m(D) = a\,D^b \qquad\qquad N(D) = N_0 D^{\mu} e^{-\lambda D}$$

- Single moment: output q (ρ_a can be calculated)

$$\rho_a q = IWC = \int_0^{\infty} aD^b N_0 D^{\mu} e^{-\lambda D}\,dD = aN_0 \frac{\Gamma(\mu+b+1)}{\lambda^{\mu+b+1}} \Rightarrow \lambda = \left(\frac{aN_0\Gamma(\mu+b+1)}{\rho_a q}\right)^{\frac{1}{\mu+b+1}}$$

- Double moment: output q and N_t

$$N_t = \int_0^{\infty} N_0 D^{\mu} e^{-\lambda D}\,dD = N_0 \frac{\Gamma(\mu+1)}{\lambda^{\mu+1}} \Rightarrow \frac{\rho_a q}{N_t} = \frac{a\Gamma(\mu+b+1)}{\lambda^b \Gamma(\mu+1)} \Rightarrow \lambda = \left(\frac{aN_t\Gamma(\mu+b+1)}{\rho_a q\Gamma(\mu+1)}\right)^{\frac{1}{b}}$$

Slides courtesy of Clothiaux, Lu, Chen

Commonly used PSD

- Mono-disperse (cloud ice/water)
- Gamma $N(D) = N_0 D^{\mu} e^{-\lambda D}$
- Exponential $N(D) = N_0 e^{-\lambda D}$
- Mixed (e.g., snow in Thompson 08) $N(D) = \frac{\mathcal{M}_2^4}{\mathcal{M}_3^3}\left[\kappa_0 e^{-\frac{\mathcal{M}_2}{\mathcal{M}_3}\Lambda_0 D} + \kappa_1 \left(\frac{\mathcal{M}_2}{\mathcal{M}_3} D\right)^{\mu_s} e^{-\frac{\mathcal{M}_2}{\mathcal{M}_3}\Lambda_1 D}\right]$

	Rain	Snow	Graupel
GFDL MP	Exp (N_0=8×10^6)	Exp (ρ=100, N_0=3×10^6)	Exp (ρ=400, N_0=4×10^6)
Thompson08	Exp (two-moment)	Exp + Gamma	Exp (ρ=500, N_0=200/q_g)
WSM6	Exp (N_0=8×10^6)	Exp [ρ=100, N_0=f(T)]	Exp (ρ=500, N_0=4×10^6)
And more …			

Slides courtesy of Clothiaux, Lu, Chen

Microphysics-consistent LUTs

- Bulk properties: single particle properties integrated over PSD
  - Mass $$m = \int_0^\infty m(D)N(D)dD$$
  - Scattering $$\beta_s = \int_0^\infty \sigma_s(D)N(D)dD$$
  - Extinction $$\beta_e = \int_0^\infty \sigma_e(D)N(D)dD$$
  - Single scattering albedo $$\omega_0 = \frac{\beta_s}{\beta_e} = \frac{\int_0^\infty \sigma_s(D)N(D)dD}{\int_0^\infty \sigma_e(D)N(D)dD}$$
  - Asymmetry parameter $$g = \frac{\int_0^\infty \sigma_s(D)g(D)N(D)dD}{\int_0^\infty \sigma_s(D)N(D)dD}$$
  - Legendre coefficients $$P_n = \frac{\int_0^\infty \sigma_s(D)P_n(D)N(D)dD}{\int_0^\infty \sigma_s(D)N(D)dD}$$

Red: from scattering DB
Blue: from PSD
Orange: bulk prop. in CRTM LUT

- Extinction per mass $\frac{\beta_e}{m}$

Per mass scattering properties

- Bulk mass and scattering coefficients

$$\beta_s = \int_0^\infty \sigma_s(D) N(D) dD \qquad m = \int_0^\infty m(D) N(D) dD$$

- Gamma distribution

$$N(D) = N_0 D^\mu e^{-\lambda D}$$

- CRTM LUTs use Scattering properties per mass.

$$\frac{\beta_s = \int_0^\infty \sigma_s(D) \cancel{N_0} D^\mu e^{-\lambda D} dD}{m = \int_0^\infty m(D) \cancel{N_0} D^\mu e^{-\lambda D} dD}$$

  - N_0 cancels!
  - Usually μ is fixed
  - Parameters λ determine scattering prop.

Slides courtesy of Clothiaux, Lu, Chen

Current CHyM efforts (Moradi/GMAO, TAMU/STAR, CRTM Team)

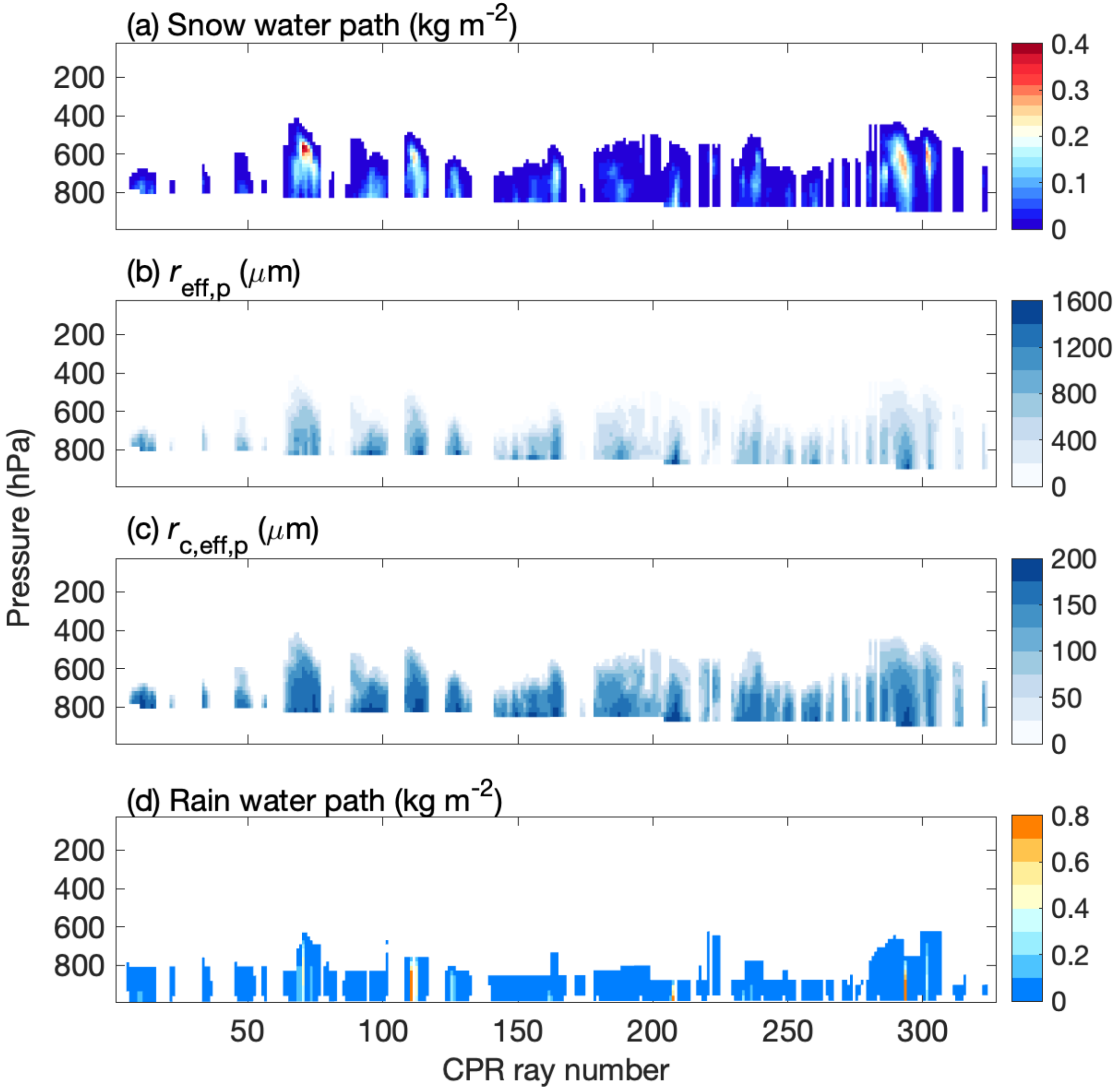
- Experimental Research: I. Moradi / GMAO
  - New scattering database generated using the DDA Uses water content for interpolation (over size) instead of effective radius
  - Changes made into CRTM CloudCoef modules to detach microwave and IR tables so the users can use different number of densities, temperatures etc for IR and MW
  - Evaluation of the CRTM scattering calculations using a collocated Era-5 and ATMS dataset
  - Progress on active sensor simulator (CASM) - the forward model and TL have been implemented and tested and AD is still under development
- TAMU provided a new cloud LUT (T. Ren, J. Ding, P. Yang, J. Coy)
- Implementation in CRTM. Preliminary tests was done against GFS model data collocated with ATMS observations and CloudSAT-GPM data. (Y. Ma, T. Ren)

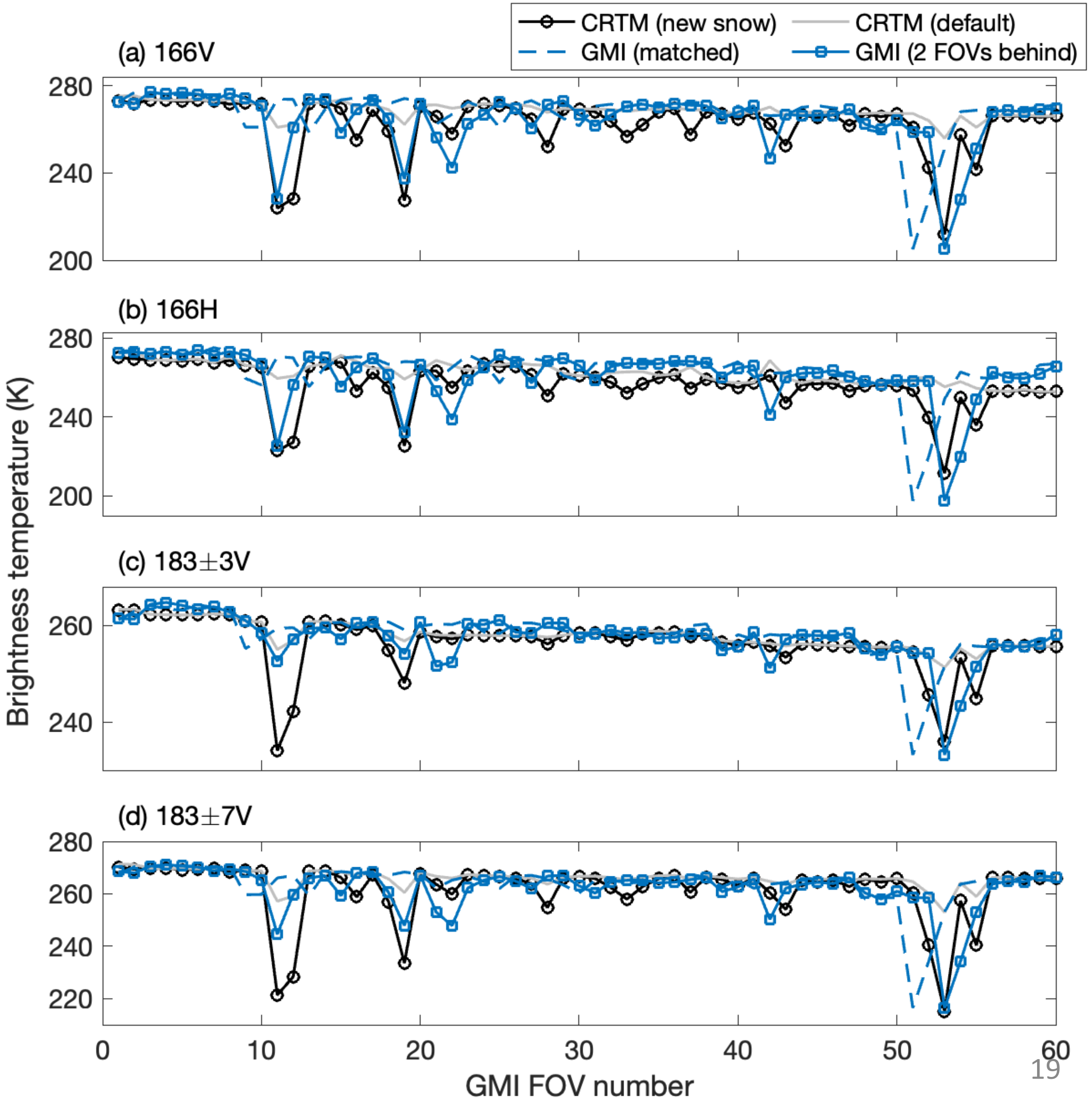
Current CHyM efforts (TAMU/STAR) [T. Ren et al, 2022]

	Snow		Graupel	
Spectral range	UV-IR (0.2-200 μm)	MW (1-874 GHz)	UV-IR (0.2-200 μm)	MW (1-874 GHz)
Spectral resolution	470 wavelengths	70 frequencies	470 wavelengths	70 frequencies
Size range/resolution	131 sizes from 2-100,000 μm		70 sizes from 2-250,000 μm	
Scheme	(1) constant bulk density of 0.1 g cm^{-3} (2) *m-D* relation in Thompson et al. (2008) (3) *m-D* relation in Heymsfield et al. (2004) (4) *m-D* relation in Brandes et al. (2007)		Five mass ratios of 0.1 to 0.9 with an increment of 0.2	Ten mass ratios from 0.1 to 1 with an increment of 0.1
Refractive index	At 266 K (Warren and Brandt 2008)	At five temperatures 190, 210, 230, 250, and 270 K (Iwabuchi and Yang 2011)	At 266 K (Warren and Brandt 2008)	At five temperatures 190, 210, 230, 250, and 270 K (Iwabuchi and Yang 2011)

Table 2. Dimensions of the snow and graupel single-scattering database in this study.

Current CHyM efforts (TAMU/STAR) [T. Ren et al, 2022]

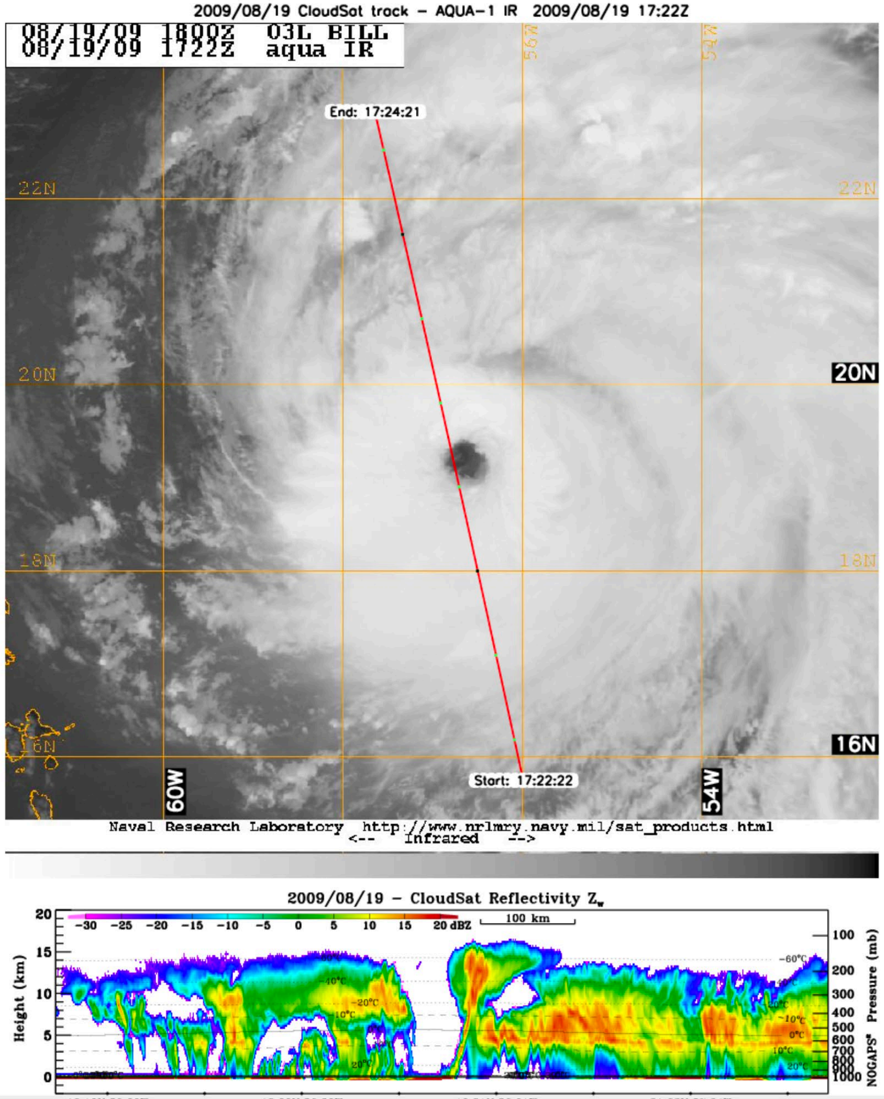




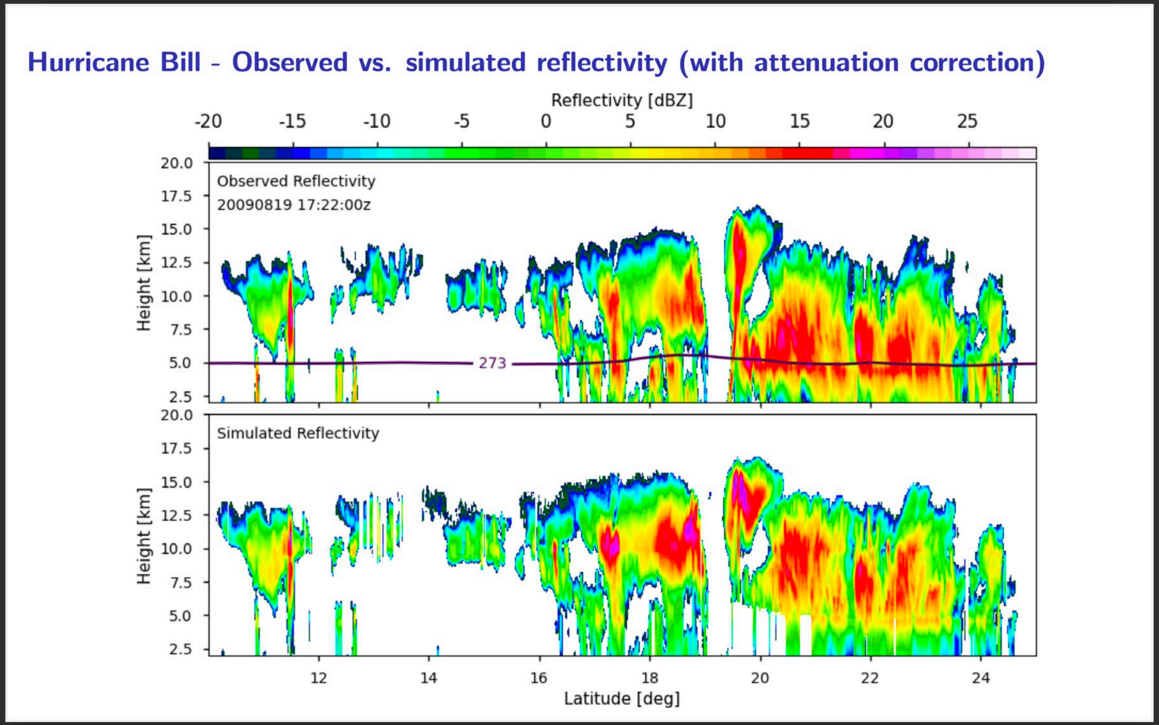
Space-based Radar Simulation (Moradi/Johnson) (cont.)

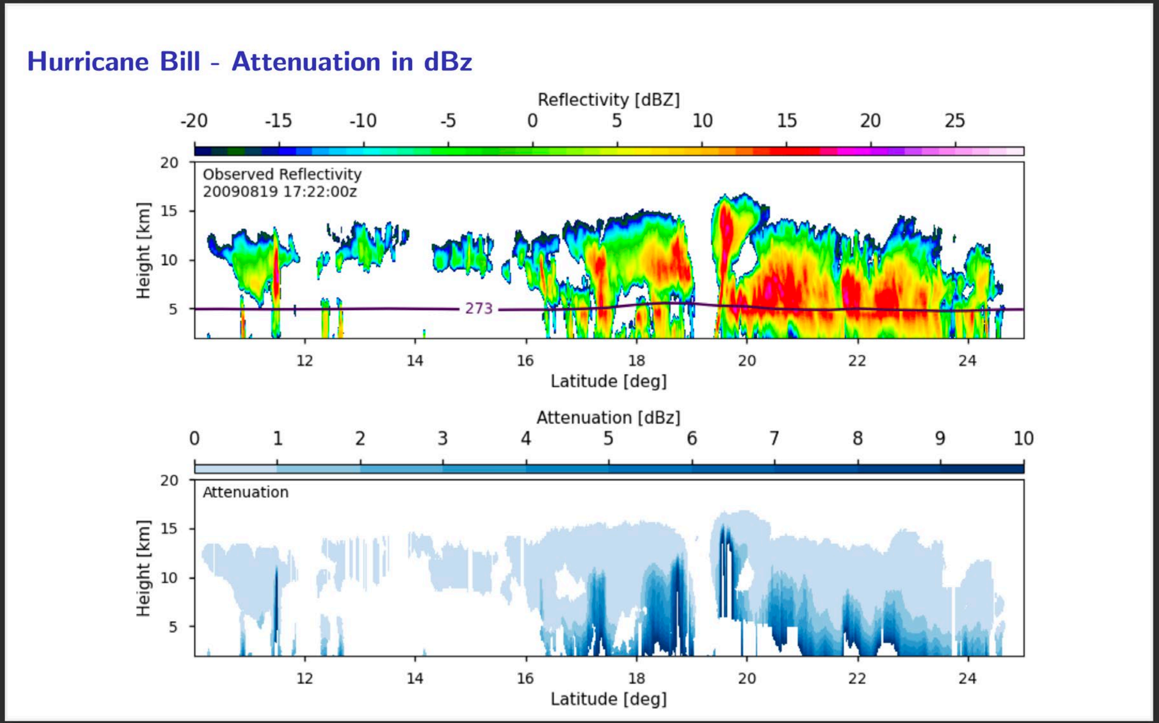
Hurricane Bill

©CIRA/CloudSat



Space-based Radar Simulation (Moradi/Johnson) (cont.)



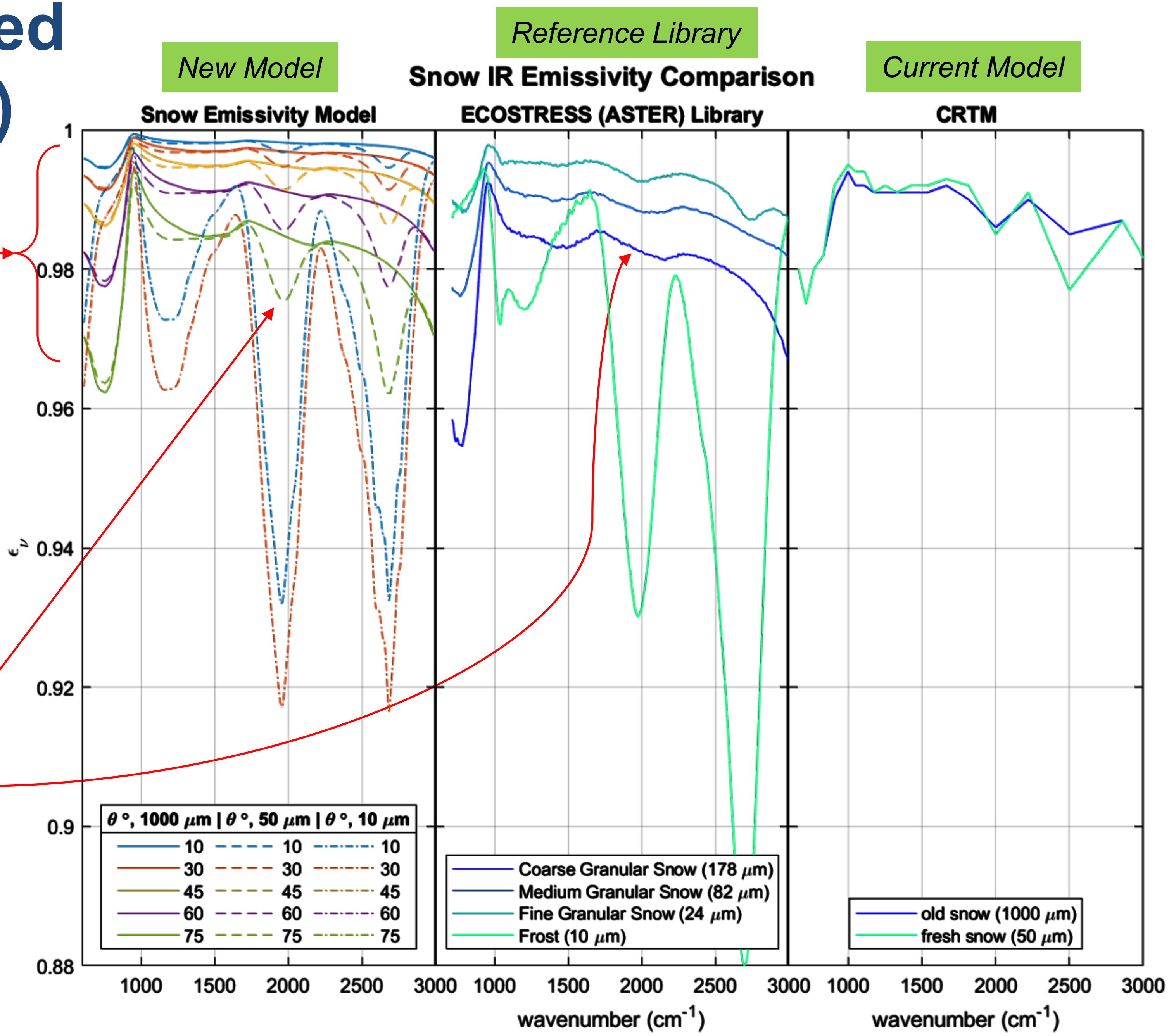


Summary of Aerosol Contents (PoC: C. Dang) [1p.02 today]

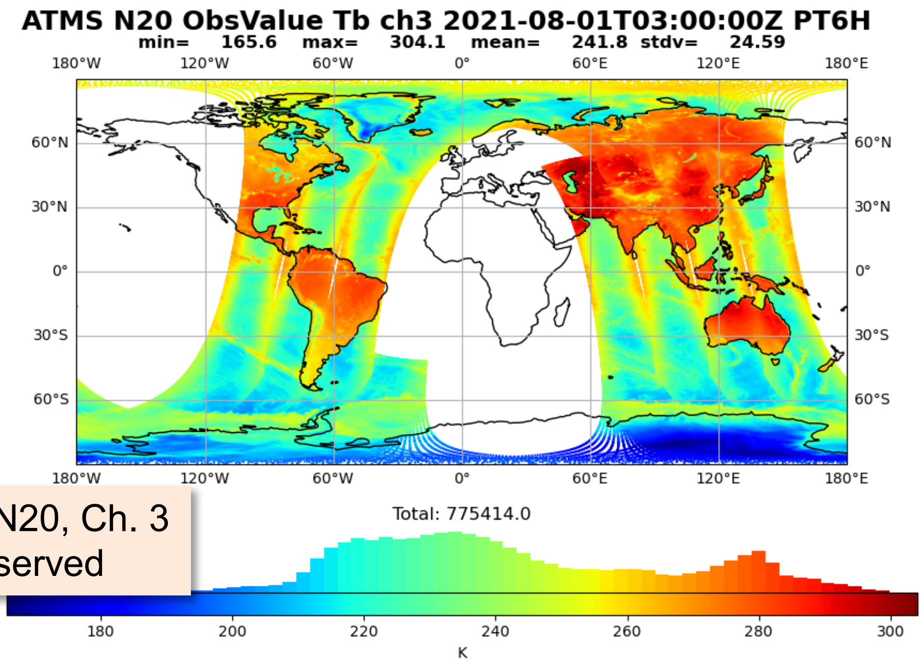
CRTM Version	Aerosol model	Aerosol species	Aerosol properties	References
All versions	CRTM (Default)	dust, sea salt, organic carbon, black carbon, sulfate	effective radius, hygroscopicity	Chin et al., 2002; Han, 2006
v2.4 – v3.0	CMAQ	dust, sea salt, water-soluble, soot, sulfate, water, insoluble, dust-like	effective radius, hygroscopicity, effective radius standard deviation	Binkowski and Roselle, 2003; Liu and Lu 2016
v2.4.1 – v3.0	GOCART -GEOS5	dust, sea salt, organic carbon, black carbon, sulfate, nitrate	effective radius, hygroscopicity	Colarco et al., 2010
v2.4.1 – v3.0	NAAPS	dust, sea salt, smoke, anthropogenic and biogenic fine particles	hygroscopicity	Lynch et al., 2016
v2.4.1 – v3.0 Internal test	RTTOV-OPAC RTTOV-CAMS	OPAC aerosols + volcanic ash CAMS: Copernicus Atmosphere Monitoring Service.	effective radius, hygroscopicity	RTTOV v13, https://nwp-saf.eumetsat.int/site/software/rttov/rttov-v13/
In dev	TAMUdust 2020	dust, volcanic ash	effective radius, shape	https://sites.google.com/site/masanorisaitophd/data-and-resources/tamudust2020

Improving Snow Covered Surfaces Infrared (Nalli) [talk 10.03 on Monday]

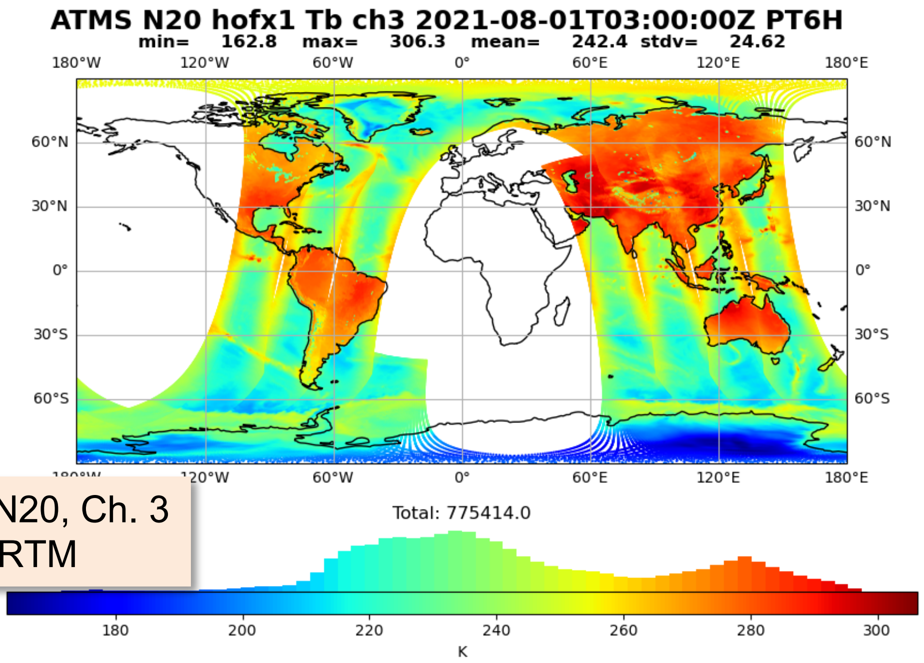
- **Simplified model**
  - Quasi-infinite optical depth assumption
  - *Warren & Brandt* (2008) optical constants for ice
- Significant **zenith angle dependence** as expected
- However, significant **differences** were seen in the spectral dependence on **particle size** from those observed in ECOSTRESS spectral library



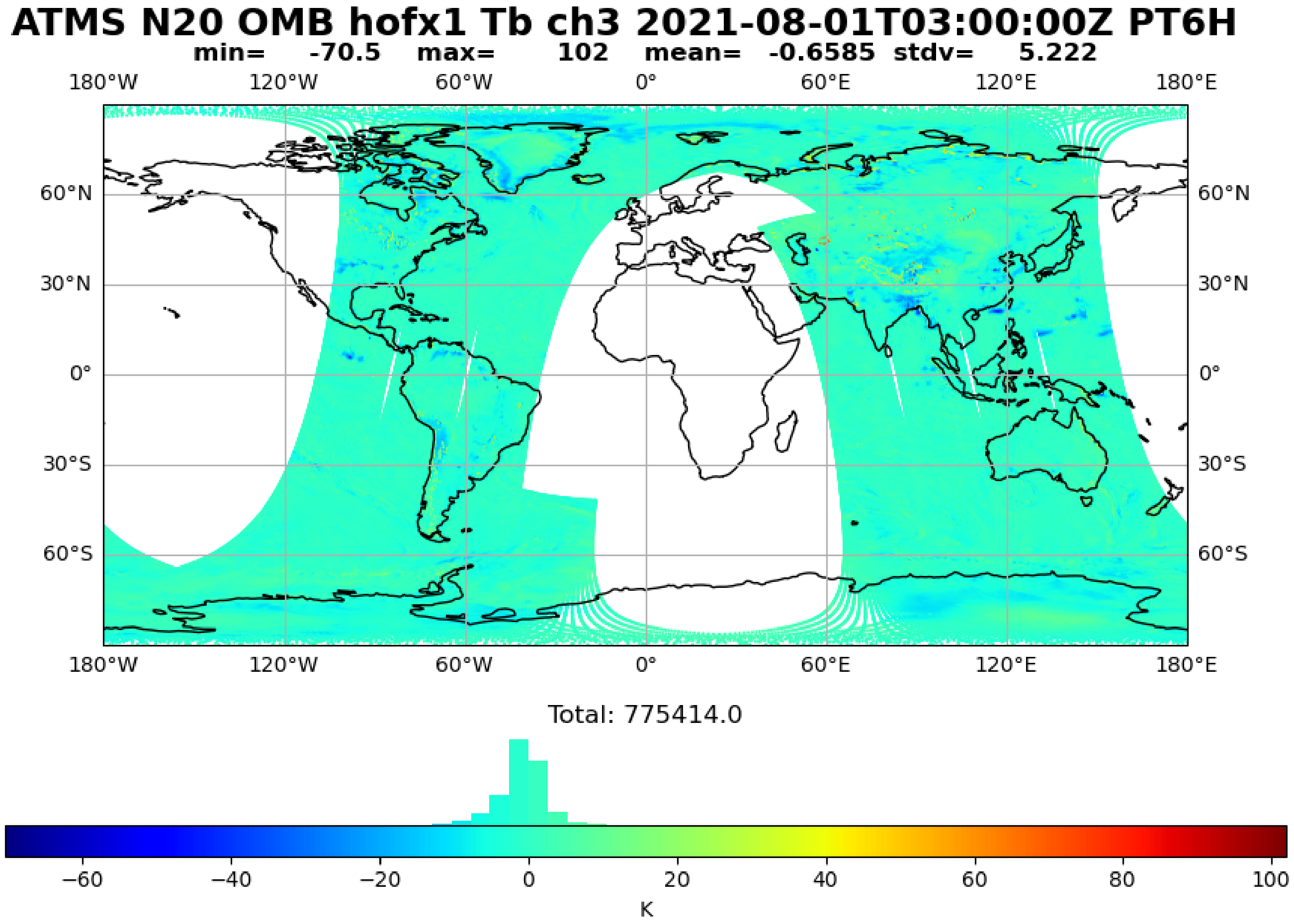
ATMS N20, Channel 3
Observed – Simulated



ATMS N20, Ch. 3
Observed



ATMS N20, Ch. 3
CRTM



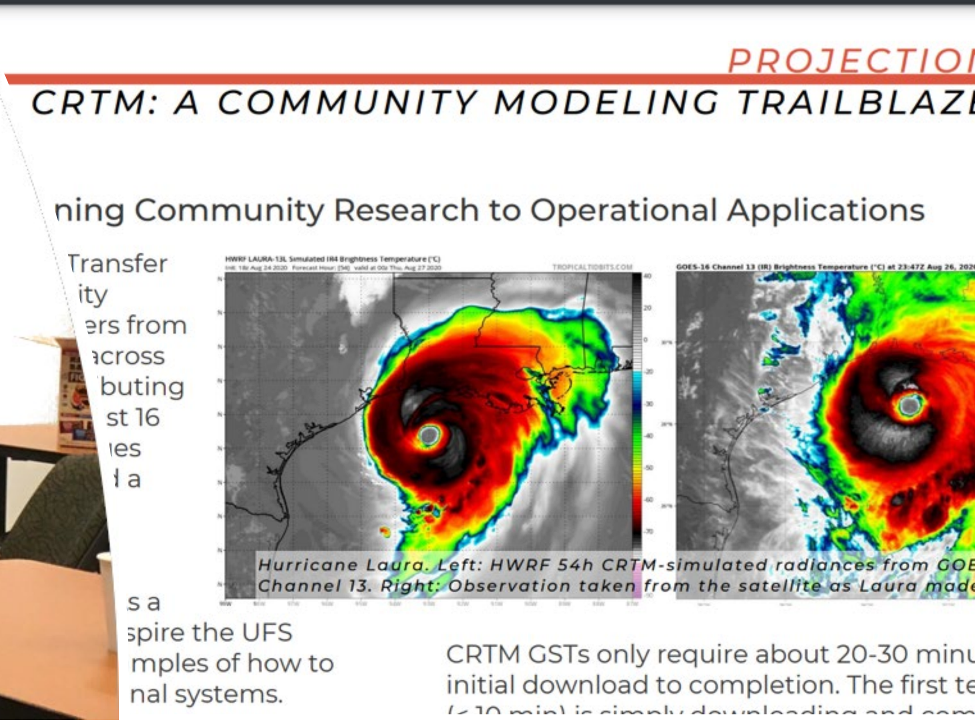
Most differences are (a) clouds, (b) ice, (c) terrain / high altitude snowpack

Key Development needs (you can help!)

- Fully polarized surface BRDFs
  - UV, VIS (in particular)
  - ISSI project
- Generic interfaces
  - User-specified physical / single-scattering inputs -> PSD integration -> optical properties
- Active sensors:
  - Ground/Space Radar / Lidar
  - multiple scattering / VH pol.
- Applications testing
- Aerosols
  - Regional datasets ?
  - Non-spherical
  - Biomass burning
  - Validation: Field campaign data
- Spectroscopy:
  - 183 GHz+, Far-IR, UV
  - LBL model improvements
- Code optimization
  - GPU porting
  - AI models for speed

Community Engagement

- CRTM User/Developer Workshop
- JCSDA Summer Colloquium
  - Summer 2023 (TBD)
- Code Sprints
  - ~2 per year (post covid)
- Seminars / Colloquia
  - ITWG/IPWG/ICAP/ISDA
- ISSI VIS/Near-IR Group
- JCSDA.org website
- STEM outreach
  - Middle school / high school mentorship in STEM



Support / Contact

Website: https://www.jcsda.org/jcsda-project-community-radiative-transfer-model

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

Support email:
crtm-support@googlegroups.com

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