The JCSDA Community Radiative Transfer Model (CRTM)

CRTM team:

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With essential contributions from: Tong Zhu, Quanhua Liu, Emily Liu, Andrew Collard, Yanqiu Zhu, Sarah Lu, Fuqing Zhang, Ping Yang, Kwo-Sen Kuo, *and 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

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 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.

AOP 2018 and 2019 Overview

AOP 2018

- Code and Solver Optimization
  - New Solvers in support of CRTM 3.0
  - Full Polarization Support
  - Optimization: OpenMP, vectorization
- Scientific Capabilities and Progress
  - Aerosols, Clouds, Surface
  - CRTM vs. RTTOV
- CRTM v2.3.x
  - CRTM 2.3.0, CRTM 2.3.1 development
- Operations and Support
  - JEDI
  - Repository

AOP 2019

- JCSDA / ECMWF / CMA joint workshop
- 3 Code Sprints
  - Surface emissivity code updates
  - Coefficient generation package
  - Python / UFO stand-alone framework
- CRTM User/Developer Workshop
  - 2 days, hands on tasks (JEDI Academy)
- 3.0 alpha integration and testing, comparisons with other models
- 3.0 beta development
- CSEM integration and testing
- NLTE updates
- JEDI / UFO development support

CRTM Management Overview

- **Code Management**
  - Github.com -> Gold Masters at local agencies
  - Agile approach with Peer review
- **Release Development and Management**
  - Priority: Coordination with operational requirements
  - Priority: Hotfixes, bug fixes
- **Operational Integration and Support**
  - Pre-release testing protocol needs to be developed with partners
- **User/Developer Support**
  - Technical and scientific support
  - Coefficient generation for non-traditional sensors
- **Collaboration**
  - JCSDA, Domestic, International

CRTM Management Deliverables

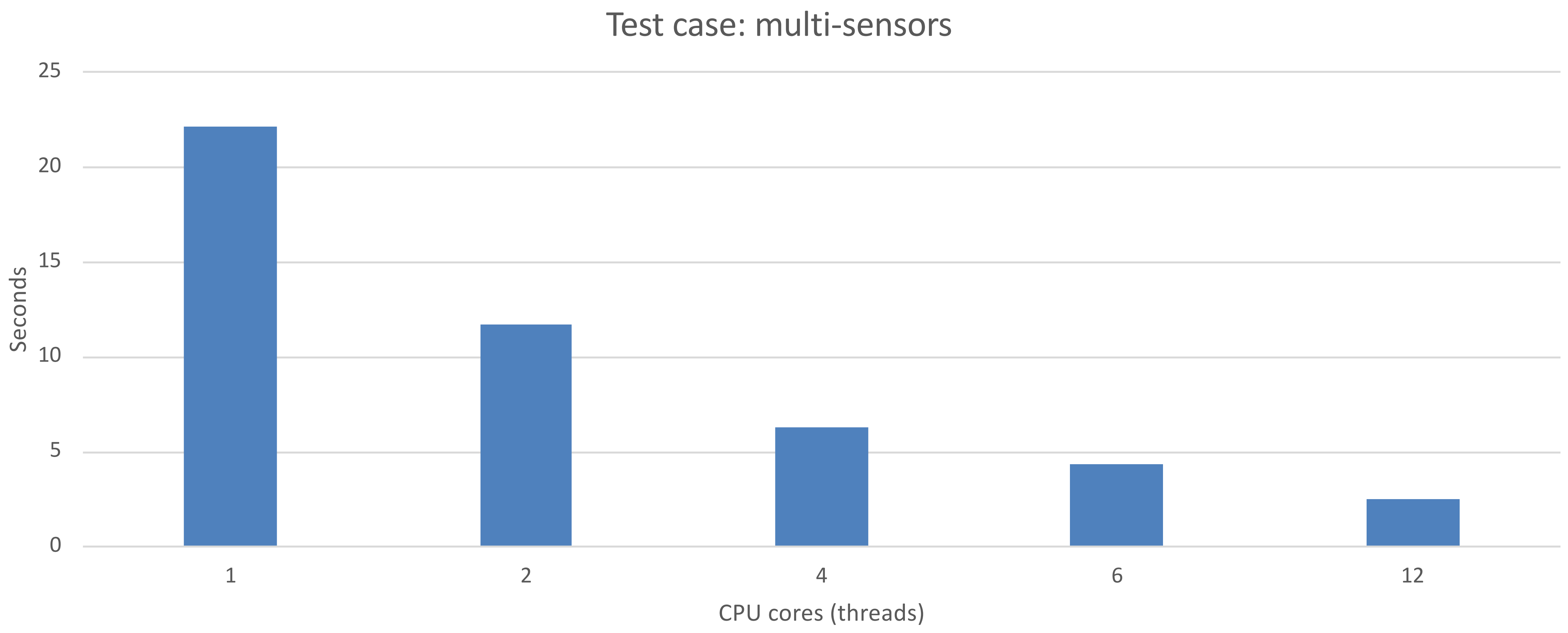
1. CRTM version 2.3.1 final release
2. CRTM version 2.1, 2.2, and 2.3 updated documentation
3. CRTM version 3.0 alpha testing.
4. CRTM version 3.0 beta initial release
5. Quarterly report on user support requests, status
6. Quarterly report on bug fixes, testing, and status
7. Next generation CRTM planning document describing high level features
8. Evaluation of radiance operators and jacobians for the JEDI/SOCA project
9. Coefficient generation for new sensors: GEO-KOMPSAT 2A AMI, MTG-I1 FCI, GOES-T ABI, FY-4A GIIRS, etc.
10. RTTOV / CRTM intercomparison using JEDI/UFO framework
11. Finalized official transition to github.com repository: (https://github.com/JCSDA/crtm_dev/)
12. Education and Outreach
    a. CRTM User/Developer Workshop: to be held late-2019, date and location TBD
    b. Code sprints
    c. International Collaboration and Coordination (IRRTM, ECMWF/RTTOV, CMA/ARMS)

CRTM Optimization

- 2.3.x extensions (Rosinski, Greenwald, Q. Liu)
  - Full polarization
  - Vectorization
  - OpenMP
  - Code memory / cache optimization
- New Solver Development in support of speed, and full polarization (Greenwald, Stegmann)
  - See Tom Greenwald's talk at 3:40

CRTM Optimization

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



Improved Loop Level Performance

- **The modified code outperforms the original from between 4X and 5X using by reversing the loops.**
  - First, n_Layers is O(100) while n_orders is O(5). This provides an opportunity for better vector performance.
  - Second, note in the original code that the “j” index for Predictor_AD%Ap was not stride-1. This leads to worse cache performance. In the revised code all memory references in the inner loop are either stride-1 or scalars (e.g. coeff(j) becomes a scalar).
  - Third, the setting of b_AD can be vectorized in the revised code.
- **These modifications result in identical answers but better performance. Many similar (non-unit-stride) looping constructs exist in CRTM.**

CRTM Optimization Deliverables

- **New radiative transfer solver** capabilities for CRTM 3.0-beta, a decision will be made as to which solver choices meet the optimization and accuracy requirements needed for operational use.
- A preliminary study on the computational and scientific impact of implementing **slant-path radiative transfer** capabilities in CRTM 3.0.
- **Vectorized code** designed explicitly for optimal parallelization, in specific coordination with the CRTM team members and other JCSDA code developments.
- Audit of CRTM codes that fail to meet scientific and/or technical standards of the CRTM project.
- **Planning and execution of CRTM specific code-sprints:**
  - CRTM CS1: Replacement of science codes that are outdated, particularly focused on surface emissivity codes and instrument-specific codes.
  - CRTM CS2: Development and testing of a new method for coefficient generation [Risk Mitigation]
  - CRTM CS3: Python framework for stand-alone CRTM, aligned with UFO/JEDI project.
- **Modified and/or replacement codes** within both CRTM release and the repository trunk
- **Conversion of all binary format lookup tables** to NetCDF format, including inspection, creation, and modification tools.
  - Consistent with deliverable 5 modifications and to be addressed during CS1 and CS2.
- **CRTM coefficient generation package** (v2)

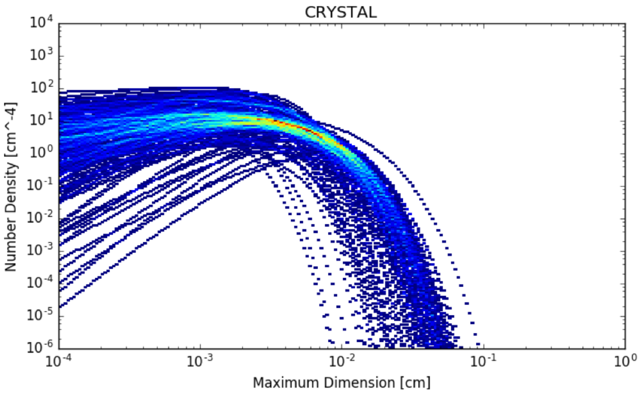
CRTM Science

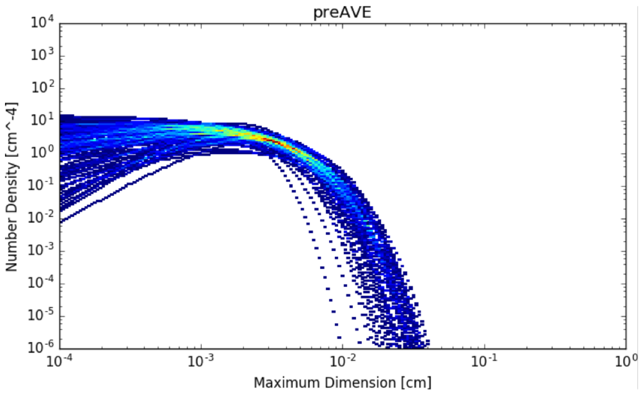
- Community Hydrometeor Model (CHYM)
  - Aerosols (S. Lu, A. Naeger*, Pagowski, P. Stegmann*)
    - *See Aaron and Patrick's talk after this one
  - Clouds & Precipitation
- Community Active Sensor Module (CASM)
  - Space-based lidar, radar (Scherllin-Pirscher, Johnson)
  - Ground-based active sensors (future)
- Community Surface Emissivity Model (CSEM)
  - Improved surface emissivity characterization
  - Framework for modular emissivity algorithms (IR/MW)

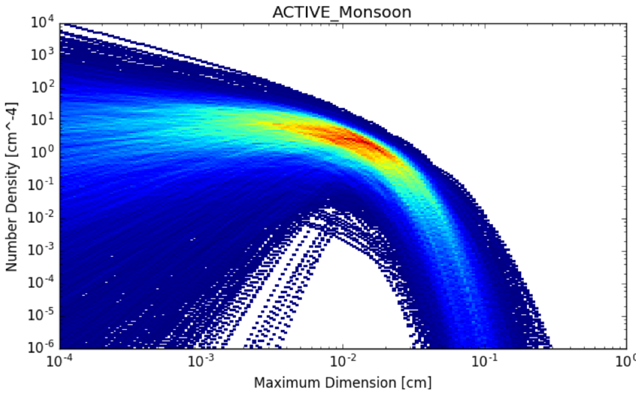
Community Hydrometeor Model CHYM

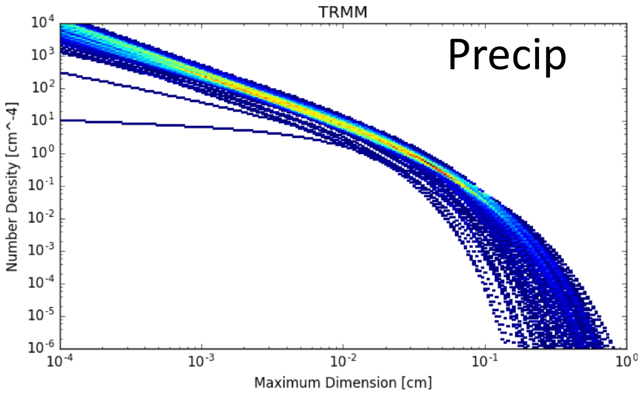
- (1) **Development of the microphysical parameters of clouds and precipitation** (Lead: Emily Liu, EMC)
  - Relate to the current and planned GFS microphysical assumptions.
  - converting mixing ratios into particle size distributions (PSD) and habit distributions, consistent with the microphysics schemes
- (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)

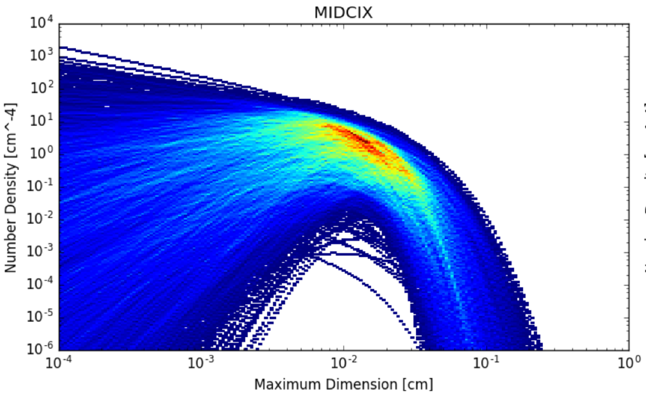
Observed Ice Particle Size Distributions

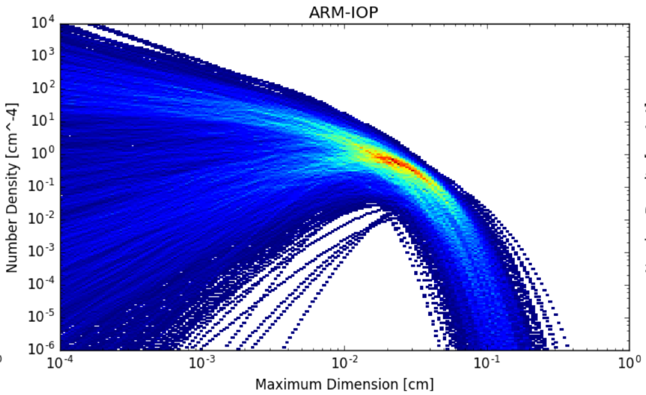


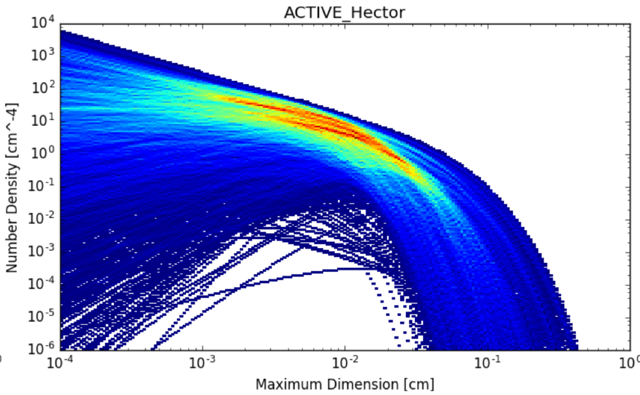


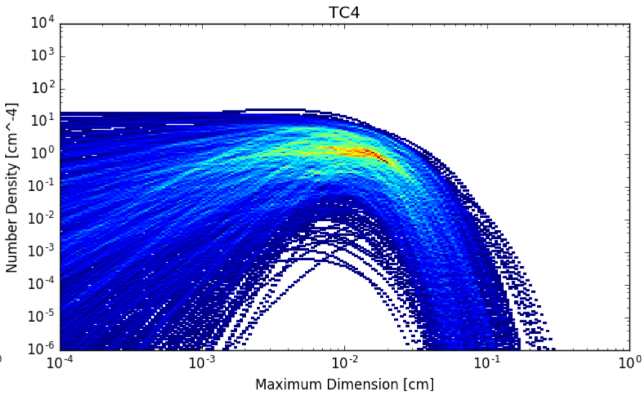


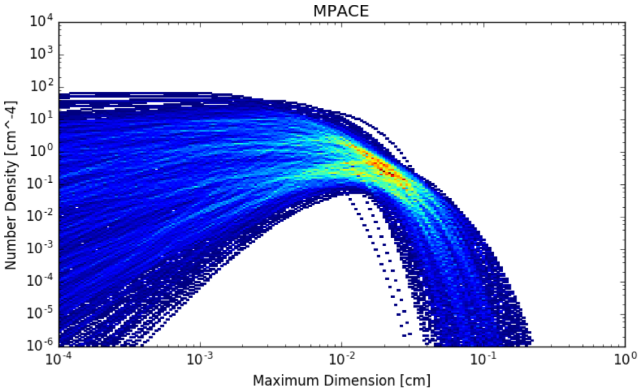


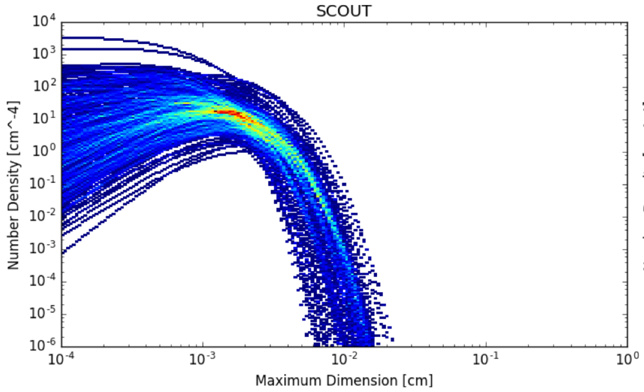


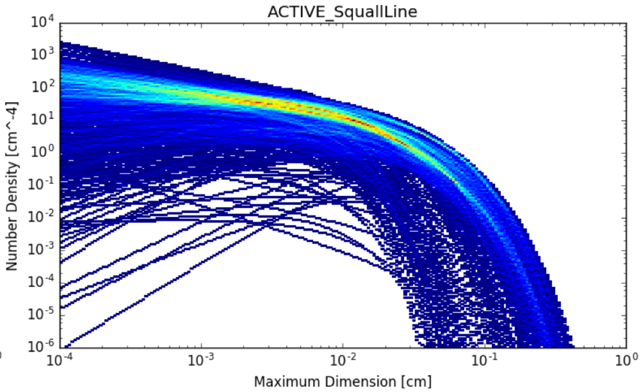












PSDs plotted using data downloaded from Brian Baum's website:
http://www.ssec.wisc.edu/ice_models/microphysical_data.htm

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

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

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

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

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

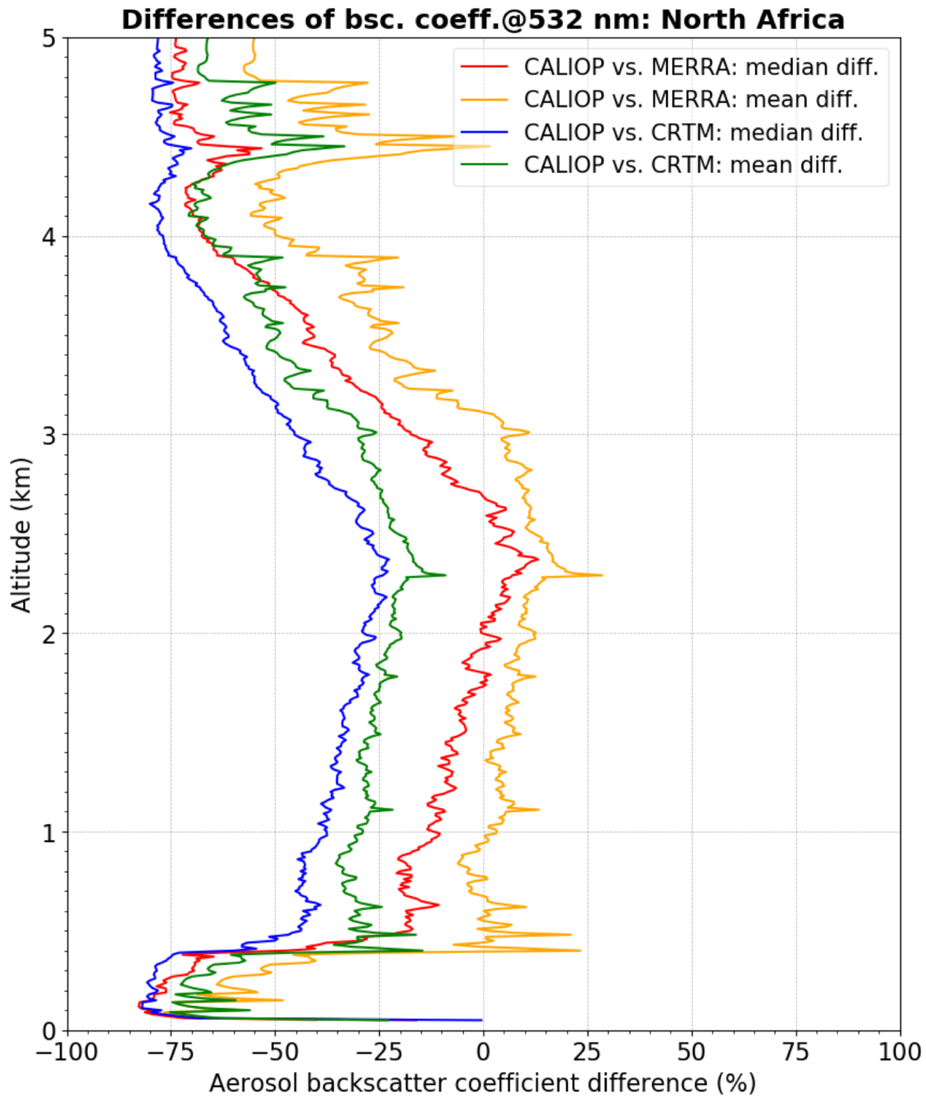
$$w_x = \rho_a q_x = a\, N_{ox}\, \Gamma(\mu + b + 1)\, \lambda^{-(\mu+b+1)} \longrightarrow \lambda = \left(\frac{a\, N_{tx}\, \Gamma(\mu + b + 1)}{\Gamma(\mu + 1)\, \rho_a q_x}\right)^{\frac{1}{b}}$$

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

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

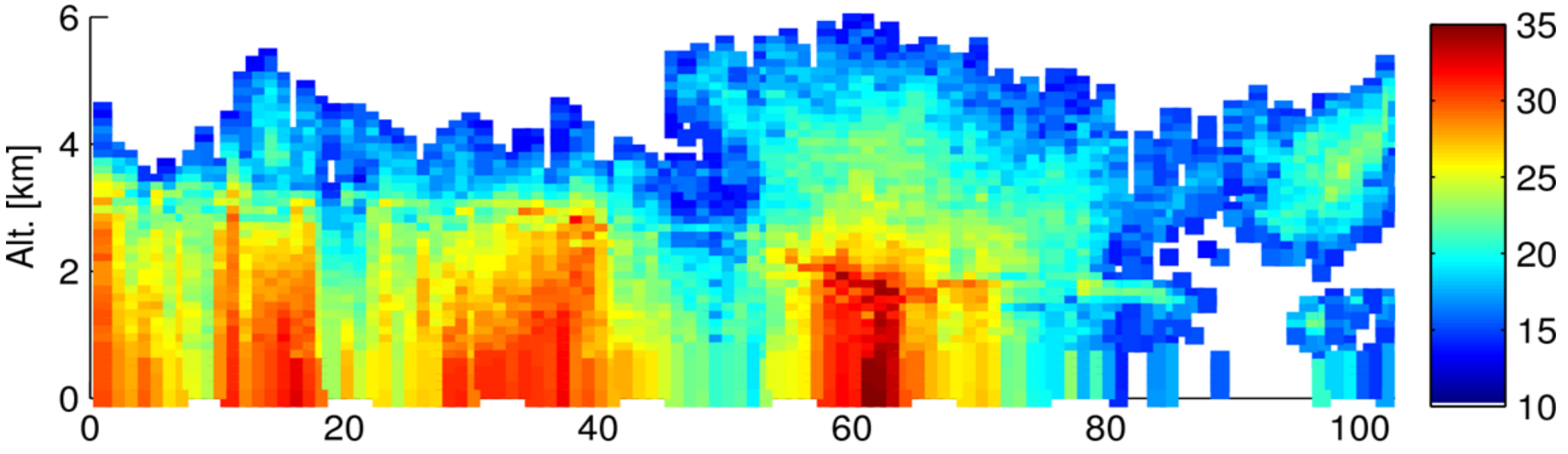


CASM :: Space-based Radar

- 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

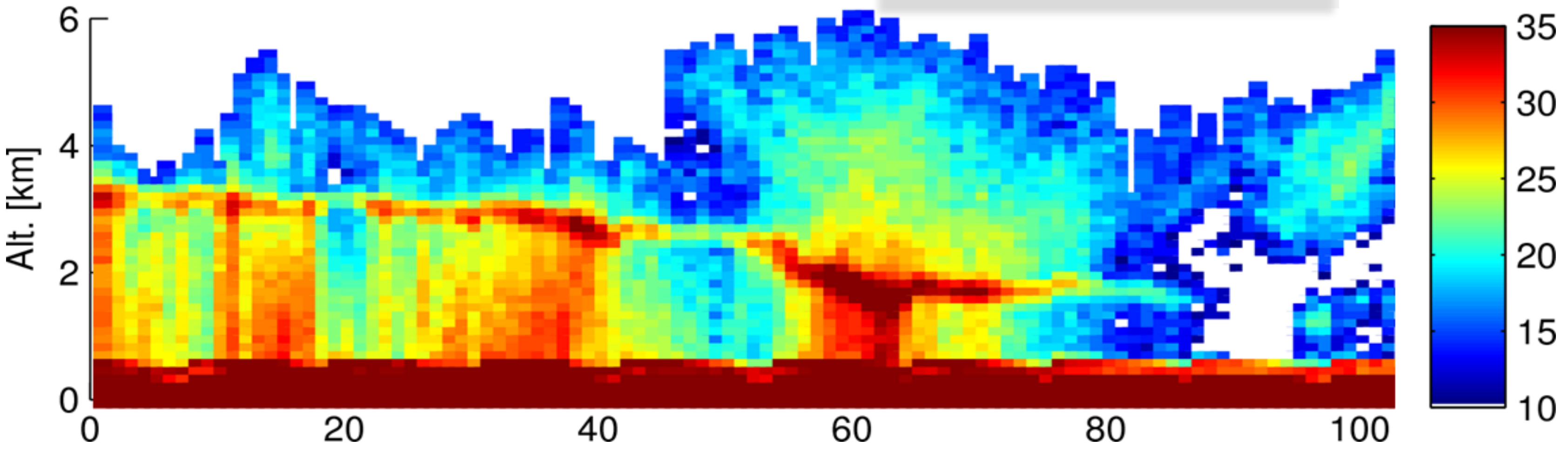
(a) CASM (Sim.) Z_m [dBZ] @ Ku-band (14 GHz)

CRTM Simulation



(b) GPM DPR (Obs.) Z_m [dBZ] @ Ku-band (14 GHz)

Observed Reflectivities



CSEM :: Surface Emissivity (Chen, Nalli)

(See Nick's poster on Wednesday and Ming's poster on Thursday)

Highlights:

1) IRSSE model upgrade (Nalli)

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

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

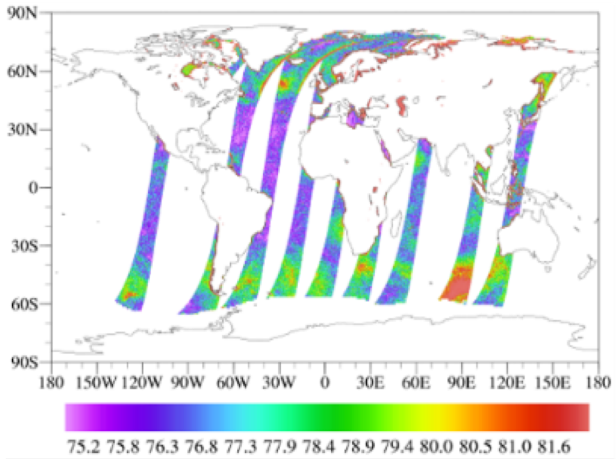
4) The tangent linear and adjoint modules of the physical MW land model implemented.

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

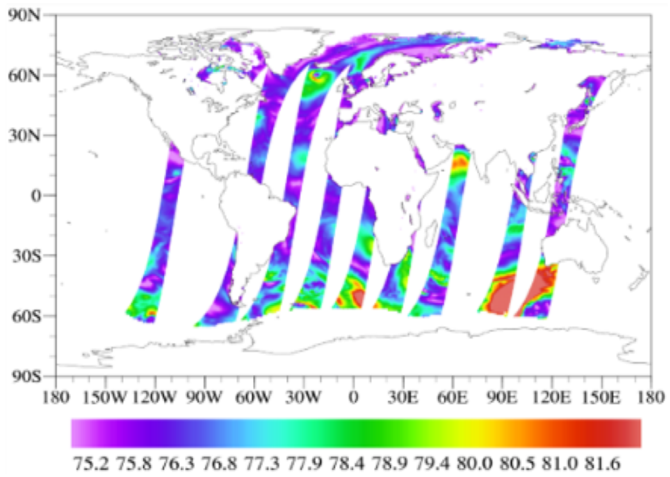
6) The testing of CRTM-CSEM in FV3 GFS/GSI is in progress.

7) 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.

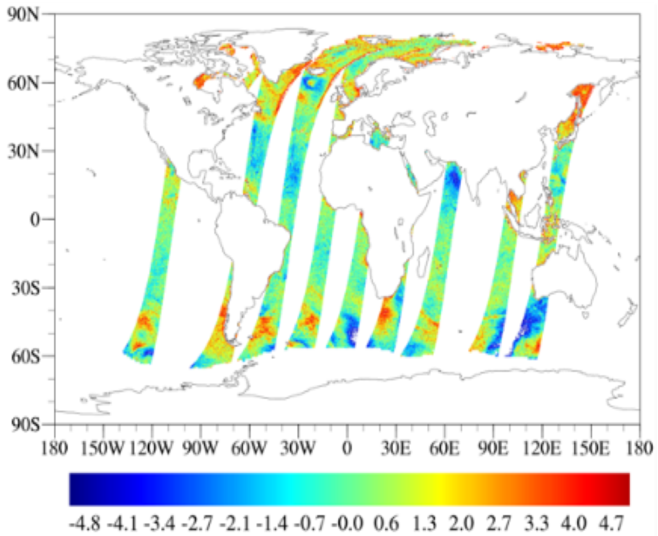
SMAP Observation

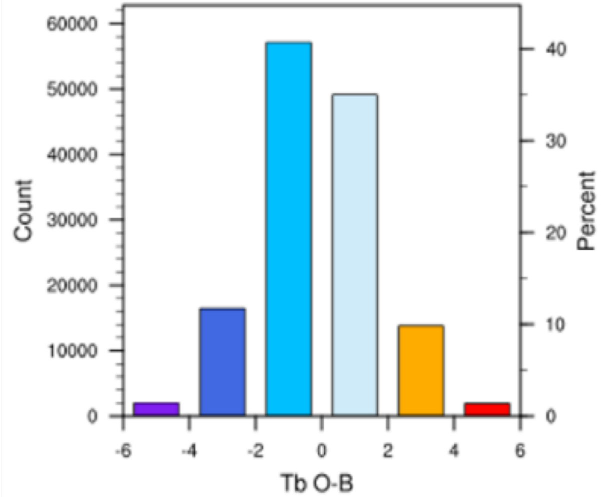


CRTM Simulation



SMAP-CRTM





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

Questions / Comments?

New Position available: JCSDA Project Scientist I - CRTM IR (College Park or Boulder)

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.

CRTM Science Deliverables

- Cloud-impacted radiance and physical model simulation improvements (UV, VIS, IR, MW) (Lead: Ben Johnson)
  - Creation of single-particle scattering databases using realistic non-spherical ice particles using snow scattering community database.
  - Implementation of Community Hydrometeor Model (CHYM) to create new integrated scattering tables that are more closely linked with model assumed microphysical properties, particularly from the FV3DA-planned GFDL microphysics implementation.
  - Emily Liu (EMC) will provide the microphysical properties databases derived from field experiments, and will work with Dr. Johnson and Dr. Stegmann on implementation.
  - Testing within GSI / FV3 and JEDI frameworks, as appropriate -- focus on finding improvements in cloudy radiance simulations and associated Jacobians. This would be closely coordinated with EMC personnel for determining operational readiness.
  - Updated CSEM software package (Lead: Ming Chen)
  - Connection of the Community Surface Emissivity Model (CSEM) with the CRTM (Ming Chen).
  - Updated IR sea surface emissivity tables to be implemented in CSEM.
  - Improved land surface physical characterization, connection with the ITOVS Study Conference (ITSC) recommendations, direct collaboration between CSEM and Ben Ruston (NRL).
- Updated aerosol models and aerosol-impacted radiance simulation (Lead: New Hire / TBD)
  - Implementation of the Community Multiscale Air Quality (CMAQ) aerosol specifications in CRTM, extending current GOCART model (coordination with NIO team).
  - Ensure CMAQ speciation covers NAAPS aerosols, and confirm using intercomparisons with previous JCSDA efforts to include NAAPS aerosol.
  - Intercomparison of AOD/aerosol speciation operators (GOCART, NAAPS, CMAQ and NGAC) from NOAA, U. Albany, and NRL personnel.
  - Aerosol Impact assessment for hyperspectral IR radiance simulation (NRL lead, Ruston)

CRTM Science Deliverables

- Spectral expansion of CRTM radiance and sensor simulation capabilities (Lead: Ben Johnson, New Hire TBD)
  - Shortwave infrared, focusing on the radiative transfer in the presence of aerosols. This would involve close coordination with GMAO and EMC researchers. [New Hire]
  - Ultraviolet radiance simulation within CRTM, primarily arising out of funded proposal with Changyong Cao
  - RADAR and LIDAR forward operator implementation, testing, within the Community Active Sensor Module (CASM).
  - NLTE assessment report and updated code as needed (coordinated with Zhenglong Li at UW/CIMSS)
- Full Stokes polarization in CRTM (Lead: T. Greenwald)
  - Includes both forward operator, tangent-linear and adjoint development
  - To be combined with vector solver work
  - Comparisons with simple polarized modification by Q. Liu will be made to determine optimal approach.

Coordination Overview for 3.0

- NCEP/EMC:
  - GSI operational implementation and testing
  - UPP update of CRTM version integration and testing
  - Radar forward operator development
  - Coefficient generation, modification
  - Cloudy and Aerosol-Impacted DA
- NESDIS/STAR:
  - Combination of CRTM efforts, legacy STAR CRTM team
  - Surface emissivity model improvements (CSEM, Nalli)
- NRL:
  - Surface, Aerosols