The JCSDA Community Radiative Transfer Model (CRTM): From Development to Operations

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With essential contributions from: Barbara Scherllin-Pirscher, Quanhua Liu, Emily Liu, Andrew Collard, Fuqing Zhang, Ping Yang, Kwo-Sen Kuo, *and many others.*

STAR Seminar Series, December 20, 2018

JCSDA Overview

What is the CRTM?

Code and Solver Optimization

Scientific Capabilities and Progress

CRTM v2.3.x and v3.0.0

Operations and Support

Education / Outreach

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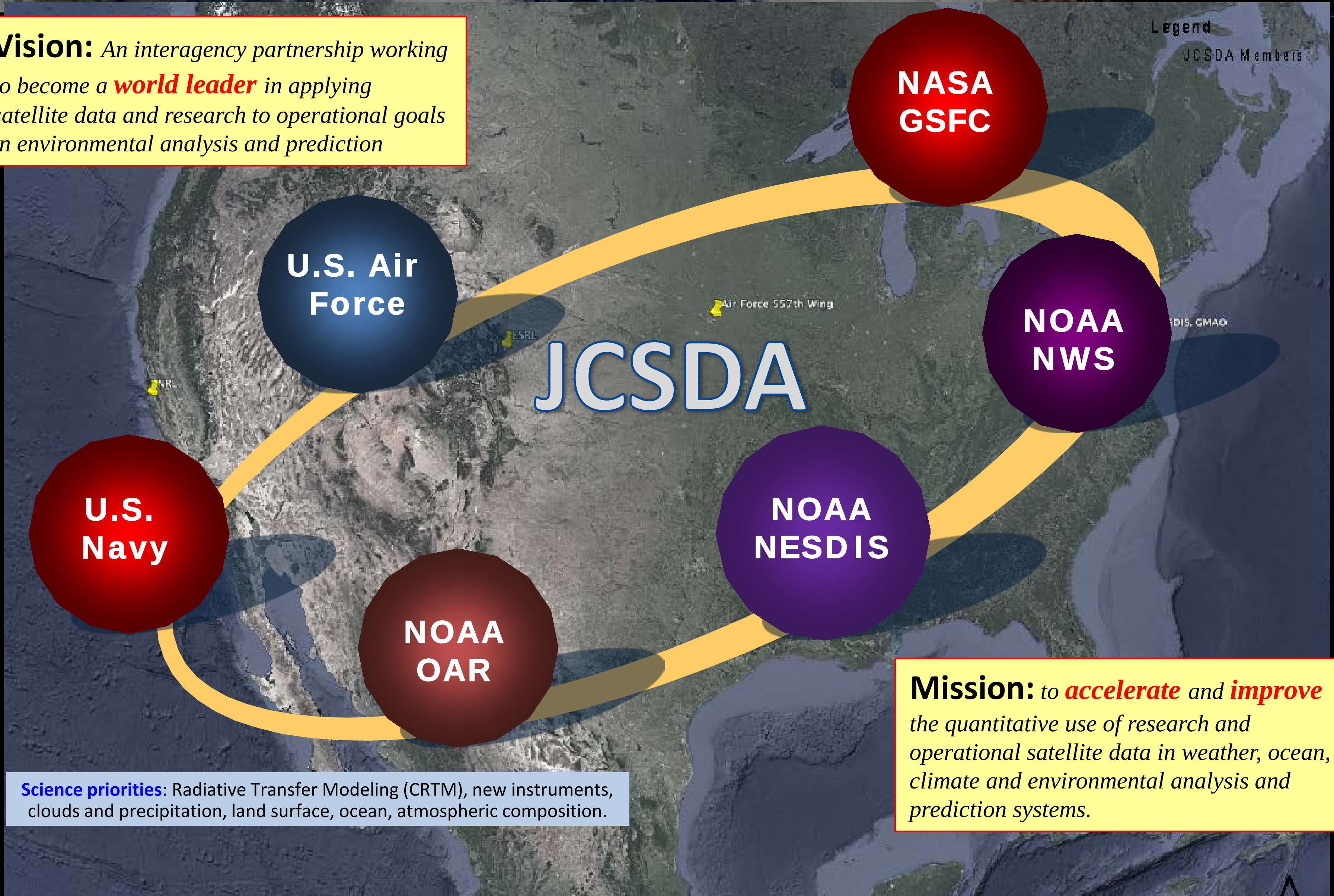
Joint Center for Satellite Data Assimilation

Vision: *An interagency partnership working to become a* ***world leader*** *in applying satellite data and research to operational goals in environmental analysis and prediction*



Science priorities: Radiative Transfer Modeling (CRTM), new instruments, clouds and precipitation, land surface, ocean, atmospheric composition.

Mission: *to* ***accelerate*** *and* ***improve*** *the quantitative use of research and operational satellite data in weather, ocean, climate and environmental analysis and prediction systems.*

JCSDA Project Structure

Director
(Tom Auligné)

- **Director's Office (DOF)**

- **Community Radiative Transfer Model (CRTM)**
  Accurately and efficiently simulate satellite radiances
- **New & Improved Observations (NIO)**
  Accelerate use of new sensors and improve use of current ones
- **Impact of Observing Systems (IOS)**
  Monitor impact of observations and provide guidance for improvements
- **Sea-ice, Ocean, Coupled Analysis (SOCA)**
  Implement science for coupled, marine system
- **Joint Effort for Data assimilation Integration (JEDI)**
  Next-generation data assimilation for the Nation

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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.

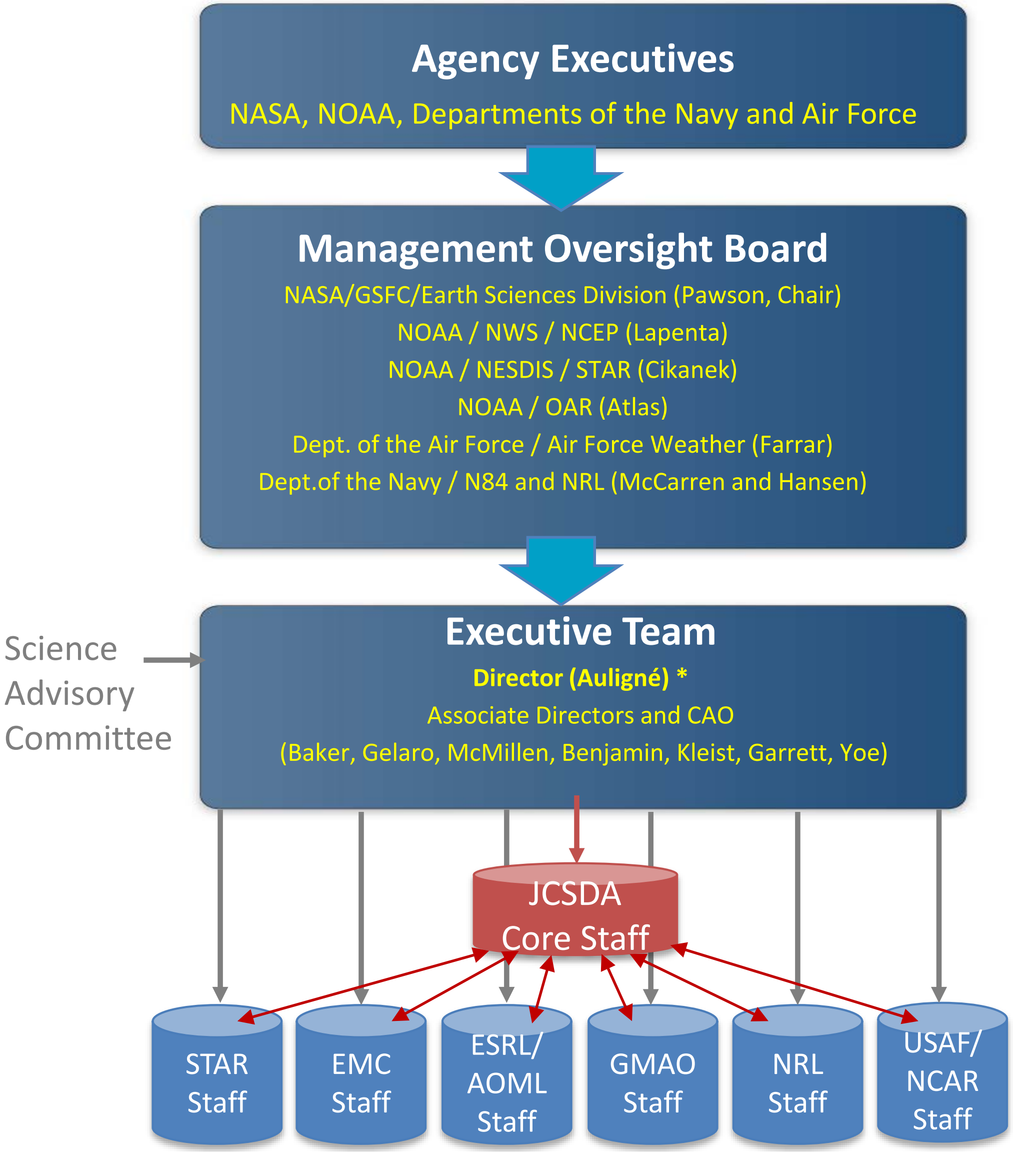
Has aerosol (GO-CART), cloud (2 species), precipitation (4 species); with unpolarized scattering and absorption. Computes gaseous absorption/emission for 6 gaseous species (ODPS).

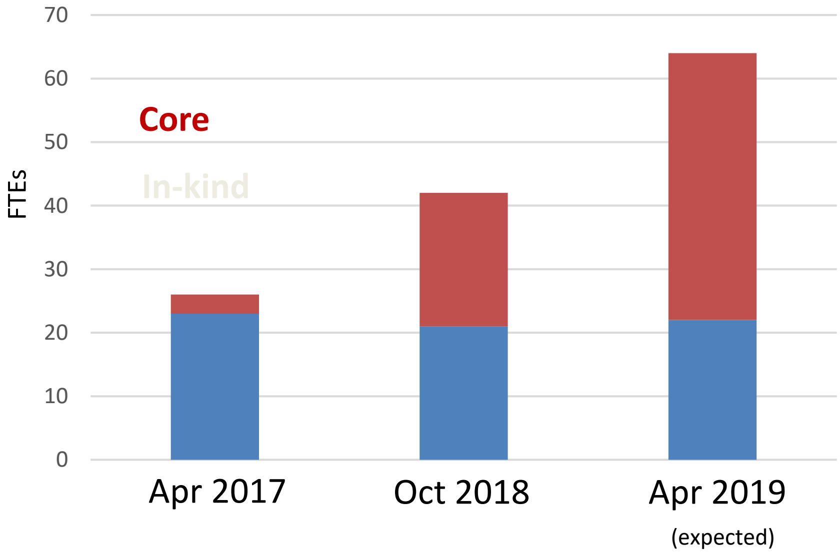
History: Originally developed (as CRTM) around 2004 by Paul van Delst, Yong Han, Fuzhong Weng, Quanhua Liu, Thomas J. Kleespies, Larry M. McMillin, and many others. CRTM Combines many previously developed models into a community framework, and supports forward, tangent linear, adjoint, and k-matrix modeling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

What is the CRTM?

- Written in (updated to) Fortran95/2003 (some elements of Fortran 2008).
- Heavy use of language features made to ease code maintenance and reuse of common components.
- Geared towards data assimilation (i.e. GSI at NCEP / JCSDA JEDI, NASA-GEOS, etc.) but used in other contexts (cal/val, satellite simulation, post-processing)
- There are separate forward, tangent-linear, adjoint, and K-matrix functions.
- Forward model is “built in” to the other functions so they are all stand-alone.

JCSDA Executive Oversight





Annual Operating Plan

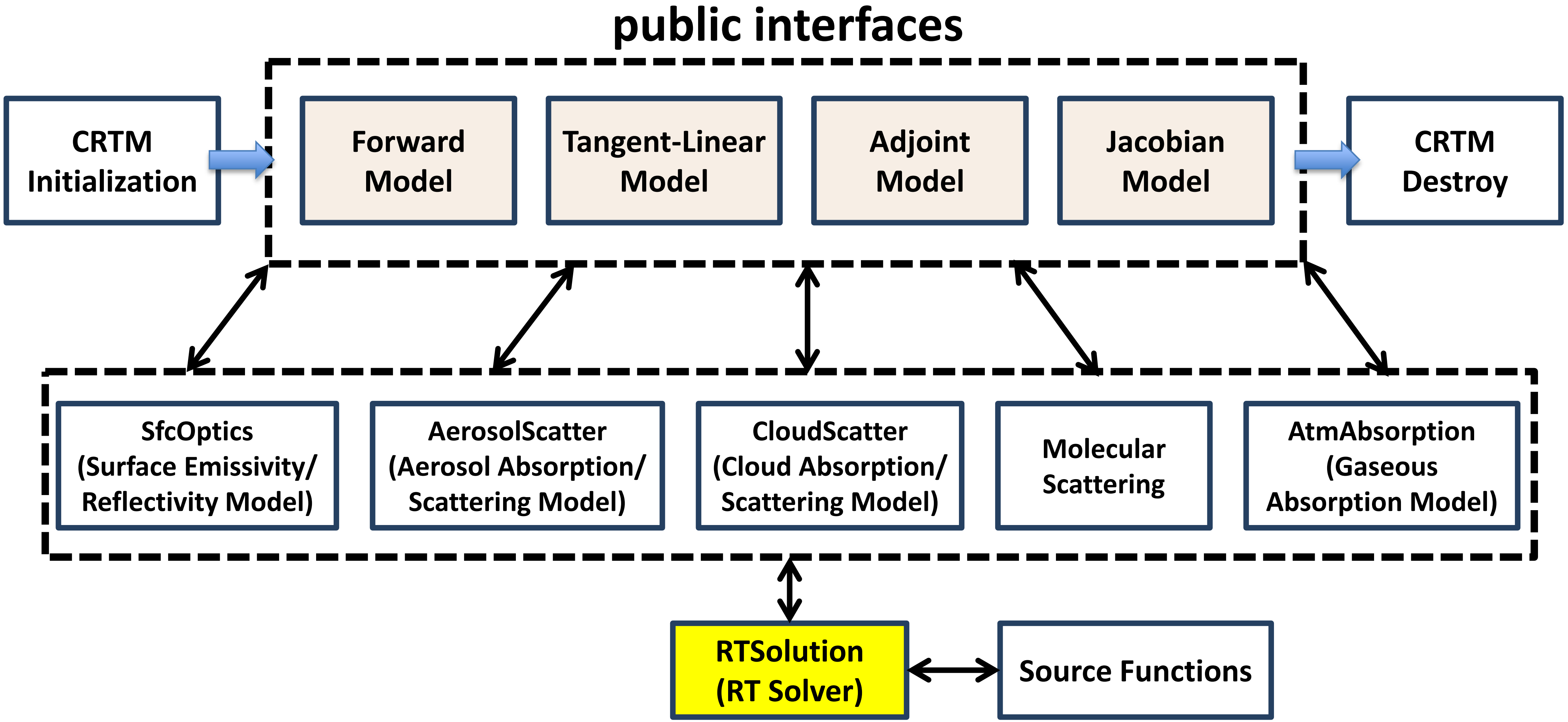
CRTM Overview

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.

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 Structure



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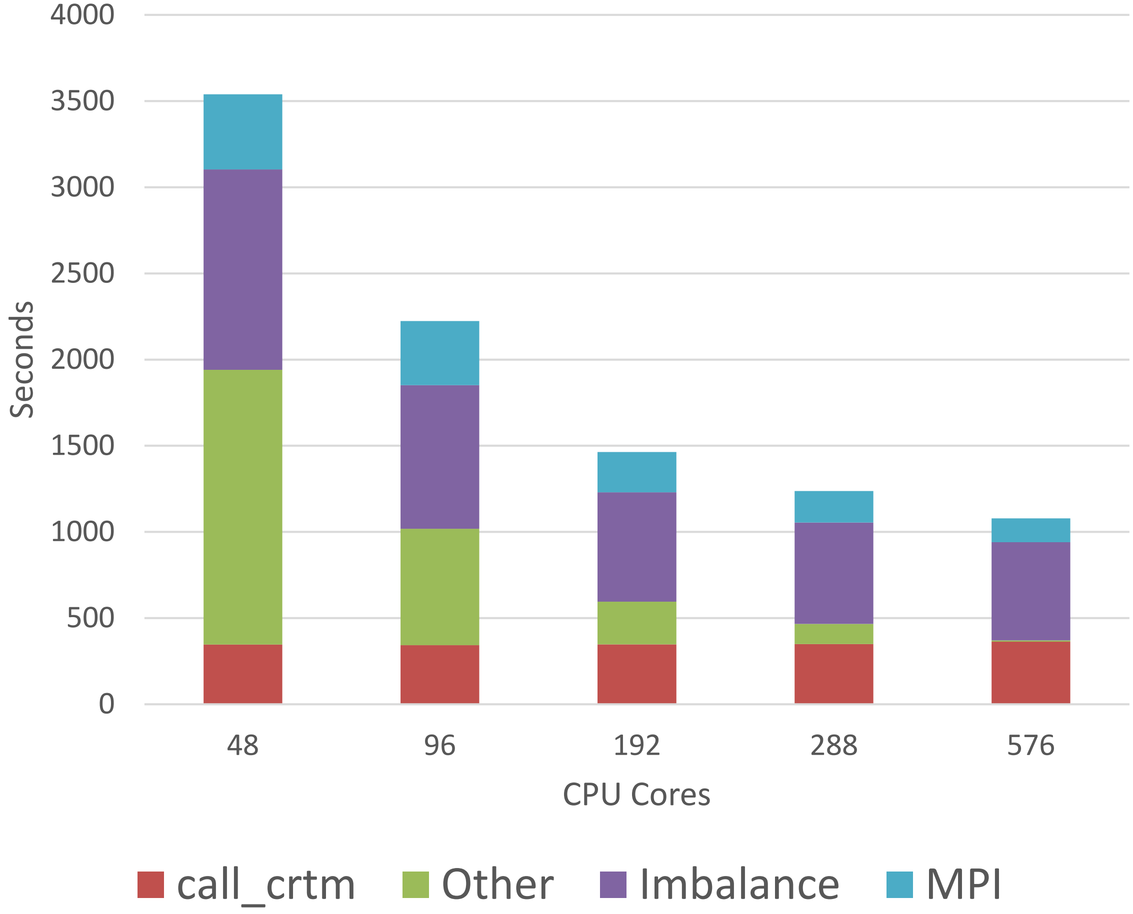
CRTM Optimization (J. Rosinski, JCSDA)

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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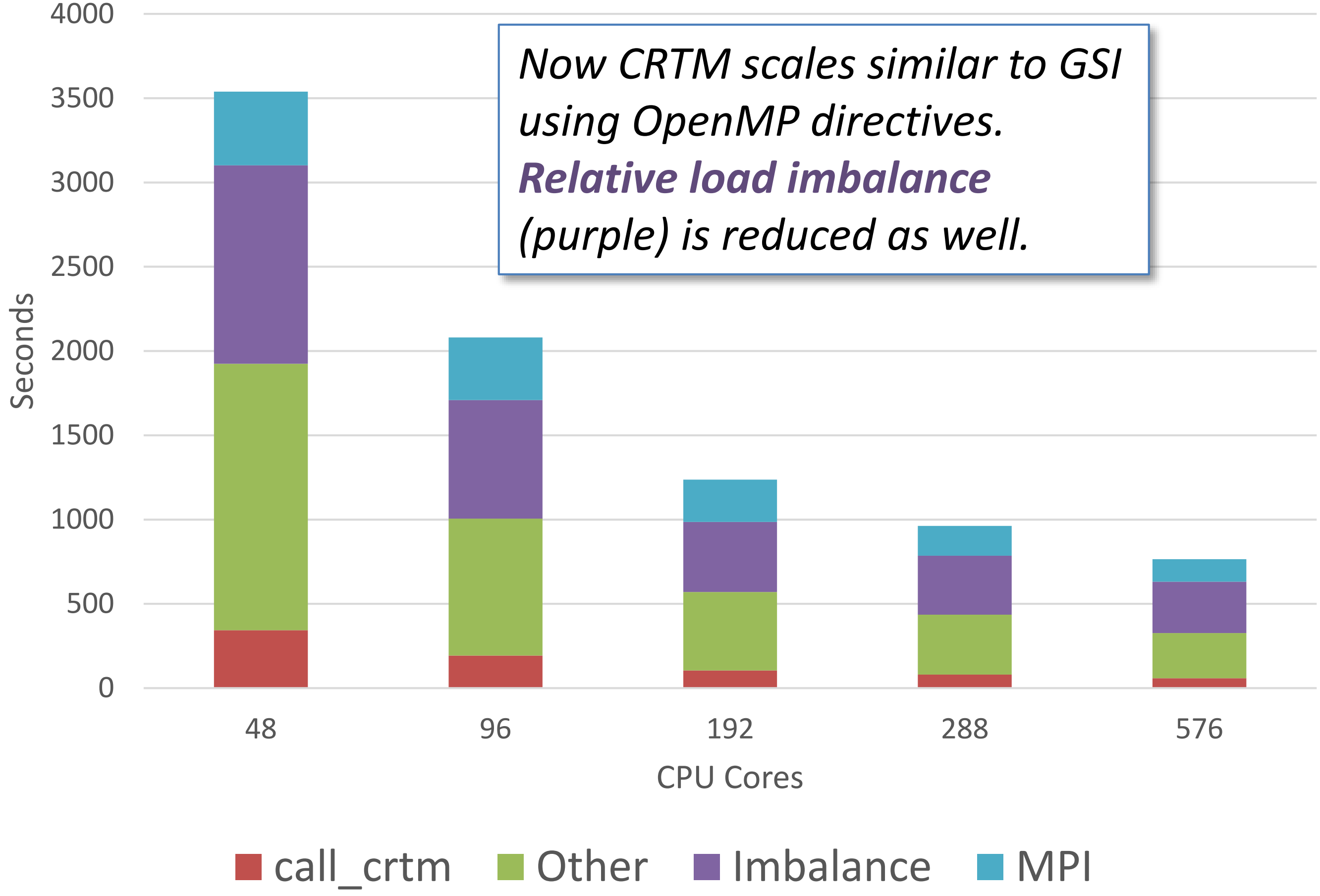
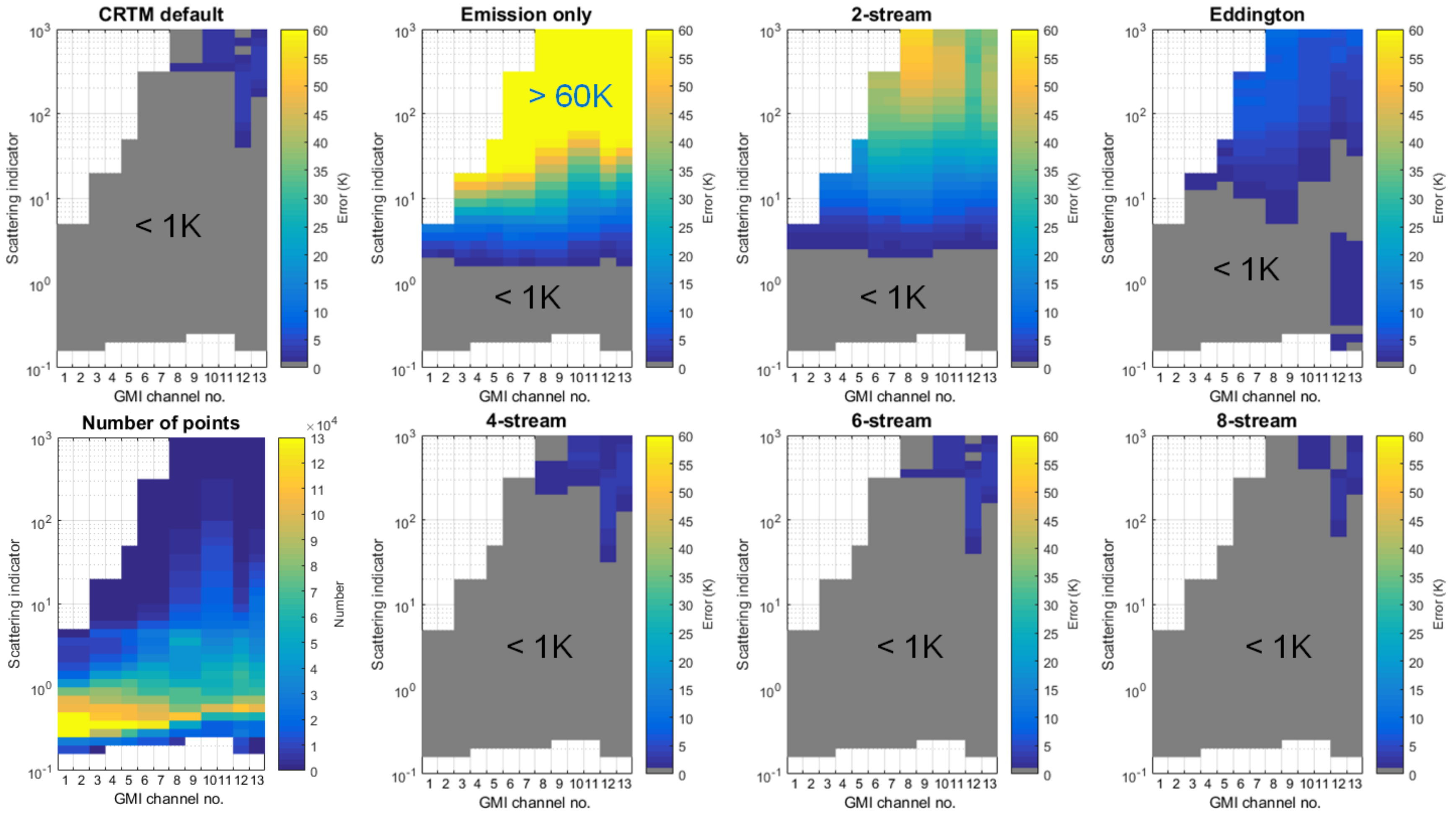


Now CRTM scales similar to GSI using OpenMP directives. ***Relative load imbalance*** *(purple) is reduced as well.*

Eddington Model Benchmark Tests

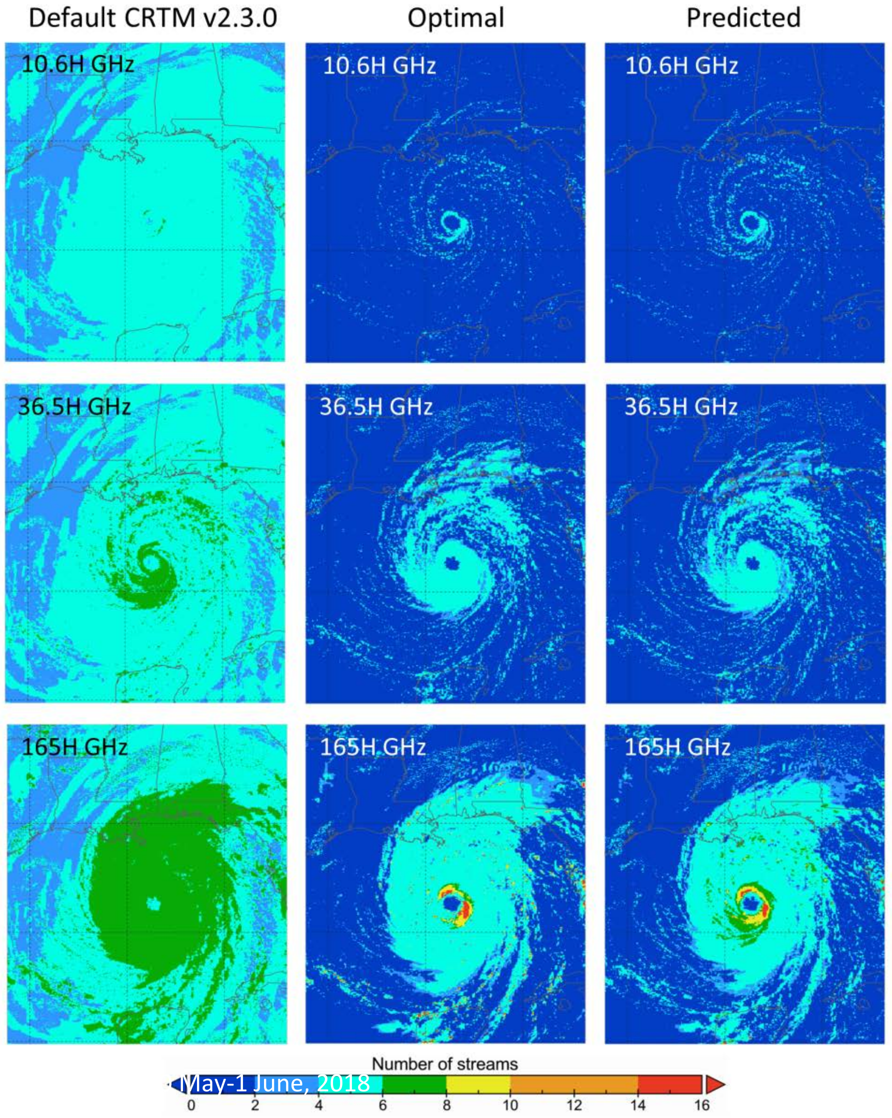
- Tests using WRF output show that Eddington model is only 33% slower than emission-only model and 2.8x faster than ADA two-stream model
- <u>Strong scattering</u>: Eddington model more accurate
- <u>Weak scattering</u>: ADA two-stream slightly more accurate
- Emission-only and Eddington models provide 4x speedup over CRTM v2.3.0



Slides courtesy of Tom Greenwald

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

Current Status of Solver Work

- Completed coding of the Eddington tangent linear and adjoint models
- Completed integration of a very fast successive-order-of-scattering (SOS) model(Greenwald et al. 2005) into the CRTM
- Integration of advanced vector adding-doubling (VAD)model for solar wavelengths (provided by P. Yang)
- Significantly modified model code in order to properly interface with the CRTM

Future Work:

- Complete testing of Eddington tangent linear and adjoint code
- Complete integration of VAD model into the CRTM
- Conduct a cloudy radiance data assimilation experiment using the Eddington model;
  - speedups of a factor of 4 are expected over the default solver used in CRTM v2.3.0

Slides courtesy of Tom Greenwald

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Gaseous Absorption

- The gaseous absorption algorithm is the core of the CRTM (or any “fast” model).
- Regular regression model is used where frequency dependent regression coefficients, $c_{i,\nu}$, are used with atmospheric state predictors, X_i, to compute the channel absorption coefficients,

$$k_{a,\nu} = c_{0,\nu} + \sum_{i=1}^{N} c_{i,\nu} X_i$$

- Two algorithms for gaseous absorption
  - ODAS (**O**ptical **D**epth in **A**bsorber **S**pace).
    - A “compact” version of the OPTRAN model with H_2O, O_3 absorption only.
  - ODPS (**O**ptical **D**epth in **P**ressure **S**pace).
    - Optical depths computed on a fixed pressure grid.
    - Better fitting statistics.
    - More trace gases: CO_2, CH_4, N_2O.
    - Enables incorporation of Zeeman model (requires fixed pressure grid).

Non-LTE model (1)

- At high altitudes, vibrational transitions depart from LTE.
- Planck function cannot be used as a source function.

Populations of NLTE and LTE high states

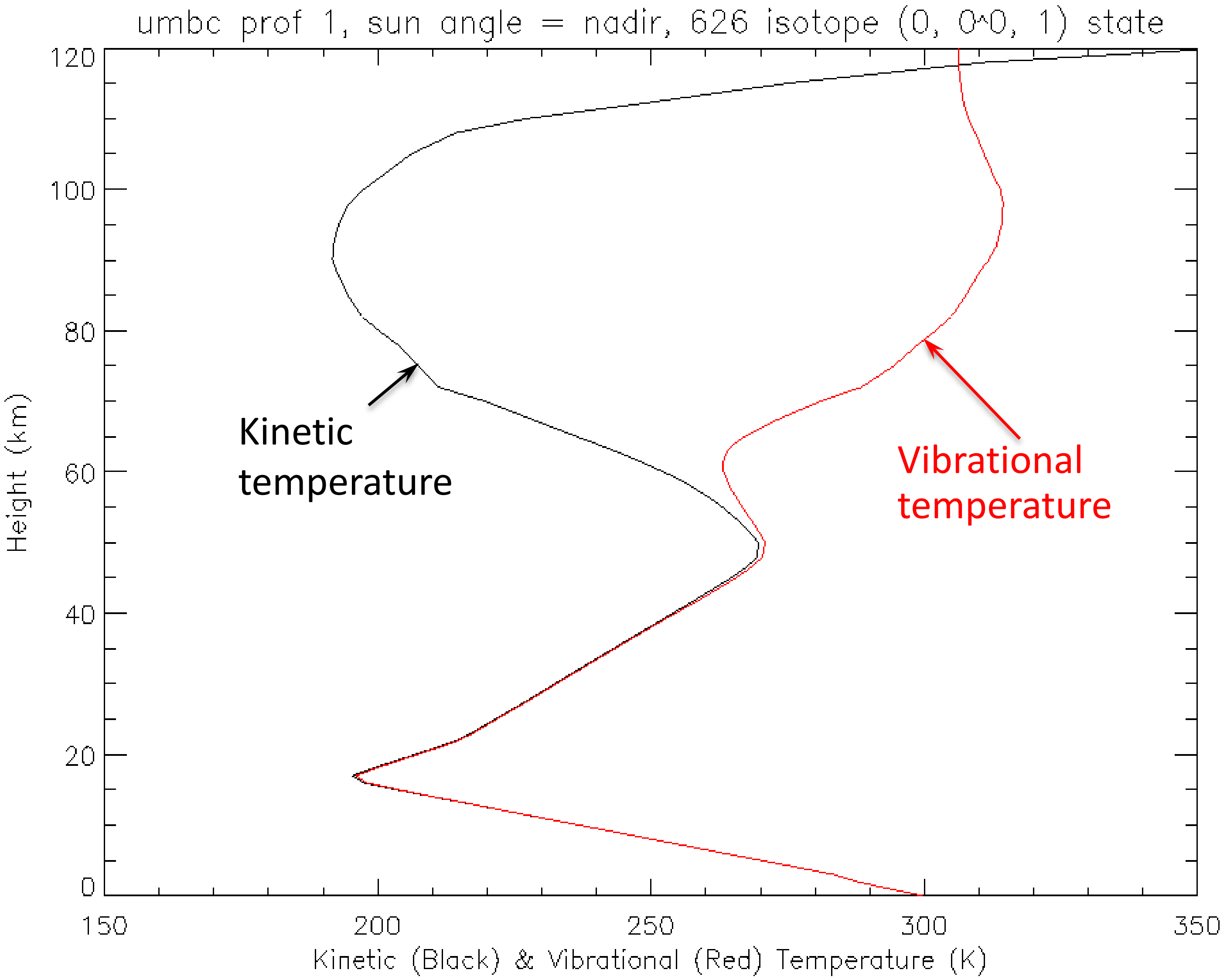
$$J_{\nu,i} = B_\nu \frac{n_{2,i}}{\bar{n}_{2,i}} \frac{\bar{\psi}_{\nu,i}}{\psi_{\nu,i}}$$

NLTE and LTE absorption coefficients

$$\frac{\bar{\psi}_{\nu,i}}{\psi_{\nu,i}} = r_{1,i}\frac{1-\Gamma_i r_{2,i}}{1-\Gamma_i}, \text{ where } \Gamma_i = \exp\left(-\frac{h\nu_0}{kT}\right)$$

$$r_{\alpha,i} = \exp\left[-\frac{E_\alpha}{k}\left(\frac{1}{T_\alpha}-\frac{1}{T}\right)\right], \text{ for } \alpha = 1 \text{ or } 2$$

Vibrational temperature



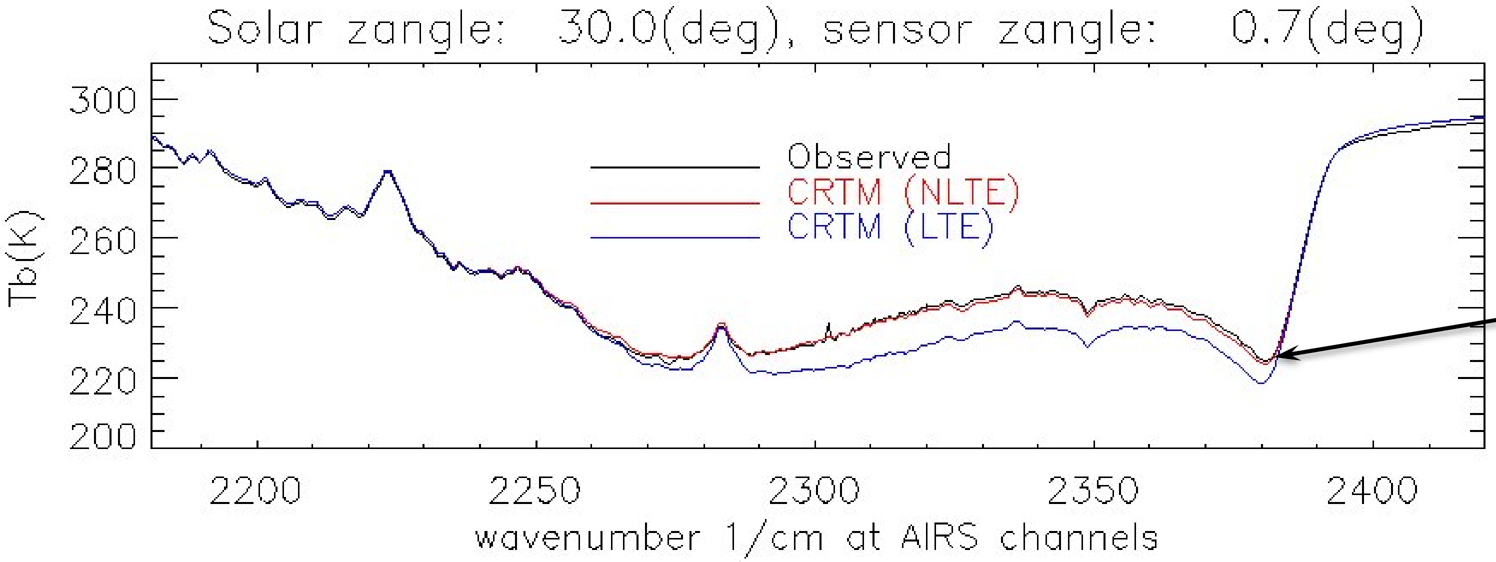
Non-LTE model (2)

- Simple regression model predicts the correction to LTE radiances,

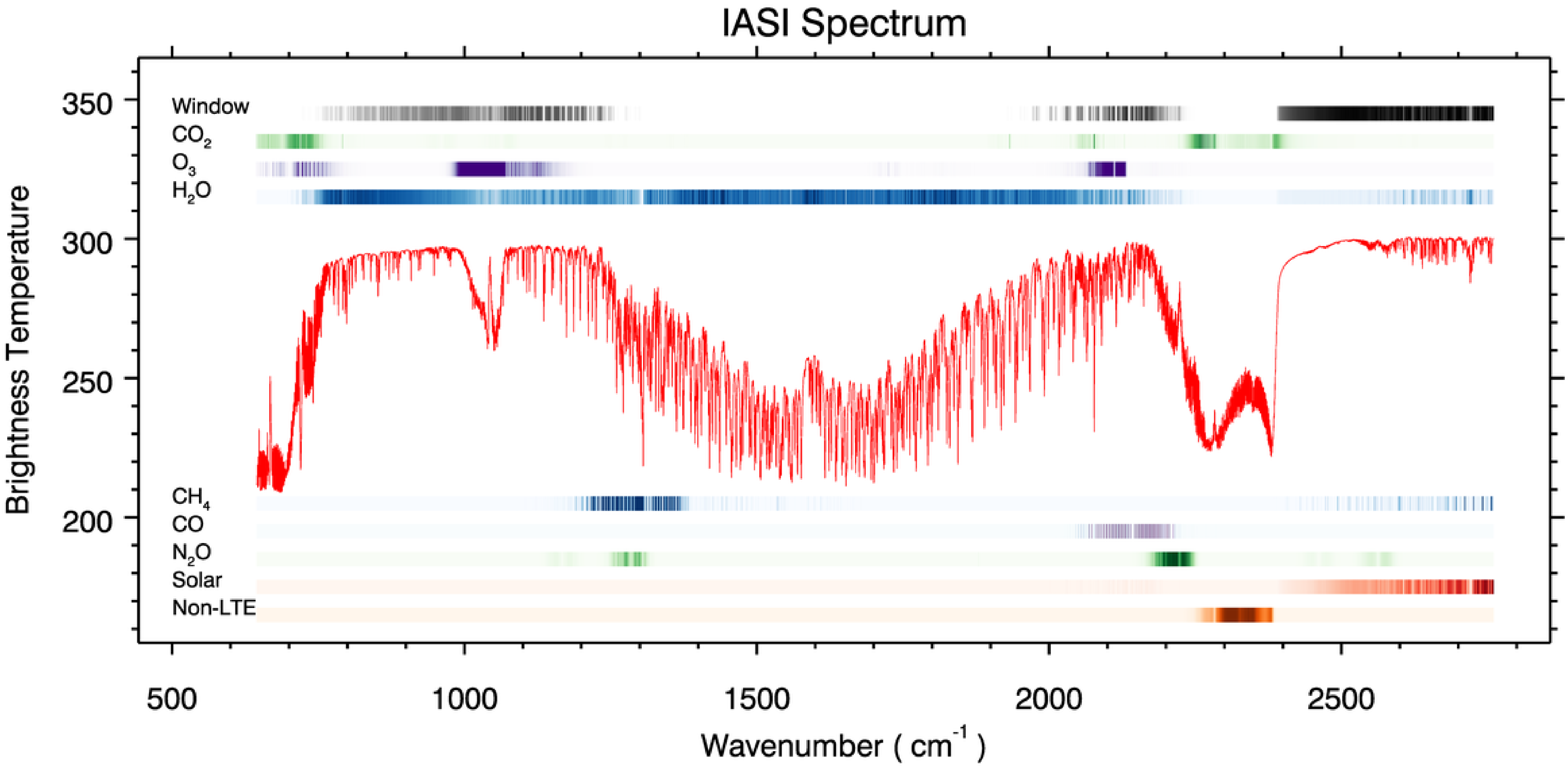
$$R_{\upsilon}^{NLTE} = R_{\upsilon}^{LTE} + \Delta R_{\upsilon}^{NLTE}$$

$$\Delta R_{\upsilon}^{NLTE} = c_{0,\upsilon} + \sum_{i=1}^{4} c_{i,\upsilon} X_i$$

Predictors	Description
X_1	Solar zenith angle
X_2	Mean temperature from 0.005-0.2hPa
X_3	Mean temperature from 0.2-52hPa
X_4	Sensor zenith angle



Remaining differences between observations and NLTE simulations in the shortwave traced to certain CO_2 isotopologues not being present in the spectroscopic database.



Courtesy Emily Liu

Assimilating satellite aerosol retrievals

With GSI, NCAR and ESRL assimilates MODIS AOD using WRF-CHEM as first guess.
The GSI option is extended to assimilate VIIRS AOD using NGAC as first guess.

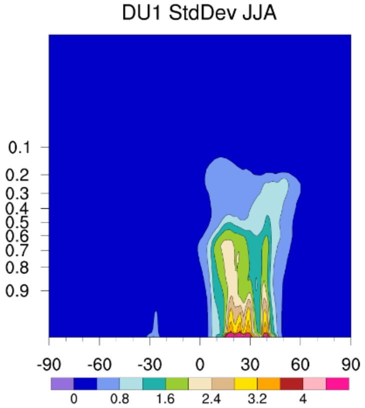
AOD DA (GSI)

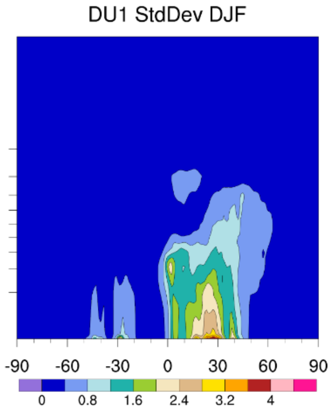
Observation operator: CRTM v2.2.3

Background Errors

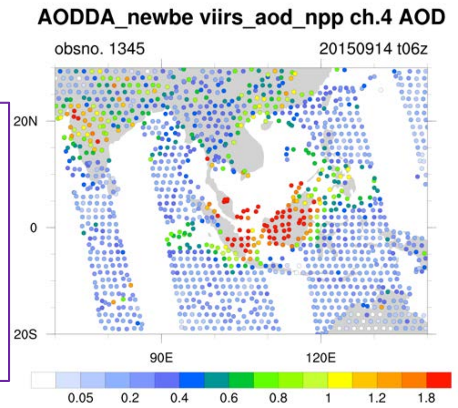
Observation Inputs (VIIRS AOD)

First guess (NGACv2)





- First global in-line aerosol forecast system at NCEP
- Multi-species forecasts (dust, sulfate, sea salt, and carbonaceous aerosols) at T126 L64



NMC method is used to determine BE from 12-month NGAC runs

- Data screening and thinning, considering offset from analysis time, distance from the grid, and retrieval quality
- Observation errors are determined from VIIRS versus AERONET comparisons

Aerosols in CRTM Planning and Coordination

Goal: Implementation of the Community Multiscale Air Quality (CMAQ) aerosol specifications in CRTM, extending current GOCART model.

Ensure CMAQ speciation covers NAAPS aerosols, and confirm using intercomparisons with previous JCSDA efforts (J. Zhang) to include NAAPS aerosol.

Intercomparison of AOD/aerosol speciation operators (GoCart, NAAPS, CMAQ and NGAC)

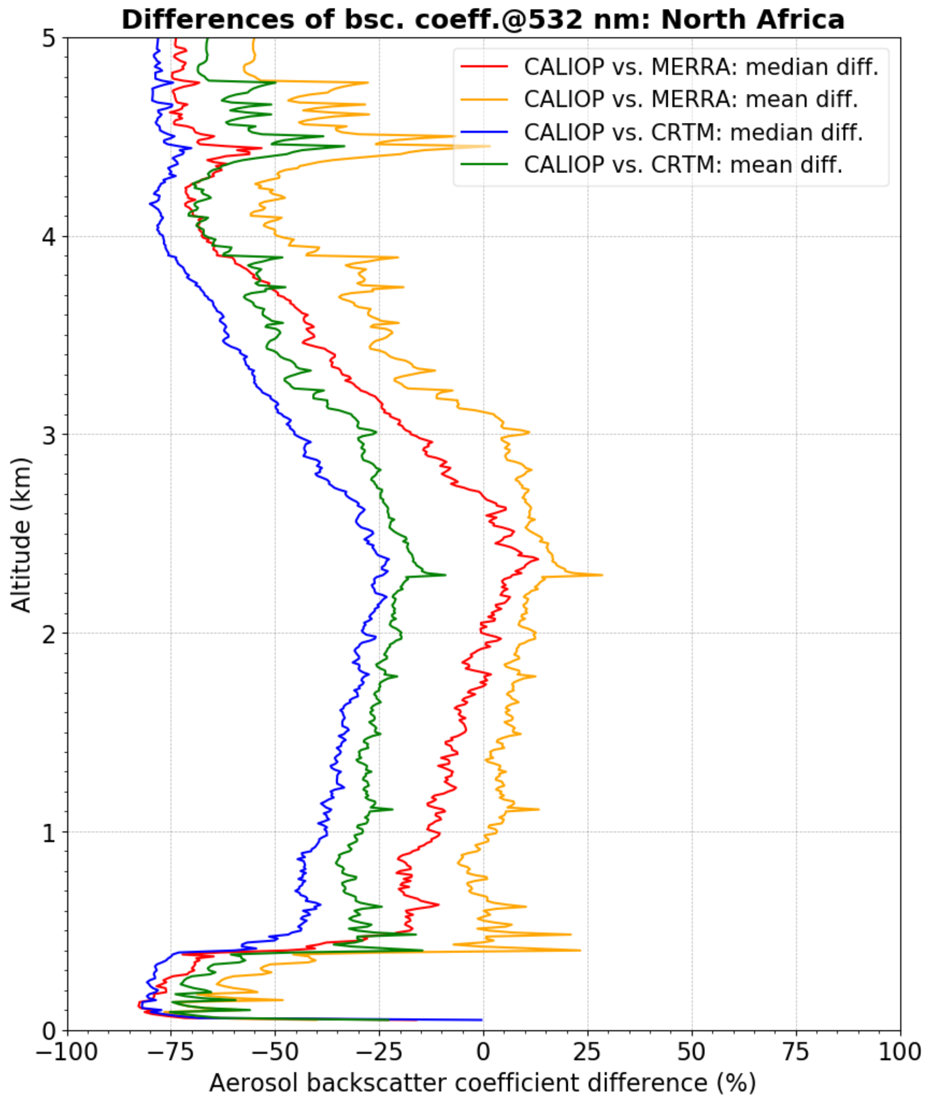
Status: actively being worked, slow progress AOD / aerosol intercomparisons are being done at partner agencies (Ooyla/Ruston, Pagowski, Sarah Lu).

Challenges: available effort and expertise, relying on in-kind contributors completely, need to have a utility to integrate and create new aerosol scattering tables, need updated specifications (CMAQ).

Aerosol + Lidar Work

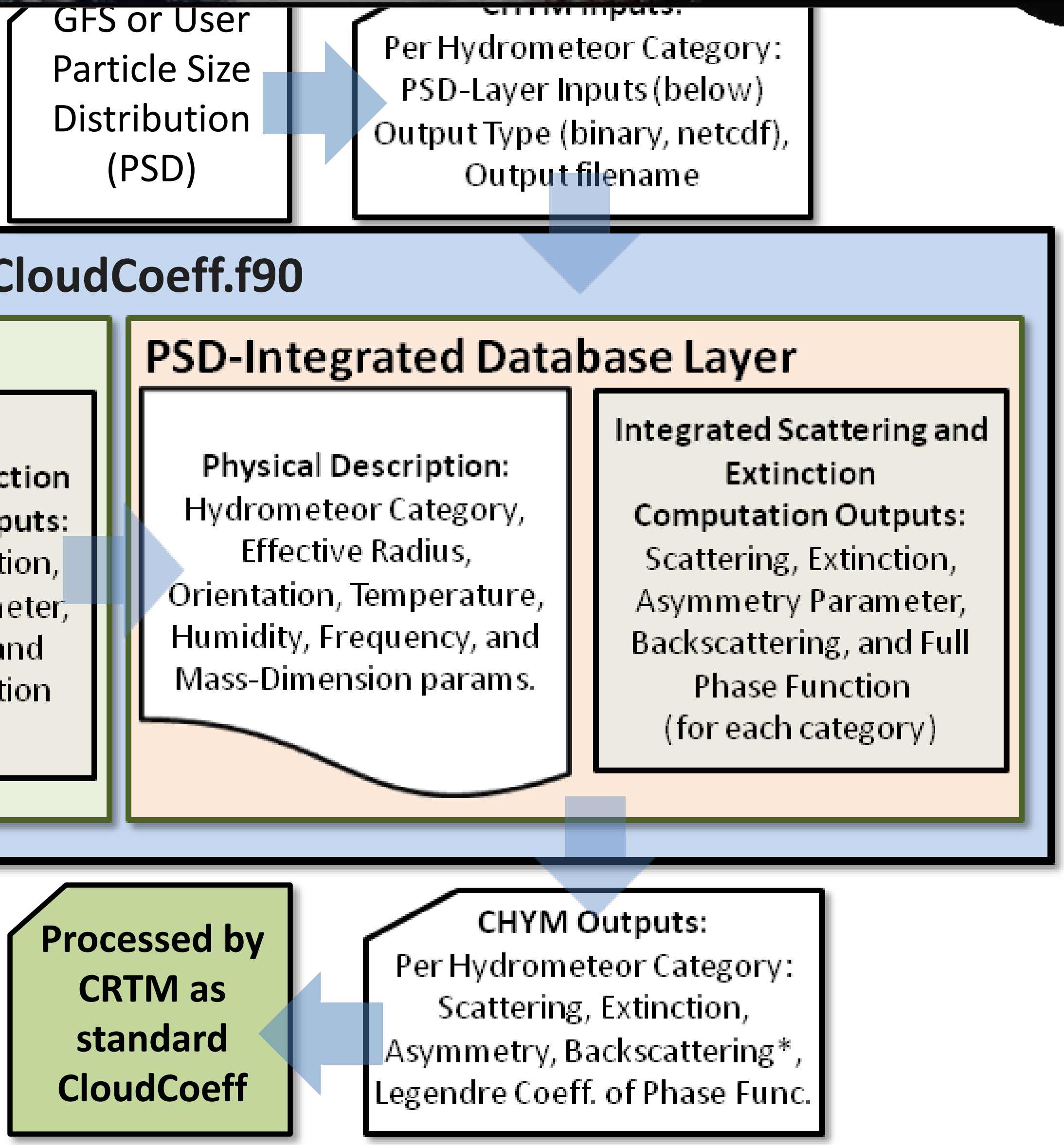
- Goal: Produce an aerosol-sensitive LIDAR forward operator for use in DA, initially focusing on CALIOP
- Output: Aerosol specific AOD and LIDAR backscattering coefficient.
- Status: Preliminary results (see fig.)
- CRTM backscattering compared to MERRA has similar variability, but is consistently too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

Aerosol Backscattering Coefficient differences at 532 nm



Community Hydrometeor Model CHYM

Community Hydrometeor Model (CHYM) (V 0.3)



B. Johnson (JCSDA / UCAR)

Community Hydrometeor Model CHYM

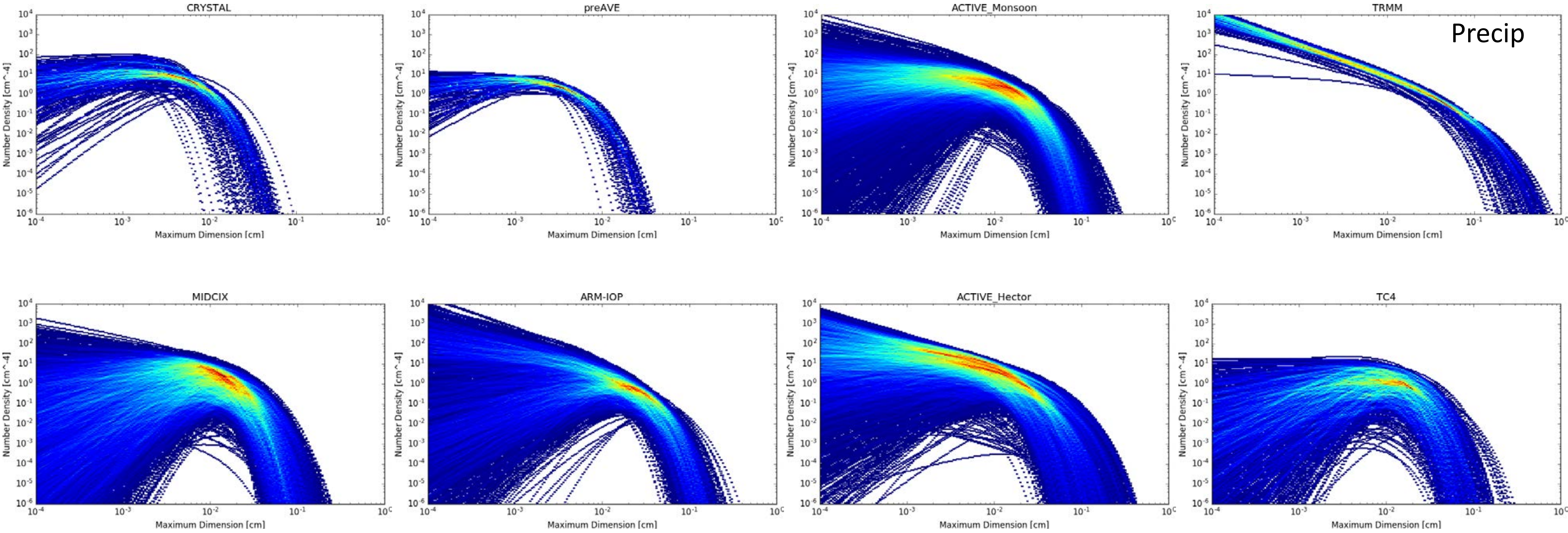
- (1) **Development of the microphysical parameters of clouds and precipitation** (Lead: Emily Liu)
  - Relate to the current and planned GFS microphysical assumptions.
  - converting mixing ratios into particle size distributions (PSD) and habit distributions, consistent with the microphysics schemes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

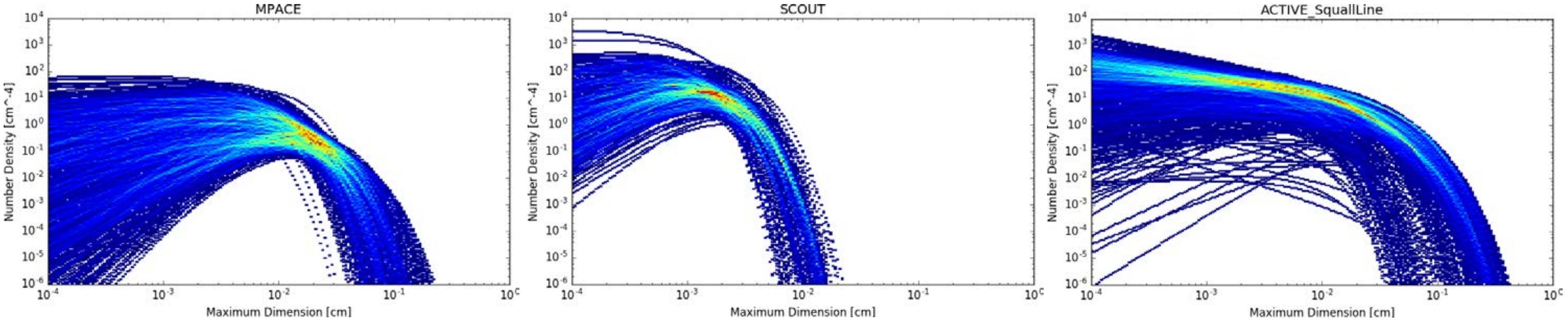
Field Campaign information

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

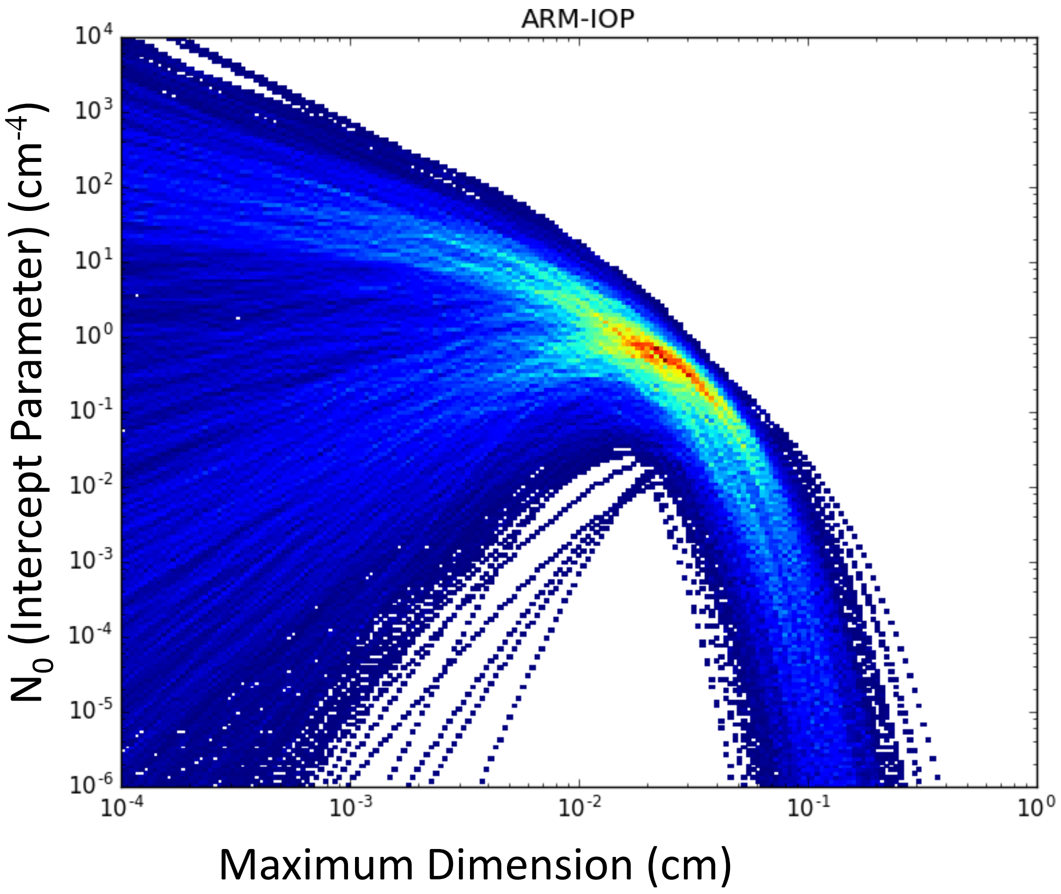


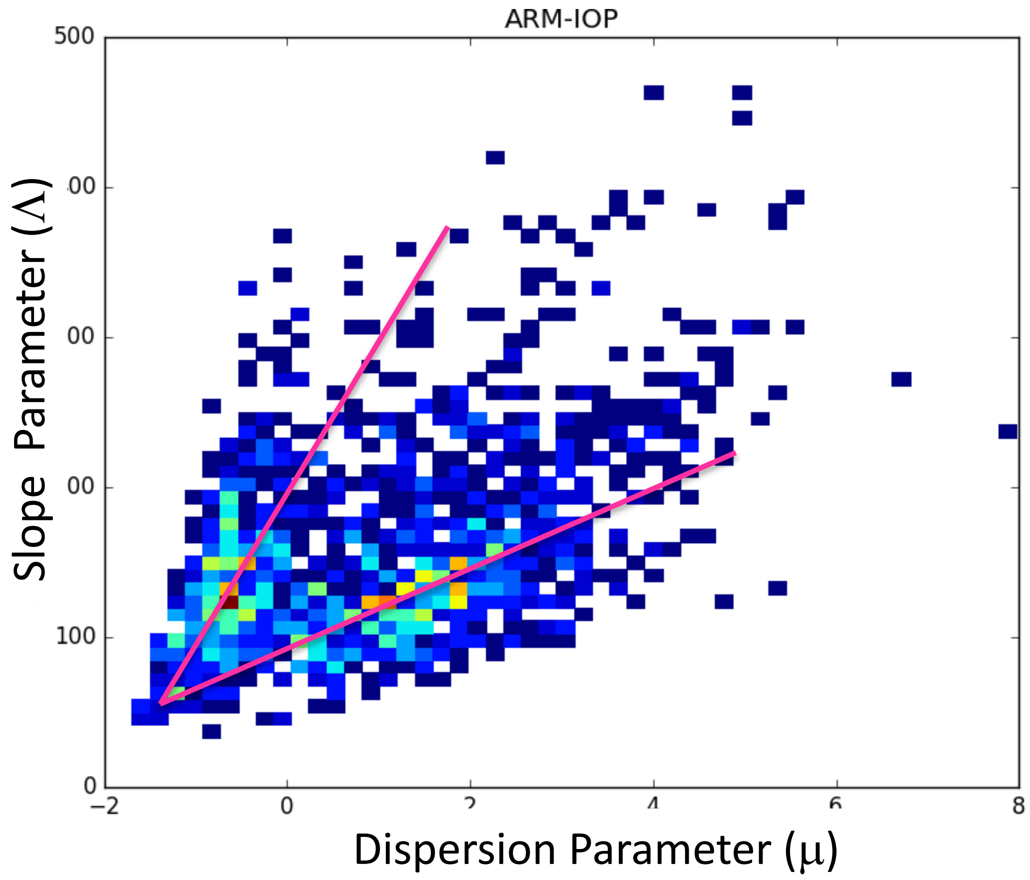


PSDs plotted using data downloaded from Brian Baum's website:
http://www.ssec.wisc.edu/ice_models/microphysical_data.htm

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

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

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)

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:

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

Single Moment

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

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:

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

Double Moment

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

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

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

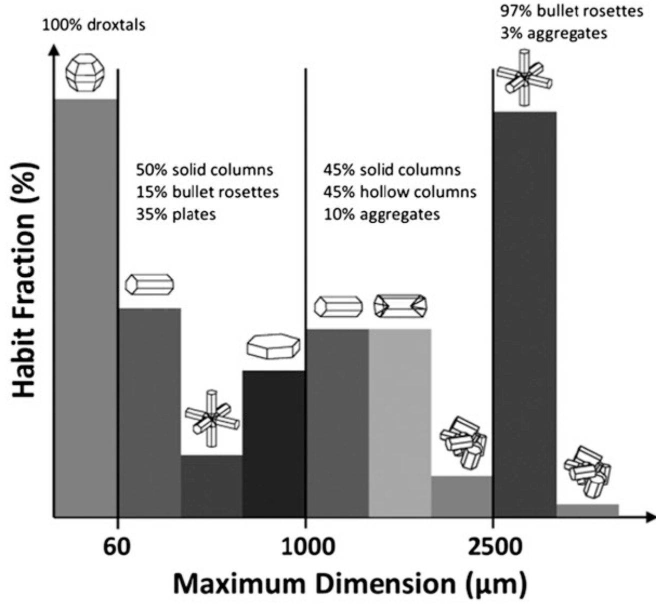
Single Particle Optical Properties

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

Bulk Optical Properties

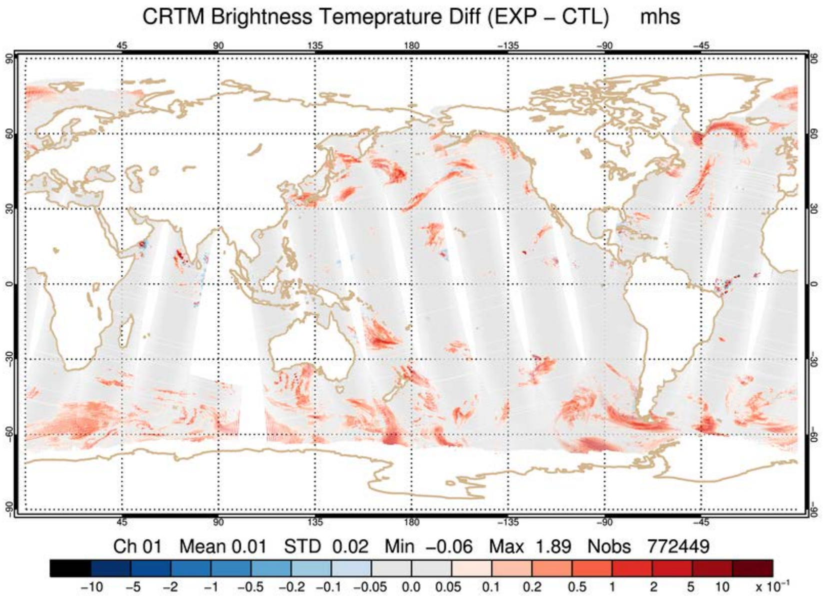
- Gamma size distribution
- Temperatures at 160K and 230K

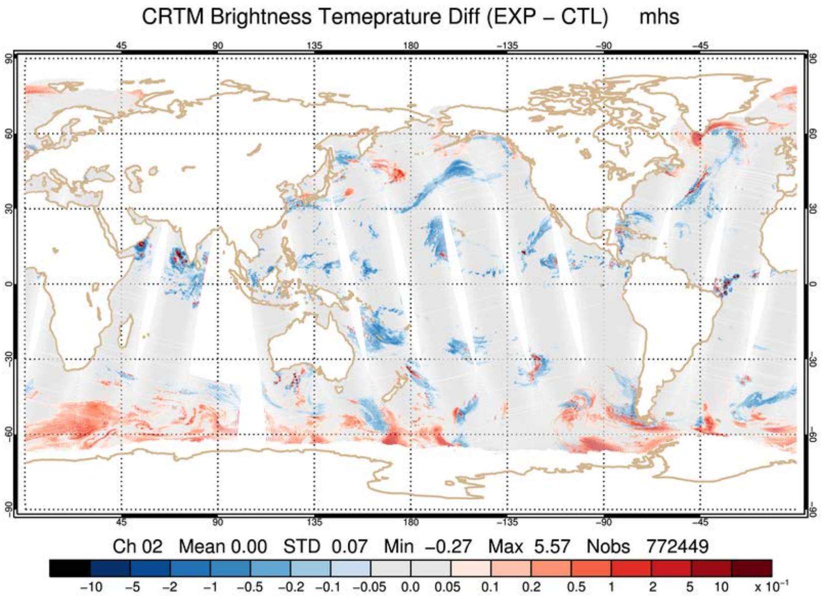
MODIS Collection 5



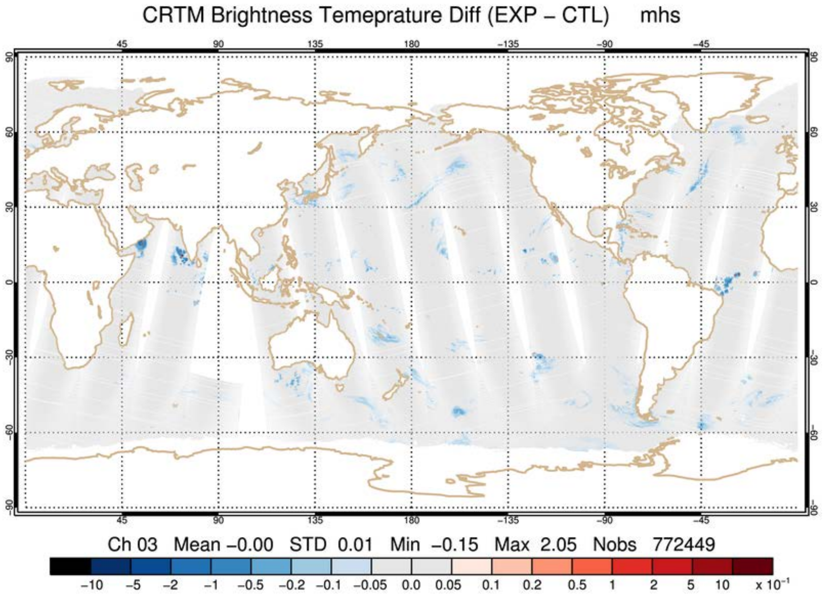
MODID Collection 6

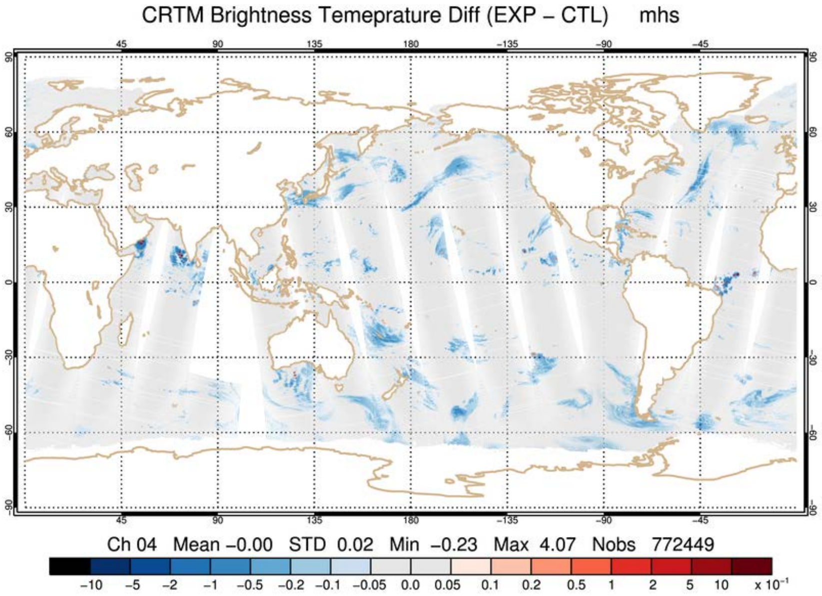
Enhancement of CRTM MC6 – Default

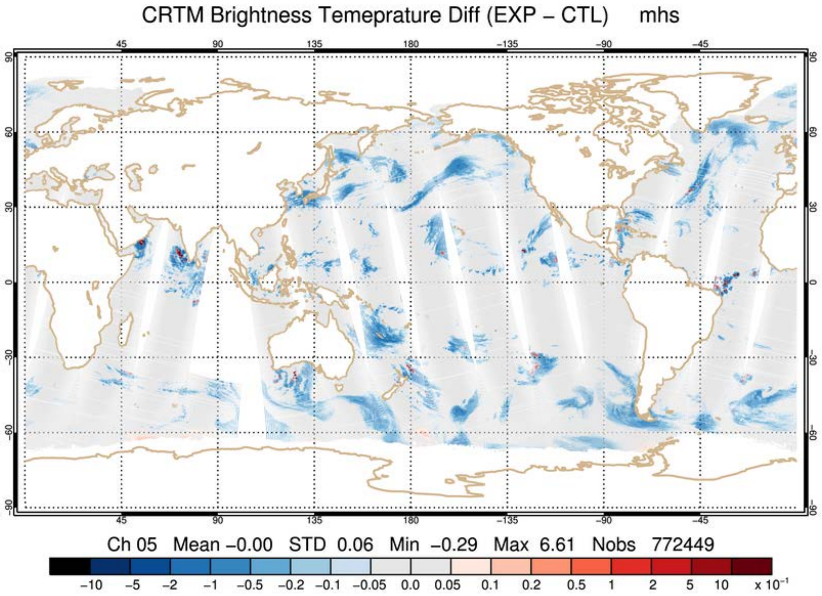




- MC6 Optical Properties evaluated at T=230 K
- Impact on AMSU-A is insignificant
- MHS Metop-a

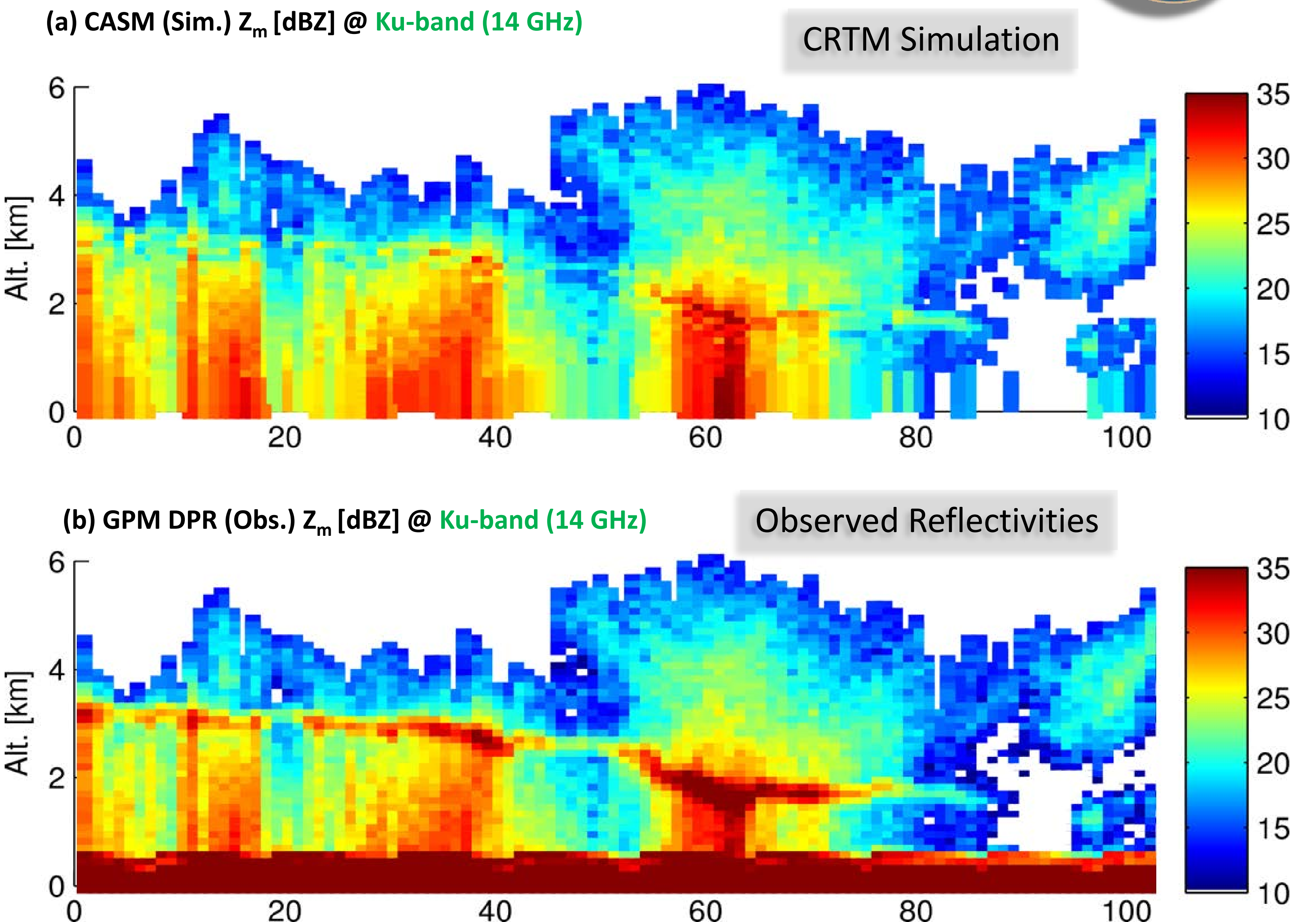






Space-based Radar Simulations (CASM)

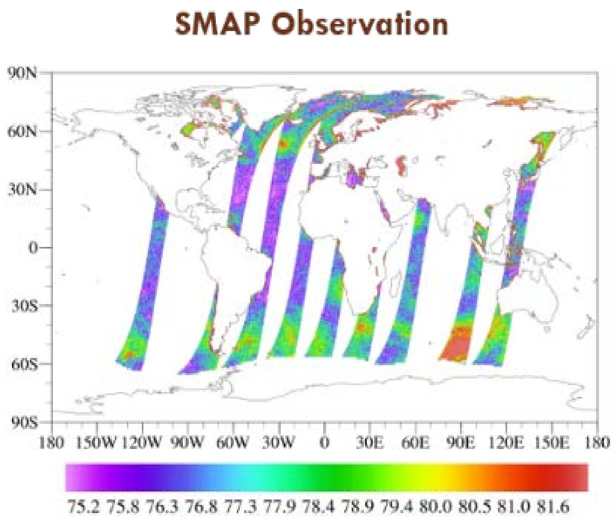
- Goal: Active Space-based Radar Simulation and Jacobians for satellite DA
- Tested for Ku, Ka, and W
- Output: Radar reflectivity and 2-way PIA
- Status: TL and AD models under testing
- Next: Melting layer model, ground-based radar, polarization

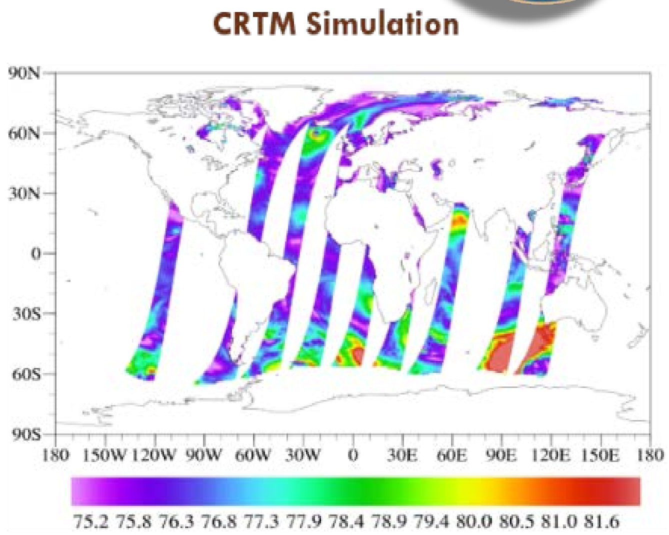


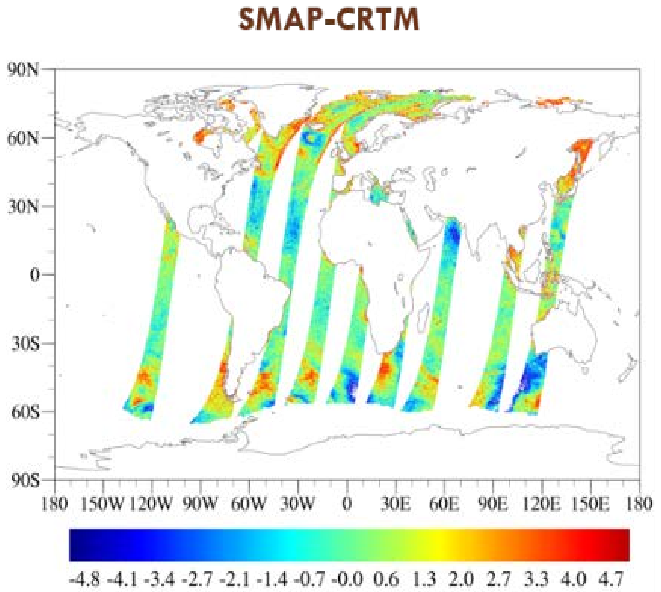
Surface Work :: CSEM (M. Chen)

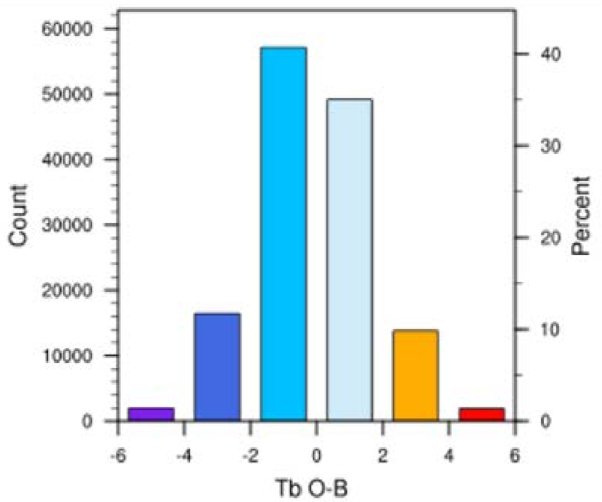
Highlights:

1) CSEM top-down interfaces were refined to support upper-level vectorised RT solvers.
2) The **first integrated CRTM-CSEM version was successfully implemented in ProdGSI**, and passed single cycle GSI testing. More comprehensive tests will be performed in collaboration with the EMC DA group.
3) The **tangent linear and adjoint modules of the physical MW land model were implemented and tested in the CSEM 1.0.0**, which will be applied to the radiance DA, GSI QC and the emissivity retrieval data assimilation.
4) **Implementation of L-band in CRTM has been tested with the integrated CRTM-CSEM**. Since the CRTM quality of the L-band channels basically relies on the surface models, several efforts are being taken to the improve the model physics. Results are very promising toward L-band radiance DA.





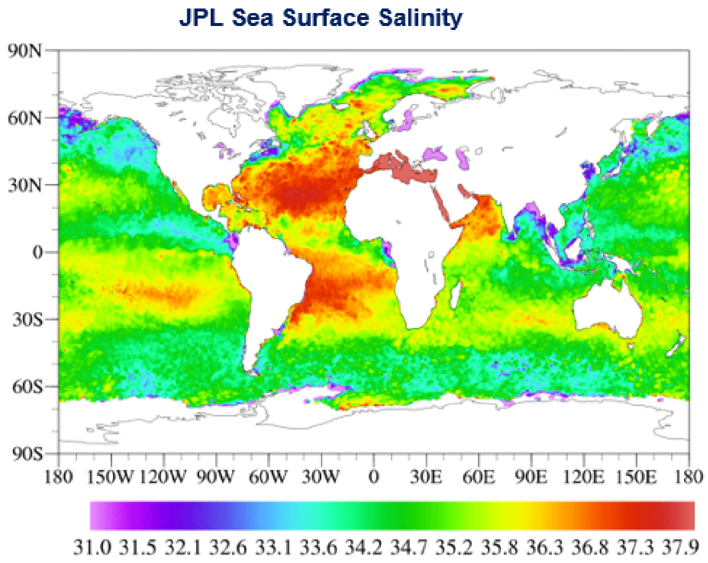


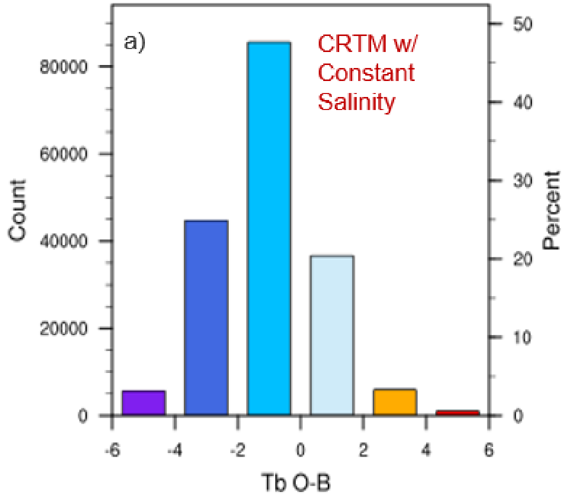


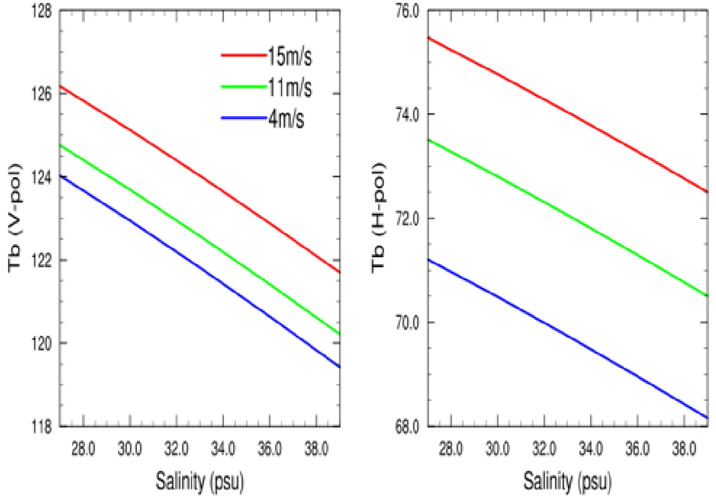
Surface Work :: CSEM (M. Chen)

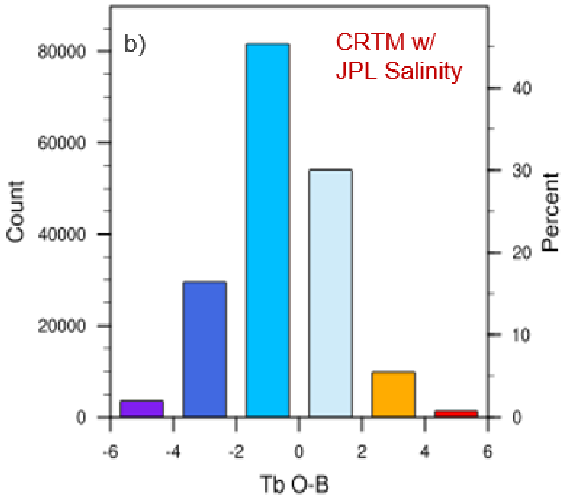
5) The **testing of CRTM-CSEM in FV3 GFS/GSI is in progress**. Such testing focuses on the comparisons among different model options of the same model class (e.g., MW-LAND). While the ultimate testing analysis will target on the O-B and O-A of different model options, the ongoing testing effort is to ensure that each CSEM model component run smoothly and correctly in parallel environment with real input ingested from GSI.

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. In the current FV3 GFS/GSI, a constant SSS value (33.0 PSU) is used, which may bring about ±0.5K bias from K-band (20-40GHz) to ±1.5K bias at L-band (1.4GHz). As shown in the Tb O-B, the negative bias with constant sea surface salinity may be reduced with the JPL Salinity as the model input.









JCSDA Overview

What is the CRTM?

Code and Solver Optimization

Scientific Capabilities and Progress

CRTM v2.3.x and v3.0.0

Operations and Support

Education / Outreach

CRTM REL-2.3.0 New features

1. All-Sky radiance simulation under various cloud_fraction conditions.
2. Use of all-sky transmittances in FASTEM-X reflection correction.
3. Improve surface reflectance in radiative transfer calculation for Microwave under scattering conditions.
4. Add ATMS SeaIce emissivity module.
5. Fix the simulation near 3.9 micron by adding solar contribution in ADA_Module.
6. Updates of CRTM Coefficients for ABI_GOES-R, AHI_Himawari -8.
7. Updates of CRTM antenna correction coefficients for MHS_N19/Metop-a.
8. Update AIRS coefficients for including NLTE correction.
9. Add new coefficients for: CrIS-fsrB1/B2/B3_NPP, CrIS*_N20, CrIS-fsr431_npp/n20, AHI_Himawari-9, ABI_G16, VIIRS-JPSS1, ATMS_N20, ATMS_N20-SRF, COWVR, tropics_designed_v1.

* In this release, there is a new feature for the simulation of all-sky (cloudy) radiance, which utilizes Fortran class functions. CRTM will support the new compiler with class functions, such as ifort version (14.0+, 15.0+, 16.0+, 17.0+), gfortran version (gcc 4.8.5, 4.9, 5.4, 6.4, 7.2), pgi/17.3, ftn/2.3.0.

CRTM REL-2.3.1 New features

CRTM Rel-2.3.1 new features:

I. Integrate New/Updated Coefficients into CRTM trunk:

1. Earth Observing Nanosatellite-Microwave: eon_mw.v1
2. Sentinel-3A Sea and Land Surface Temperature Radiometer: slstr_sentinel3a
3. Meteosat-11 SEVIRI: seviri_m11, and sent to users at NRL and OSPO
4. New coefficient for ABI_G17, and updated IDs from ABI_GR to ABI_G16
5. New coefficients for Metop-C sensors: AVHRR3_Metop-C, IASI(b1,b2,b3)_Metop-C, IASI300_Metop-C, IASI316_Metop-C, IASI616_Metop-C
6. SMAP and SMOS for STAR Ocean and Land Teams data assimilation projects
7. MI-L_COMS.v2: Update for a shifted WV band SRF
8. Tempest-D_cubesat: 5 microwave bands at 87, 164, 173, 178, and 181 GHz, designed at CSU/JPL

II. Integrate Bug fixes:

1. In CRTM_CloudCover_Define.f90, fixing “Intent(in)” to “Intent(inout)” for using gfortran compiler error
2. In CRTM_CloudCover_Define.f90, when using the “Maximum-Random” scheme to calculate Total Cloud Cover
3. ATMS_SnowEM_module: Comment out uninitialized (also unused) variables and calculations
4. Correction to make.dependencies generation
5. Corrected overflow / underflow issue with allocated arrays not being zeroed (found with gfortran 8.2.0)

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.
- **SW / IR improvements in CRTM:**
  - Aerosol + solar impacted IR expert needed!
- **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 and J. Gasteiger)
  - Update toward CMAQ specifications (Team)
  - Improve Lidar backscattering and attenuation calculations (Pagowski, Scherllin-Pirscher)

JCSDA Overview

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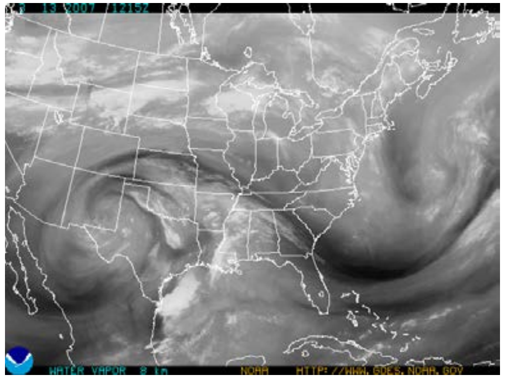
CRTM Role in Operations

- **CRTM enables satellite data assimilation**
  - Forward model simulates satellite radiances or brightness temperatures
  - Jacobian simulates radiance sensitivity to changes in model state (dR/dx or dTB/dx)
- CRTM is used in dozens of operational, reanalysis, and research models:
  - NOAA, Navy, Air Force, NASA
- The only other competitive model is RTTOV used by the European and other non-U.S. weather communities.
  - Significant heritage shared between CRTM and RTTOV over the past decade of coordination and collaboration on scientific advancement, which continues today.
- CRTM will be used in future systems, including NGGPS, and JEDI as the key driver for satellite DA.

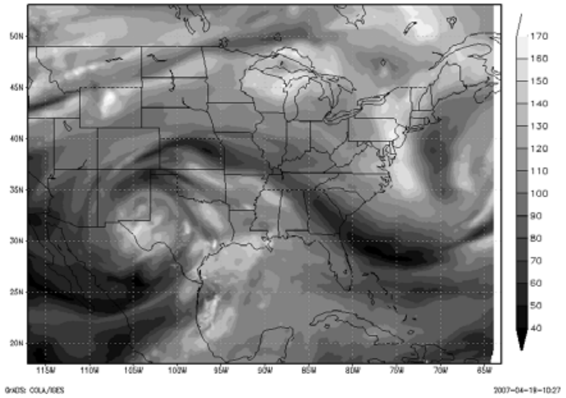
Simulated GOES Imagery vs Analysis:

Spring case. Verified at 12 UTC March 13 2007

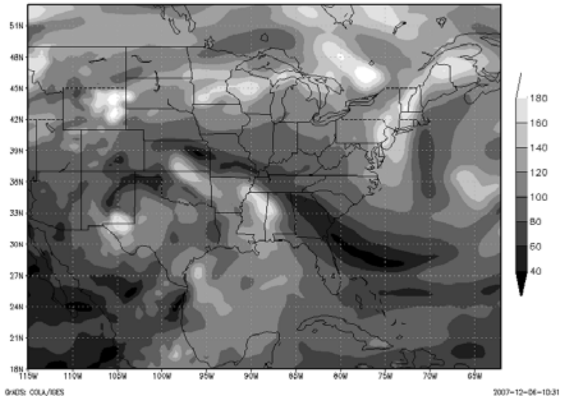
GOES 12 Ch 3 (6.7μm)



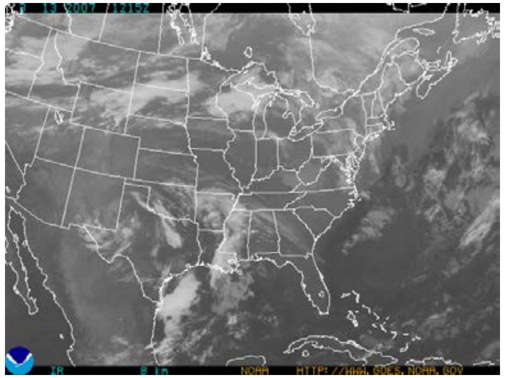
NAM Analysis

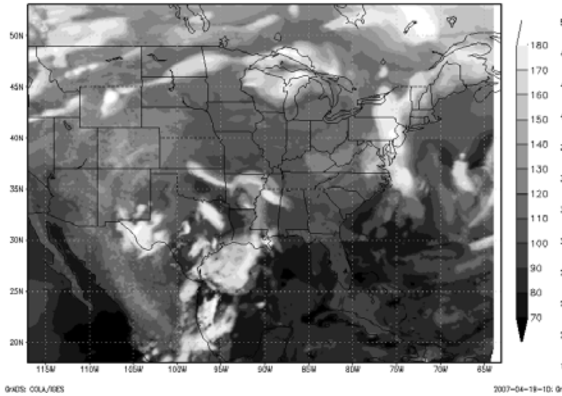


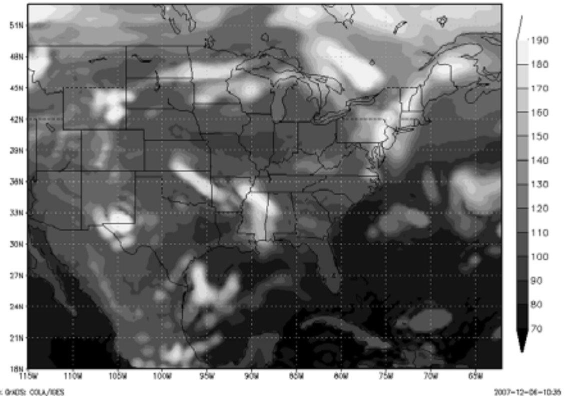
GFS Analysis



GOES 12 Ch 4 (10.7μm)





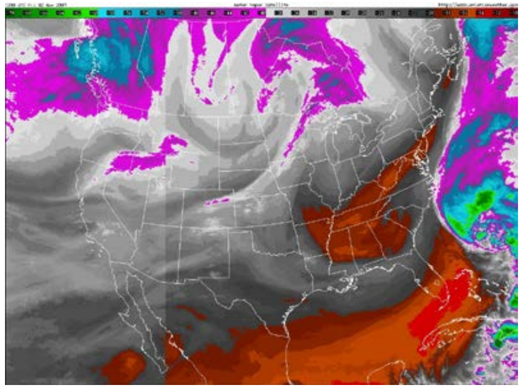


Slide courtesy of Andrew Collard

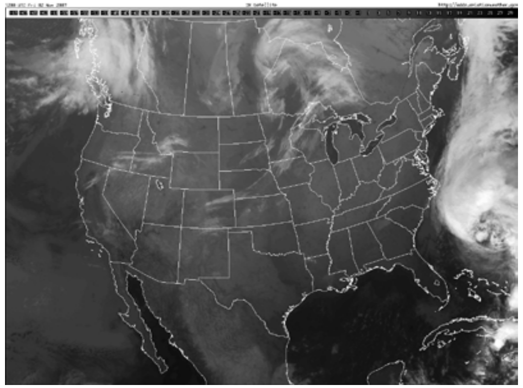
Simulated GOES Imagery vs Forecast:

Tropical Storm Noel. Verified at 12 UTC November 2 2007

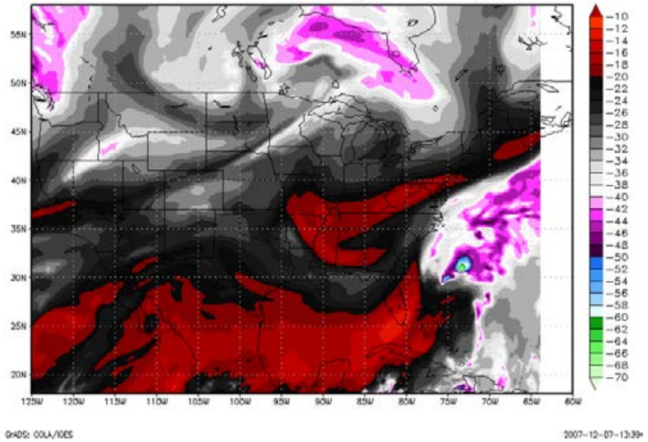
GOES 12 Ch 3 (6.7μm)

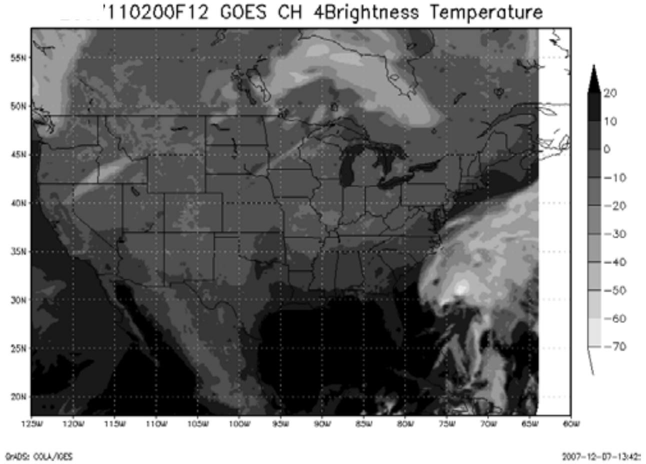


GOES 12 Ch 4 (10.7μm)

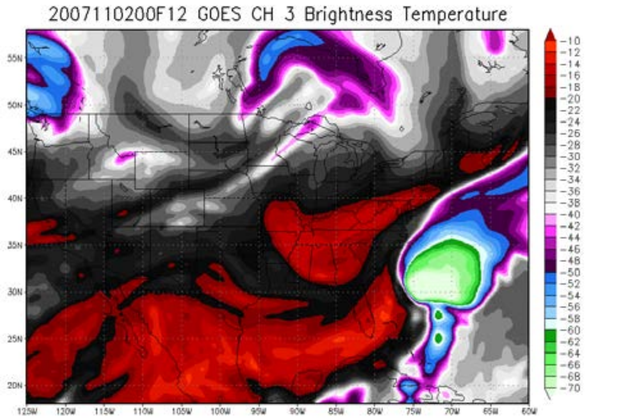


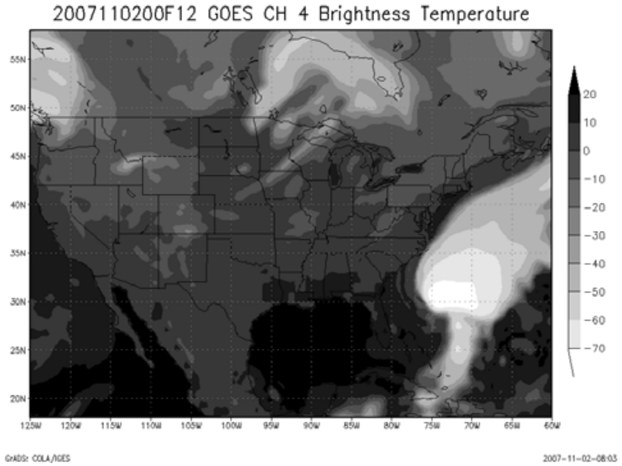
NAM 12 Hr Forecast





GFS 12 Hr Forecasat

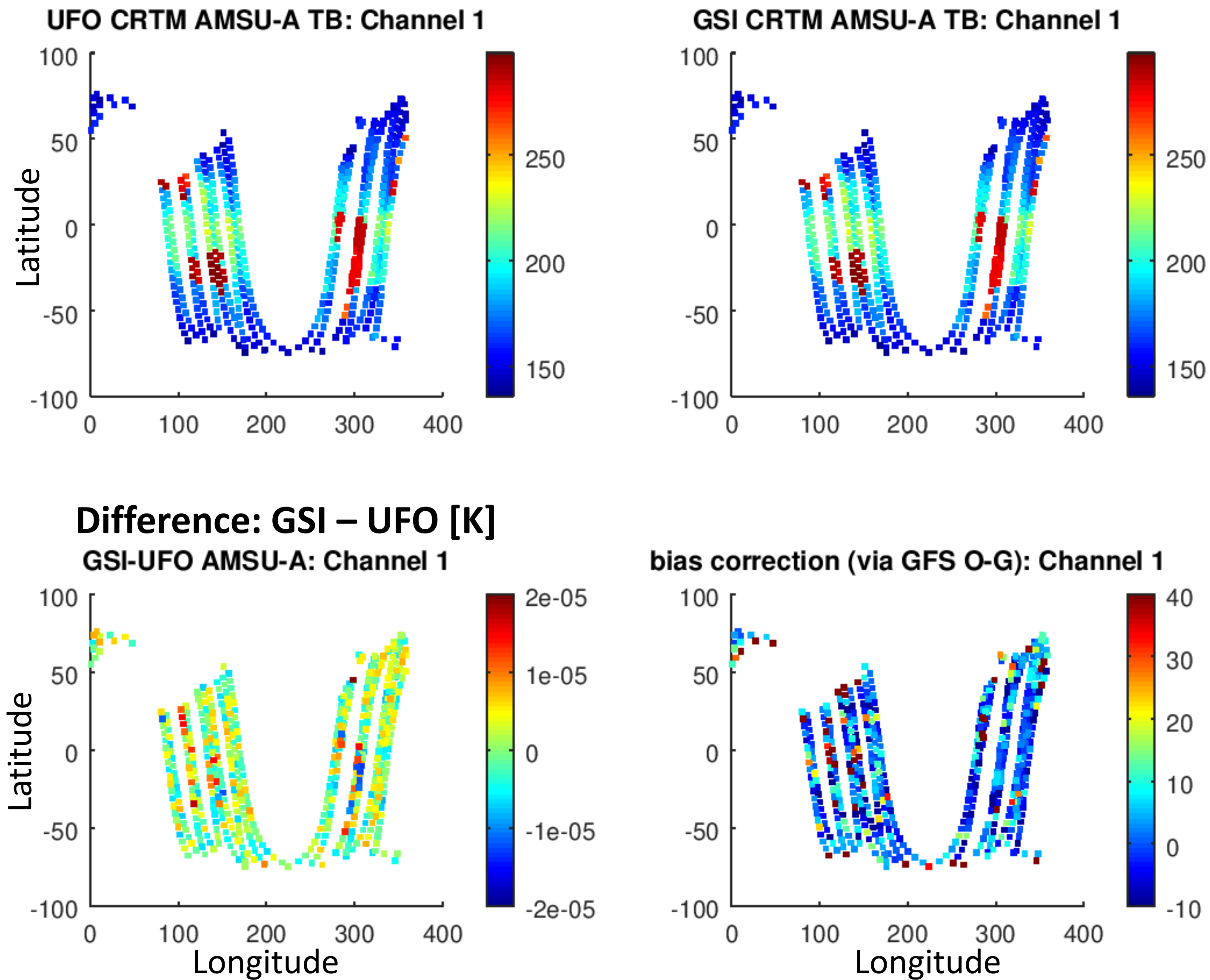




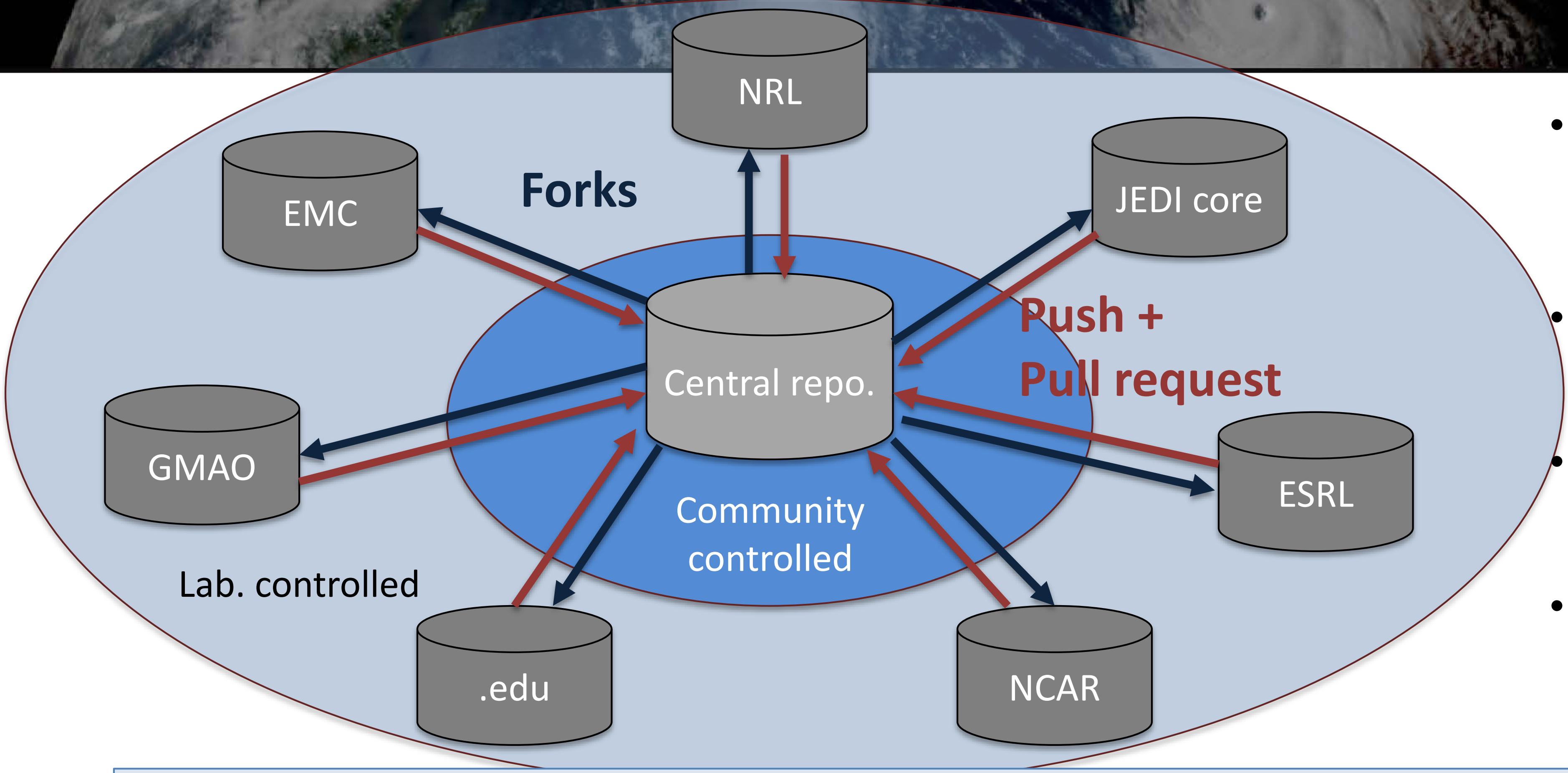
Slide courtesy of Andrew Collard

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.



JCSDA:: Revolution in Ecosystem and Working Practices

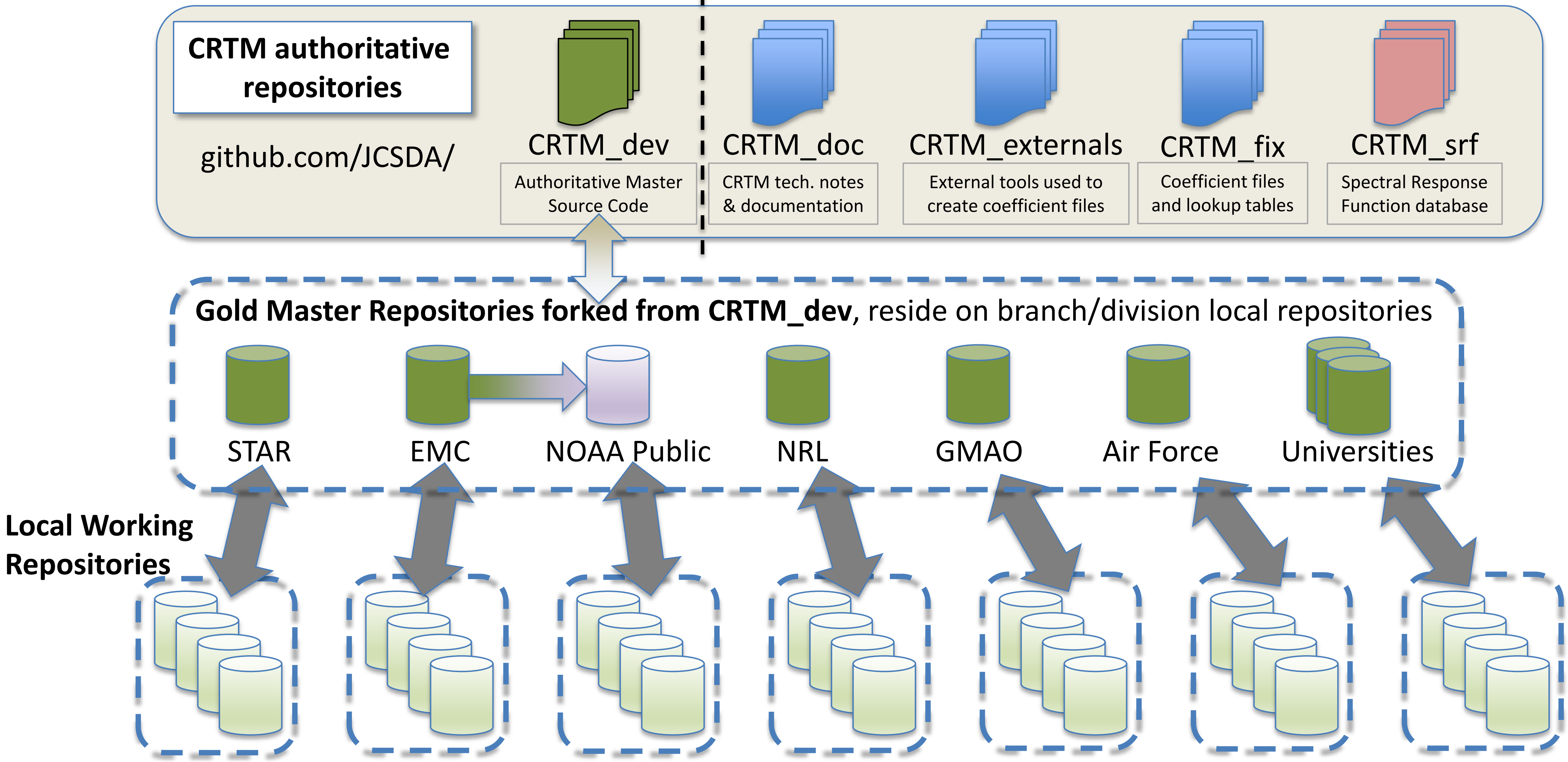


- Strong community engagement @coding level (not 'working groups')
- Transparent and inclusive process
- Continuous online discussions + testing
- Fast-paced code development + reviews

- 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

CRTM Umbrella Repository Strategy

(Goal: complete consistency and interoperability with UFS/NGGPS/JEDI strategy)



User and Developer Support

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.

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Education / Outreach

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. Feedback was overwhelmingly positive.

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

Final Remarks about the CRTM Workflow

Conceptual leap

- New and more unified approach to development, distribution, and maintenance of software

Streamlined processes and operations

- Targeted inter-dependent activities with measurable deliverables
- Annual Operating Plan improving coordination and accountability
- State-of-the-art collaborative ecosystem

Operating within a Center of excellence

- Unprecedented level of collaboration at scientific/technical level
- Highly skilled core staff committed to the success of JCSDA projects

Focus on transitional research

- Faster, better, cheaper, safer transition between research and operations
- Constantly striving to be proactive and available to operational requirements

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

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Field 07 Snow Particle Size Distribution

IWC

T_c

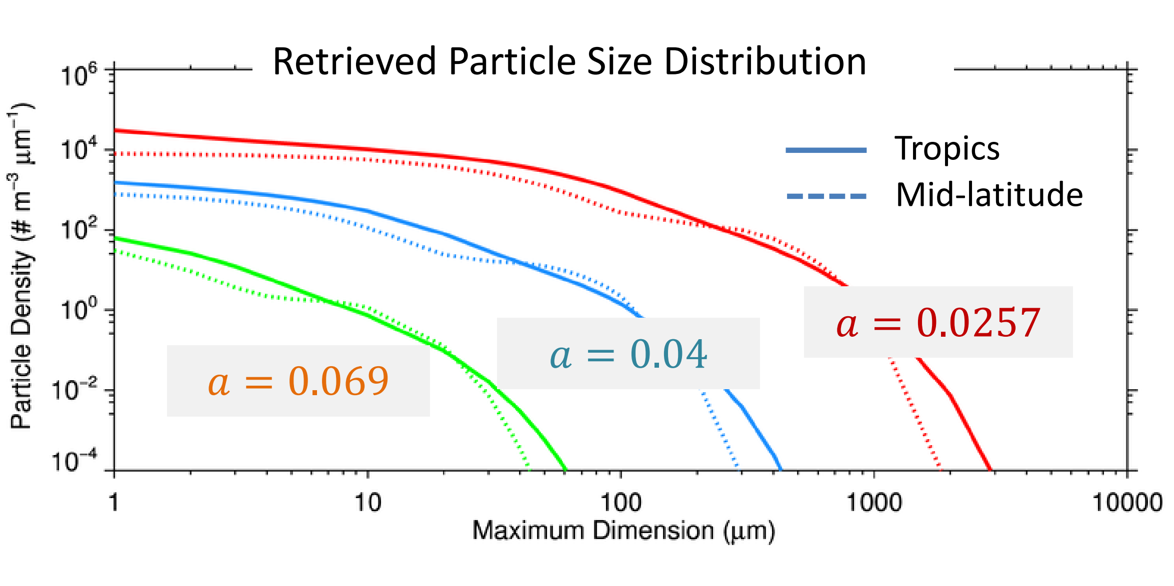
Mass-Dimensional Relationship

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

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

$$T_c = -49.7\ °C$$

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



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:

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

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 q_i N_{ti} $w_i = \rho_a q_i$	Spherical	0.89	$a_i D^{b_i} = \frac{\pi}{6}\rho_i D^3$	Exponential $N_{oi}\, D^{\mu_i}\, e^{-\lambda_i D}$	$\mu_i = 0$ $\lambda_i = \left(\frac{a_i\, N_{ti}\, \Gamma(\,\mu_i + b_i + 1\,)}{\rho_a\, q_i\, \Gamma(\,\mu_i + 1\,)}\right)^{\frac{1}{b_i}}$ $N_{oi} = \frac{N_{ti}\, \lambda_i{}^{\mu+1}}{\Gamma(\,\mu_i + 1\,)}$	$D_{ei} = \frac{M_3}{M_2}$ $= \frac{\int_0^\infty D^3 N(D) dD}{\int_0^\infty D^2 N(D) dD}$ $= \frac{\Gamma(\,\mu_i + 4\,)\lambda^{-(\,\mu_i + 4\,)}}{\Gamma(\,\mu_i + 3\,)\lambda^{-(\,\mu_i + 3\,)}}$ $= \frac{3}{\lambda_i}$

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

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) $\begin{cases} x = D\frac{M_2}{M_3} \\ \Phi_{23}(x) = N(D)\frac{M_3^3}{M_2^4} \end{cases}$ $N(D) = \Phi_{23}(x)\frac{M_2^4}{M_3^3}$	$M_n = A(n)\exp[B(n)T_c]\,M_2^{C(n)}$ $A(n) = exp(13.6 - 7.76n + 0.479n^2)$ $B(n) = -0.0361 + 0.0151n + 0.00149n^2$ $C(n) = 0.807 + 0.00581n + 0.0457n^2$ $w_s = \rho_a q_s = a_s M_{b_s} \rightarrow M_{b_s} = \frac{w_s}{a_s} = \frac{\rho_a q_s}{a_s}$ $M_2 = \left(\frac{M_{b_s}}{A(b_s)\,exp[B(b_s)T_c]}\right)^{\frac{1}{C(b_s)}} \rightarrow M_n = A(n)\exp[B(n)T_c]\,M_2^{C(n)}$ Tropical Regime: $\Phi_{23}(x) = 152e^{-12.4x} + 3.28x^{-0.78}e^{-1.94x}$ Mid-latitude Regime: $\Phi_{23}(x) = 141e^{-16.8x} + 102x^{2.07}e^{-4.82x}$	$D_{es} = \frac{M_3}{M_2} = \frac{\int_0^\infty D^3N(D)dD}{\int_0^\infty D^2N(D)dD}$

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

All units are defined in SI units unless noted

AOP 2018: Core and In-Kind Contributions

Core

Name	FTE	Funding Source
Core JCSDA	**21**	
Thomas Auligne	1.00	NASA
Whitney Robinson	1.00	STAR
Benjamin Johnson	1.00	STAR
Guillaume Vernieres	1.00	STAR
Hui Shao	1.00	STAR
Francois Vandenberghe	1.00	OSAAP
Yannick Tremolet	1.00	NGGPS
Sandra Claar	1.00	STAR
TBD: Executive Officer	1.00	NGGPS
TBD: New Software Engineer	1.00	NGGPS
Suryakanti Dutta	1.00	OSAAP
Hamideh Ebrahimi	1.00	NASA
Stephen Herbener	1.00	NGGPS
Mark Miesch	1.00	NGGPS
TBD: New Software Engineer	0.50	USAF
TBD: New Software Engineer	0.50	NRL
Dan Holdaway	1.00	NASA
Xin Zhang	1.00	STAR
Patrick Stegmann	1.00	STAR
Jim Rosinski	0.50	STAR

In-kind

Name	In-kind FTE
NASA / GMAO	**4.25**
Ron Gelaro	*0.05*
Isaac Moradi	*0.10*
Will McCarty	*0.30*
Amal El Akkraoui	*0.10*
Jing Guo	*0.50*
Ricardo Todling	*0.40*
Santha Akella	*0.20*
David Carvalho	*0.10*
ROSES External Research	*2.5*
Navy / NRL	**2.3**
Nancy Baker	*0.10*
Bryan Karpowicz	*0.40*
Benjamin Ruston	*0.30*
Mayra Oyola	*0.20*
Sergey Frolov	*0.20*
Rolf Langland	*0.40*
Sarah King	*0.20*
John Michalakes	*0.20*
Pedro Tsai	*0.10*
Bill Campbell	*0.20*
NWS / NCEP	**3.45**
James G. Yoe	*0.50*
Daryl Kleist	*0.05*
Huichun (Emily) Liu	*0.20*
Yanqiu Zhu	*0.10*
Travis Sluka (NOAA / CPC)	*0.50*
TBD: New Hire (EMC prepbufr)	*0.20*
Stylianos Flampouris	*0.70*
Yan Ho	*0.40*
Rahul Mahajan	*0.40*
Andrew Collard	*0.20*
Hyun-Chul Lee	*0.10*
Dave Groff	*0.10*

OAR / ESRL (and AOML)	**2.8**
Stan Benjamin	*0.05*
Jim Rosinski	*0.20*
Chris Harrop	*0.50*
Jeff Whitaker	*0.10*
Mariusz Pagowski	*0.30*
Scott Gregory	*0.10*
Clara Draper	*0.10*
Bryan Flynt	*0.50*
Ming Hu	*0.40*
Anna Shlyaeva	*0.30*
Lidia Cucurull (AOML)	*0.10*
Eric James	*0.15*
NESDIS / STAR	**4.7**
Kevin Garrett	*0.45*
Ling Liu	*0.25*
Yingtao Ma	*0.25*
Changyong Cao	*0.10*
Ming Chen	*0.80*
Tong Zhu	*1.00*
Biljana Orescanin	*1.00*
Krishna Kumar	*0.25*
TBD: New Scientist	*0.50*
TBD: New Scientist	*0.10*
USAF / NCAR	**3.7**
Jeffrey Cetola	*0.05*
Dave Gill	*0.20*
TBD: New Hire (USAF / NCAR)	*0.80*
Gael Descombes	*0.30*
BJ Jung	*0.50*
Soyoung Ha	*0.25*
Jake Liu	*0.10*
TBD: New hire(s)	*1.00*
Craig Schwartz	*0.50*

CRTM Management and Oversight

- **CRTM Core Team**
  - **What:** UCAR/JCDSA employees directly funded to support CRTM.
  - **Responsibilities**: manage all aspects of CRTM development, implementation, testing, support, and outreach.
  - **Members:** Benjamin Johnson, Patrick Stegmann, and Jim Rosinski (0.5 FTE)
- **CRTM In-Kind Contributors**
  - **What:** Researchers whose work aligns closely with the JCSDA CRTM vision and are authorized by their managers to contribute to the CRTM development.
  - **Responsibilities:** Contribute to the CRTM development and management tasks through shared responsibility and intent. Submit quarterly reports on activities, and present relevant research / contributions at AMS.
  - **Members:** Tong Zhu, Ming Chen, Kevin Garrett, Emily Liu, Mariusz Pagowski, Sarah Lu, Andrew Collard, Mayra Ooyla, Ben Ruston
- **CRTM External Contributors**
  - **What:** Externally funded contributors that have successfully proposed to and obtained funding through ROSES or NOAA FFO, or unfunded community contributors who wish to contribute to the CRTM mission.
  - **Responsibilities:** Meet their proposed deliverables, present at conferences, and provide a quarterly report. Unfunded community members have no specific responsibilities imposed upon them.
  - **Members:** Tom Greenwald

CRTM Licensing and Distribution

- CRTM consists of source codes authored by over a dozen researchers over a period of 14+ years.
- Most of the codes are copyrighted via the code authors.
- Some of the authors were civil servants, those portions of the code, by federal law, become public domain.
- Some of the codes contain Gnu Public License 2.0 with an upgrade clause. These specifically prevents the use of CRTM in any operational framework since no operational models (current or future) are conformant with GPL.
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