The Community Radiative Transfer Model

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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, covering UV, VIS, Near-IR, IR, subMM, MW

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

Has aerosol (GO-CART), cloud (2 species), precipitation (4 species); with unpolarized scattering and absorption (in v2.x). Uses pre-computed transmittance regression coefficients and various LUTs for speed.

Outputs: Radiance/TB (H(x)), Jacobian (J(x) = dTB/dx

Scientific Applications of the Community Radiative Transfer Model

The Community Radiative Transfer Model (CRTM) provides the critical link between satellite radiances and physical properties of the Earth system:

- Operational Satellite Data Assimilation → Analysis, Forecasting
- Calibration / Validation
- Satellite Simulations
- Reanalysis
- Real-time Weather Analysis / Support
- Satellite Sensor Health Monitoring
- Field Experiment Support
- Education and Outreach

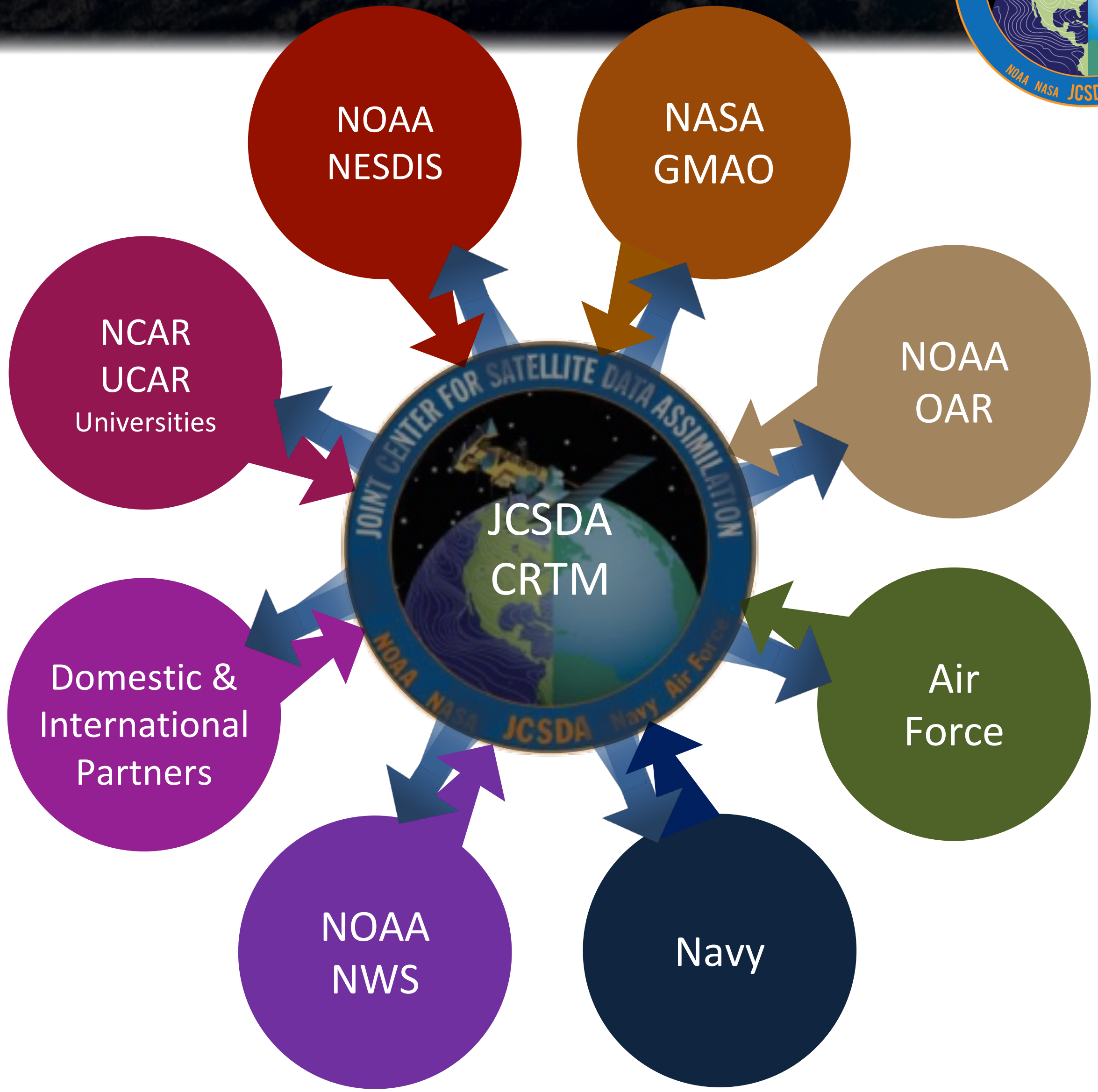
CRTM Vision

CRTM is a Community Model

- Open Source and Open Access
- Version Control (git) and code review
- Distributed Collaboration (GitHub, Zenhub, Google)
  - https://github.com/JCSDA/crtm
- Modern Fortran (2003+)
- Public Domain License

Education and Outreach

- CRTM User/Developer Workshop(s)
- JCSDA Summer Colloquium
- Code Sprints
- Seminars / Colloquia
- JCSDA.org website



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 operational NWP
  - 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: 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)

- Enables DA in US systems
  - UFS, GFS, RRFS, UPP, etc.
  - JEDI/UFO, MPAS-JEDI, WRF-DA, etc.
  - GEOS, MERRA
  - Navy / Air Force

CRTM v2.4.0 – v3.2-pre summary

https://github.com/JCSDA/CRTMv3

What's New Since ~v2.4.0 to now (maybe a few missing items, just to give you an idea)

1. Quiet Printing and Logging Improvements
Multiple PRs focused on making the model's output less verbose and more controllable. This includes adding quiet print options, commenting out unnecessary informational outputs, and fixing the quiet option inside src/CRTM_LifeCycle.f90.

2. Aerosol, Cloud, and Active Sensor Capabilities
Significant enhancements were made to support aerosol and cloud data handling, including a new CRTM AOD module and aerosol bypass functionality. Several PRs merged Active Sensor and DDA cloud coefficients

3. Transition to CMake
A major structural update involved moving from ecbuild to a standalone CMake-based build system. This included reworking CMakeLists.txt, removing hard-coded installation prefixes, and providing options to build either shared or static libraries. These changes improve portability, maintainability, and flexibility in various build environments.

4. Performance and Stability Fixes
OpenMP-related segfaults were addressed, as well as issues involving thread settings for certain profile cases. Additional memory and initialization fixes (e.g., zeroing allocated arrays in RTV_Create).

5. Data I/O and Coefficient Handling
Enhancements were made to improve reading/writing of cloud, aerosol, and surface emissivity data. Tools for handling CRTM coefficient files were expanded, enabling binary-to-netCDF conversions, generating associated ACCoeff and NLTECoeff NetCDF files, and allowing local tarball specification for coefficient downloads.

6. Surface Properties and Reflectance Output
Changes ensured that surface properties (reflectivity, direct_reflectivity, emissivity) are bounded correctly, though one bounding PR was later reverted. Reflectance output capabilities were added to enable direct reflectance assimilation.

7. Miscellaneous Maintenance and Housekeeping
Numerous smaller fixes were made, including correcting typos, removing redundant code lines, updating versioning for releases, ensuring make install works properly, and merging tested changes back into the develop branch. These collectively improve the overall cleanliness and reliability of the codebase.

8. Multiple new sensor coefficients added (detailed later)

New Features Under Development

https://github.com/JCSDA/CRTMv3

Status: **CRTM v3.2.0 under development**

- Land Surface emissivity model updates (e.g., CAMEL v3 land emissivity atlas)
- Various Surface emissivity interface updates (replacing NESDIS* routines (long term updates)
- SURFEM fast ocean surface emissivity model implementation for MW/IR (ala RTTOV, PARMIO)
- Aircraft-level calculation: forward and tangent linear modules for upward/downward radiance/BT calculations at user-specified pressure level. (under code review, in collaboration with STAR)
- Default netCDF support for all files [complete]
    - Requires minor changes to CRTM defaults and UFO interface to CRTM
- Generic Optical Properties Interface New Sensors: GEOXO-Sounder (GXS, via STAR), tomorrow.io (tmos), Orbital Microsystems (gems-2), PolSIR, AMPR, 3dS-INSAT imgr/sndr (via STAR),
    - under development: GOES-19 coefficients (IR only so far, via STAR), PACE coefficients (vis / near-IR), AOS (TBD)
- GEMS/WRF-Chem/MPAS AOD DA: new modules for offline CRTM/WRF-Chem calculations, including aerosol species mapping and WRF-Chem data I/O. (in collaboration with S. Ha, MMM)

CRTM Coefficient Generation Package

https://github.com/JCSDA/CRTM_Coef

Status: Under continuous development in collaboration with NOAA STAR, NASA GMAO, commercial partners

Recent Updates

Updated all TROPICS coefficients to reflect correct polarization basis, polarization angles, version numbers. Deliveries on 9/12/24, 8/30/24, and 4/18/24.

Added COSMIR / COSMIR-H development support (NASA GSFC)

Created/delivered PolSIR coefficients (to Vanderbilt) (6 ch and 12 ch)

Created/delivered AMPR coefficients (to NASA JPL)

Created Tomorrow.io sounder coefficients (still validating against theirs)

Updated GEMS-2 coefficients (Orbital Microsystems) (still validating against theirs).

Work Needed (incomplete list) (this is at least 2 FTEs of work):

Ozone contribution(s) at submillimeter frequencies (114 GHz, 240 GHz, and higher) – monoRTM integration into coefficient generation package (or use STAR package).

Visible coefficients for reflectance calculations

Proper treatment of polarization basis across scans for various instruments

Updates to CO2 profiles used in training

Improved constituent training / profiles

Hyperspectral Microwave support in CRTM / UFO (coefficient, testing, evaluation)

Hyperspectral Infrared support in CRTM / UFO (coefficient, testing, evaluation)

CRTM Recent Coefficients

abi_g19
v.abi_g19
cpr_cloudsat
dpr_gpm
fci_mtg-i1
giirsB1_fsr_fy4a
giirsB2_fsr_fy4a
gxs_geoxo_lw
gxs_geoxo_mw
iasi-ng_metop-sg-a1
imgr_insat-3ds
metimage_metop-sg-a1
mhs_metop-c
mwi_metop-sg-a1
mwi_wsf-m1
mws_metop-sg-a1
sndr_insat-3ds
tms_tomorrow-s01_v4
tms_tomorrow-s02_v4
tms_tomorrow-s03_v4
tms_tomorrow-s04_v4
tms_tomorrow-s05_v4
tms_tomorrow-s06_v4
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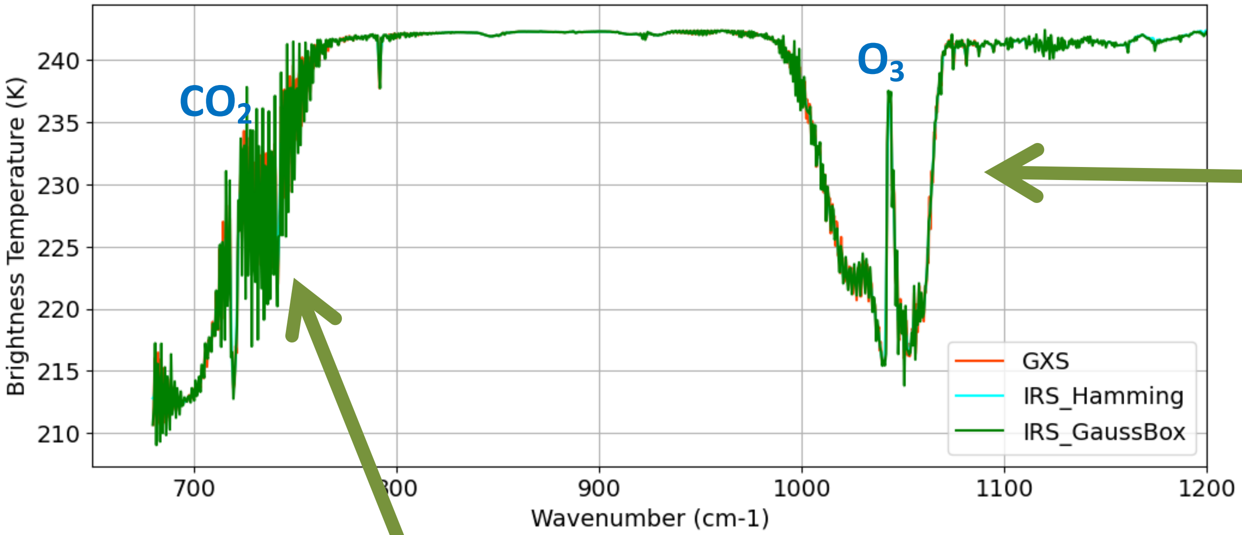
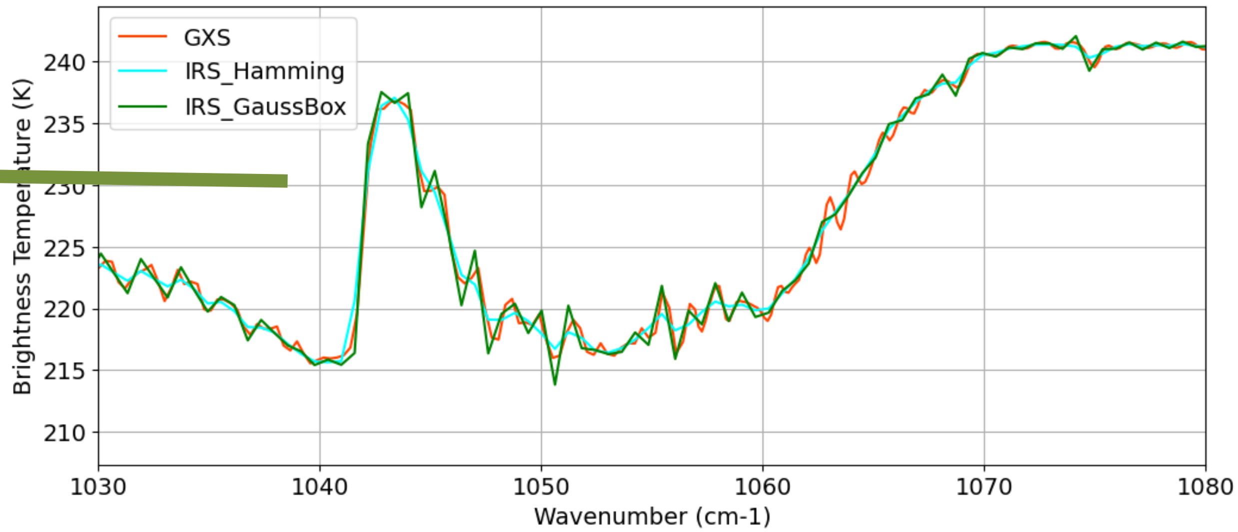
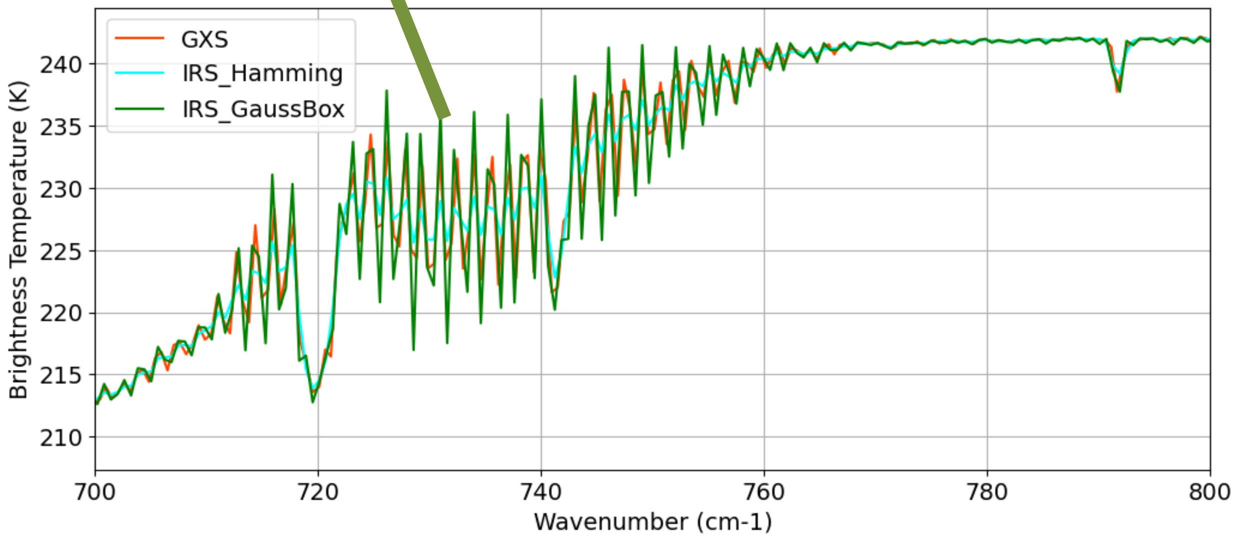
CRTM simulation of GXS and IRS (STAR, Y. Ma.)





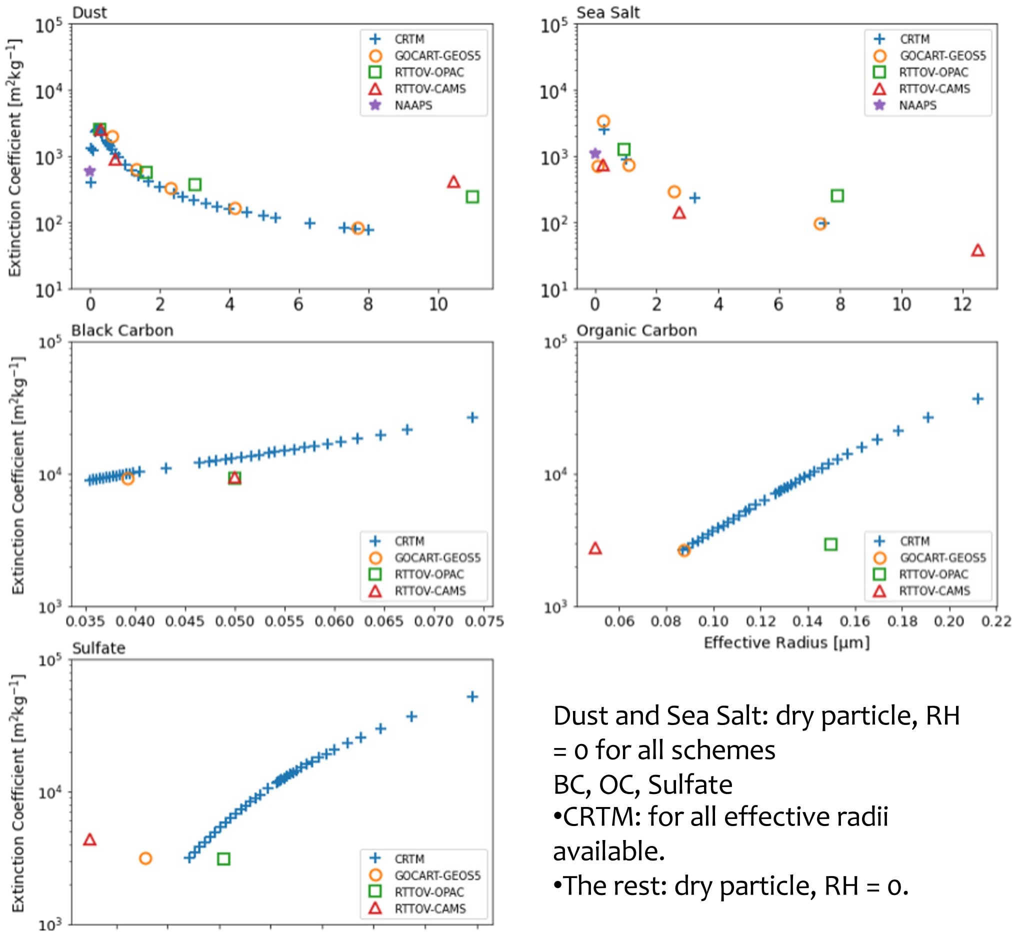


CRTM simulation of longwave bands from GXS and IRS

Slide courtesy of Yingtao Ma (NOAA STAR)

Aerosol Updates

CRTM Version	Aerosol model	Aerosol species	Aerosol properties
All versions **Binary**	**CRTM** (Default) *Chin et al., 2002; Han, 2006*	dust, sea salt, organic carbon, black carbon, sulfate	**effective radius**, **hygroscopicity (implicit)**
v2.4 – v3.1 **NetCDF**	**CMAQ** *Binkowski and Roselle, 2003; Liu and Lu 2016*	dust, sea salt, water-soluble, soot, sulfate, water, insoluble, dust-like	effective radius, hygroscopicity (implicit) **radius standard deviation**
v2.4.1 – v3.1	**GOCART -GEOS5** *Colarco et al., 2010*	dust, sea salt, organic carbon, black carbon, sulfate, nitrate	effective radius, **hygroscopicity**
v2.4.1 – v3.1	**NAAPS** *Lynch et al., 2016*	Bulk aerosol properties: dust, sea salt, smoke, anthropogenic and biogenic fine particles	hygroscopicity
v2.4.1 – v3.1 (internal)	**RTTOV-OPAC RTTOV-CAMS** *RTTOV v13*	dust, sea salt, organic carbon, black carbon, sulfate, nitrate CAMS: aerosol climatology developed by Copernicus Atmosphere Monitoring Service	effective radius, hygroscopicity



Dust and Sea Salt: dry particle, RH = 0 for all schemes

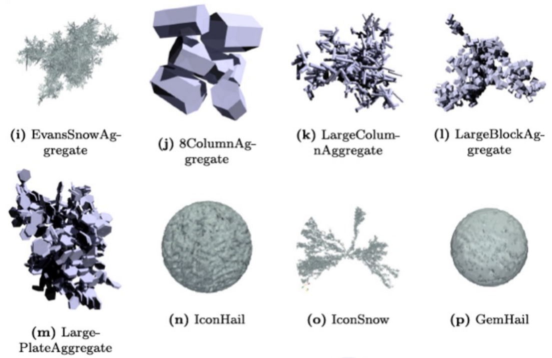
BC, OC, Sulfate

- CRTM: for all effective radii available.
- The rest: dry particle, RH = 0.

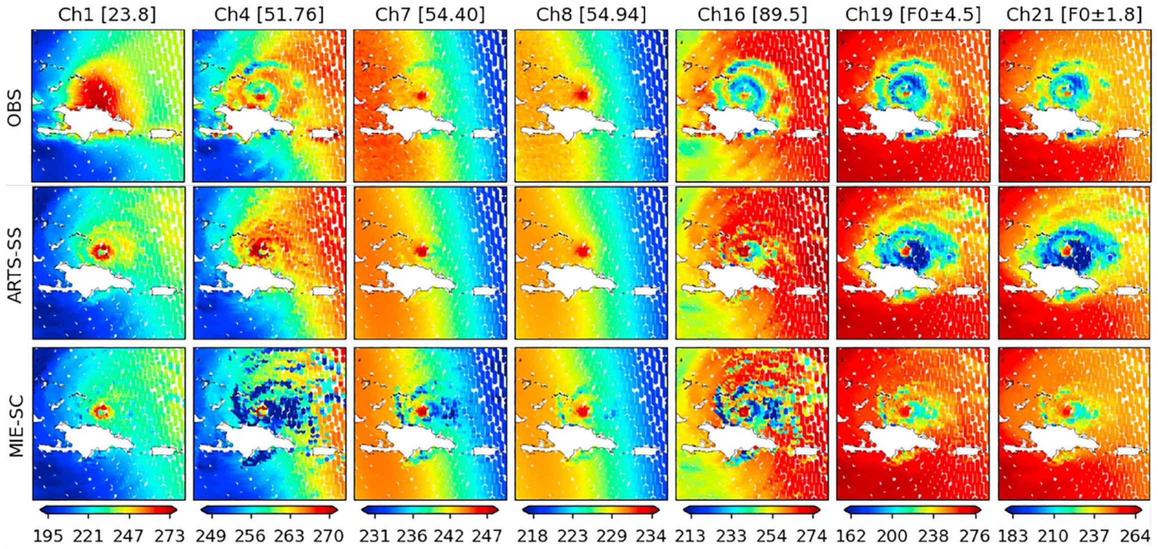
Figures: Aerosol extinction coefficients of selected species across the CRTM default, GOCART-GEOS5, NAAPS, and RTTOV LUTs. [550nm]

Cloud Updates

CRTM Version	Cloud Schemes	Table Content/Highlight
All versions **Binary**	**CRTM** (Default) *Liu and Lu, 2016*	• Water, rain, snow, graupel, ice/hail • Spherical assumptions all hydrometeors. • Mie-Lorenz theory. • Single-scattering properties and phase functions. • Temperature (liquid only), effective radius, and frequency.
v2.4 – v3.1 **NetCDF**	**PSU**	• Experimental tables with liquid and solid hydrometeors based on scheme (1) GFDLFV3 (2)Thompson08 (3) WSM6. • Microwave bands only.
v2.4.1 – v3.1	**Moradi** *Moradi et al., 2022*	• Non-spherical hydrometeors in the microwave bands. • Discrete Dipole Approximation (DDA) technique. • ARTS Single scattering database from Eriksson et al (2018) • Introduces cloud water content as model input. • Adds new parameter backscattering coefficients. • Higher resolution for temperature, water content and frequency.
v3.2 (incoming)	**TAMU** *Tong et al., 2023*	• Non-spherical particle shape for graupel/snow over UV/VIS/IR/MW spectral ranges. • Temperature-dependent ice refractive index for MW frequencies. • Extended spectral range and particle size range. • Polarized phase matrix.



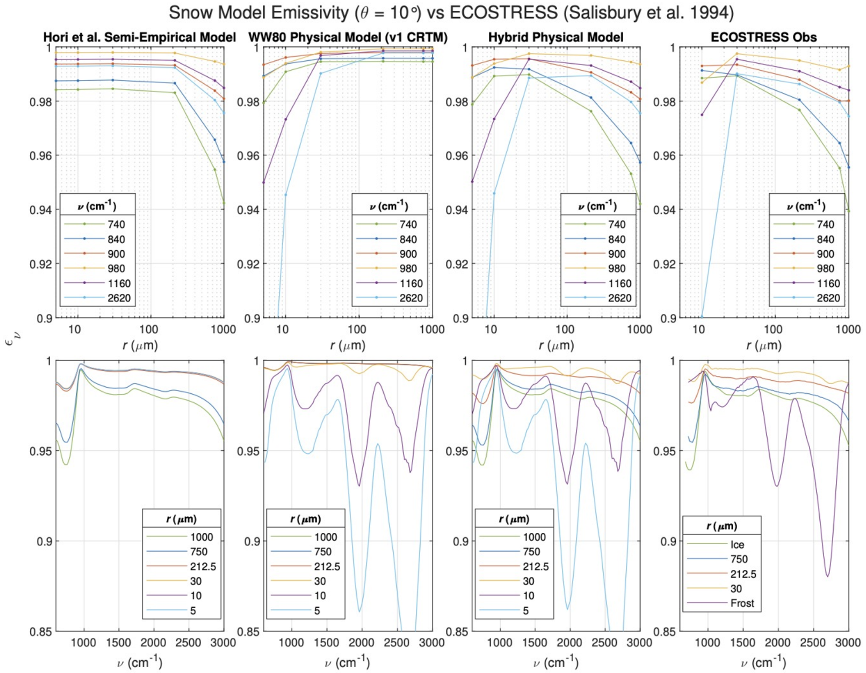
Example of aggregates from the ARTS database included in the CRTM cloud lookup tables. [*Moradi et al., 2022*]



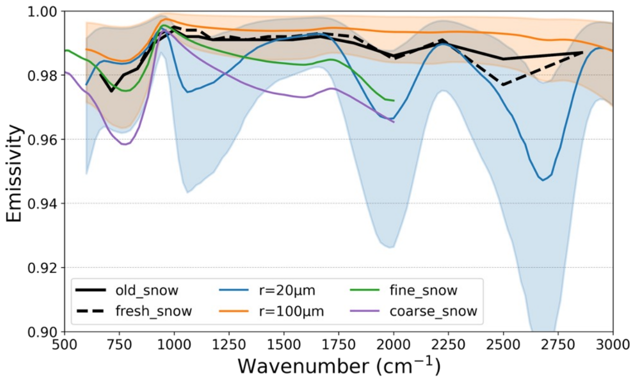
Figures: ATMS observed versus CRTM simulated Tbs for Hurricane Irma using IFS as input and different CRTM lookup tables. The first row in top panel shows ATMS observations and all other rows show simulations performed using CRTM with either ARTS or Mie lookup tables. [*Moradi et al., 2022*]

Recent surface Updates

CRTM Version	Surface	Table Content/Highlight
All versions **Binary**	**Water** **Land** **Ice** **Snow** *Liu and Lu, 2016*	• Visible, IR, MW • Land types • Ice/Snow age • Water
v2.4.1 – v3.1 **NetCDF**	**TIR Water** *Nalli et al., 2023a*	• Infrared Sea Surface Effective-Emissivity (IRSSE) Model • Temperature-dependent water optical constants • modeling thermal IR “effective emissivity” in a manner that accounts for both surface emission and quasi-specular reflectance.
v2.4.1 – v3.1	**TIR Snow** *Nalli et al., 2023b*	• Physically based snow/ice emissivity model • A hybrid of layer-scattering model and specular-facet model. • Temperature-dependent ice optical constants • Zenith-angle/snow grain size dependence.



Figures: TIR snow/ice model spectral emissivity calculations versus ECOSTRESS laboratory measurements for an observer zenith angle of 10. [*Nalli et al., 2023b*]



Figures: snow spectral emissivity:
1. CRTM (old/fresh snow)
2. Nalli (r=20 and 100 microns)
Orange and blue shades: zenith angle from 0 – 75 degrees
3. U Michigan (fine/coarse snow)

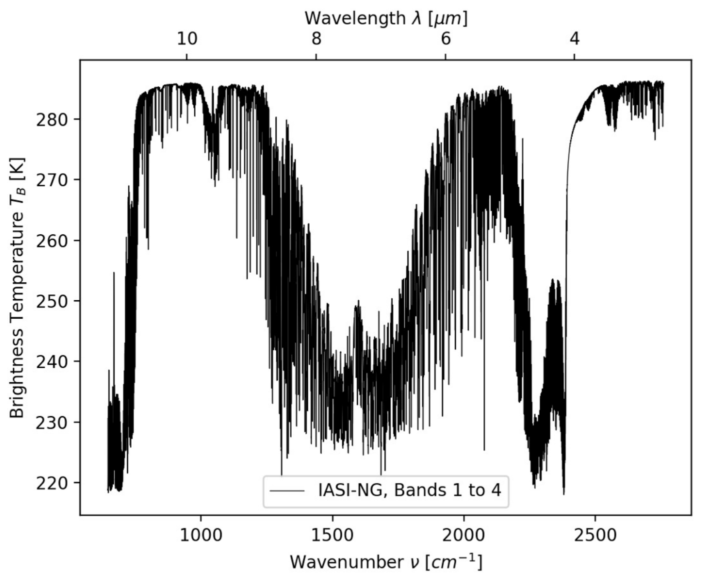
Instrument Coefficients

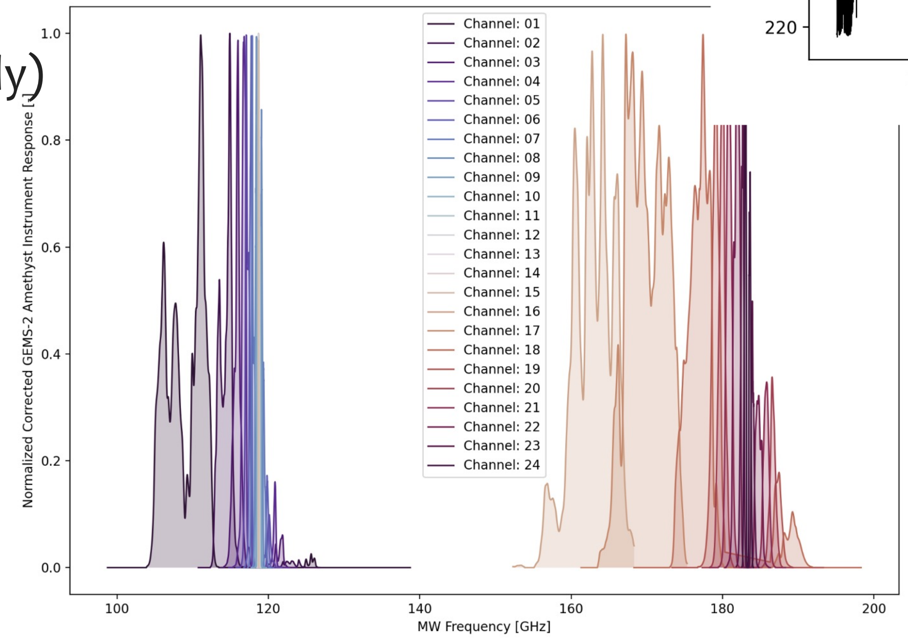
CRTM transmittance/spectral coefficient generation package: https://github.com/JCSDA-internal/CRTM_coef
(please email us for access to this internal repository)

Selected list of recently developed instrument coefficients

- TROPICS (the entire constellation)
- GEMS 1&2
- ATMS-NG (hyperspectral MW concept study)
- IASI-NG
- ATMS NOAA-21
- VIIRS NOAA-21

- PolSIR
- Tomorrow.io





Animation of GOES 16/18 ABI & MRMS (Sluka/Thompson, CRTM/UFO)

2024-04-26 00:00:00Z

ABI - GOES 16/18
ch 1+2 (day/visible)
ch 13 (night/IR)

Simulated

Observed

Cooperative Institute for Satellite Earth System Studies

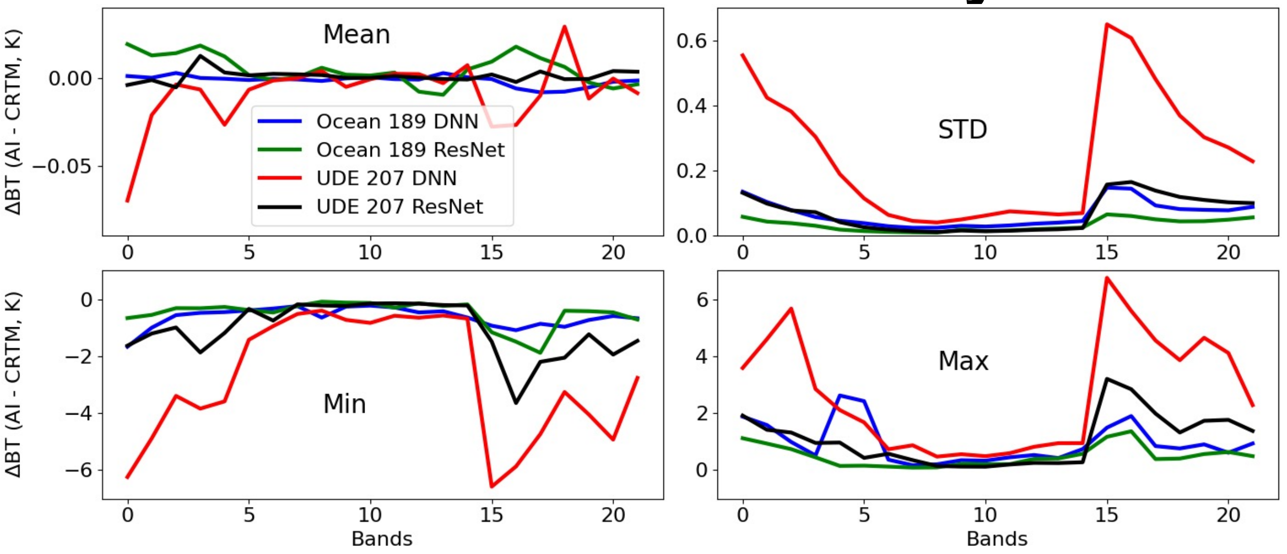
Improving AI_CRTM by Combination of ResNET and Physical Constraints

Xingming Liang, UMD; Quanhua Liu, STAR/NOAA; and Christopher Grassotti,

Objectives

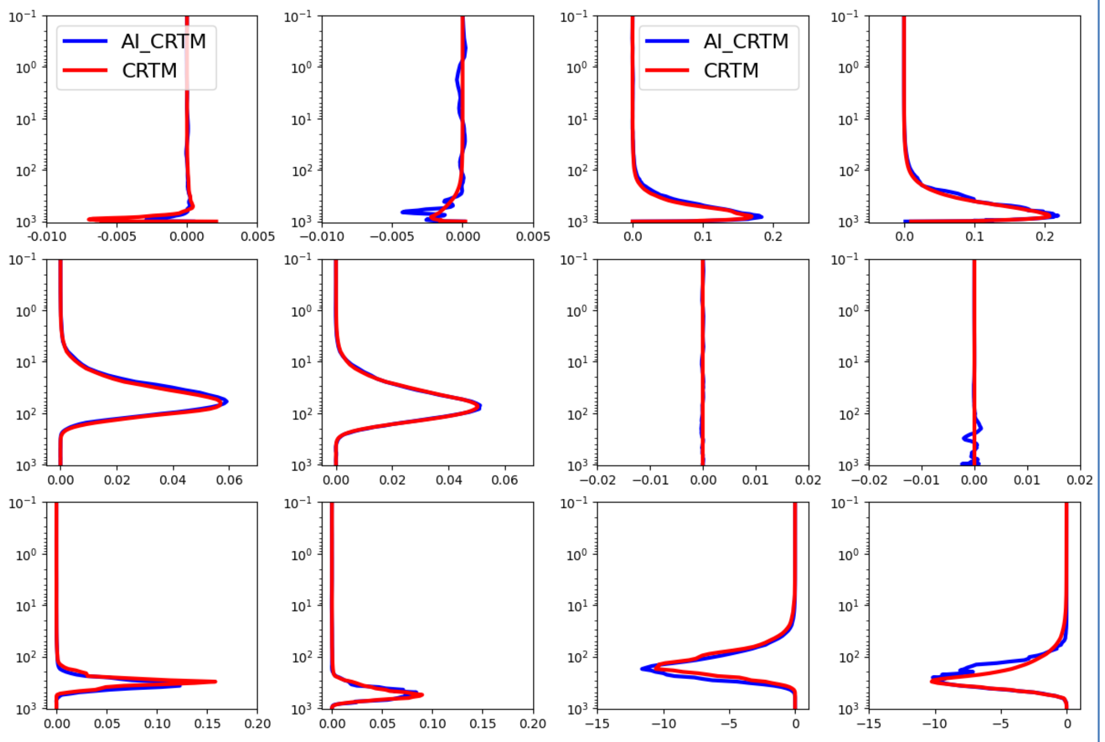
- Goals for AI_CRTM Algorithm Development:
  - Enhance accuracy for both AI brightness temperatures (BTs) and Jacobians
  - Meet requirement of NOAA retrieval systems and data assimilation
  - Extend functionality to include analysis for both land and sea domains

BT Prediction Accuracy



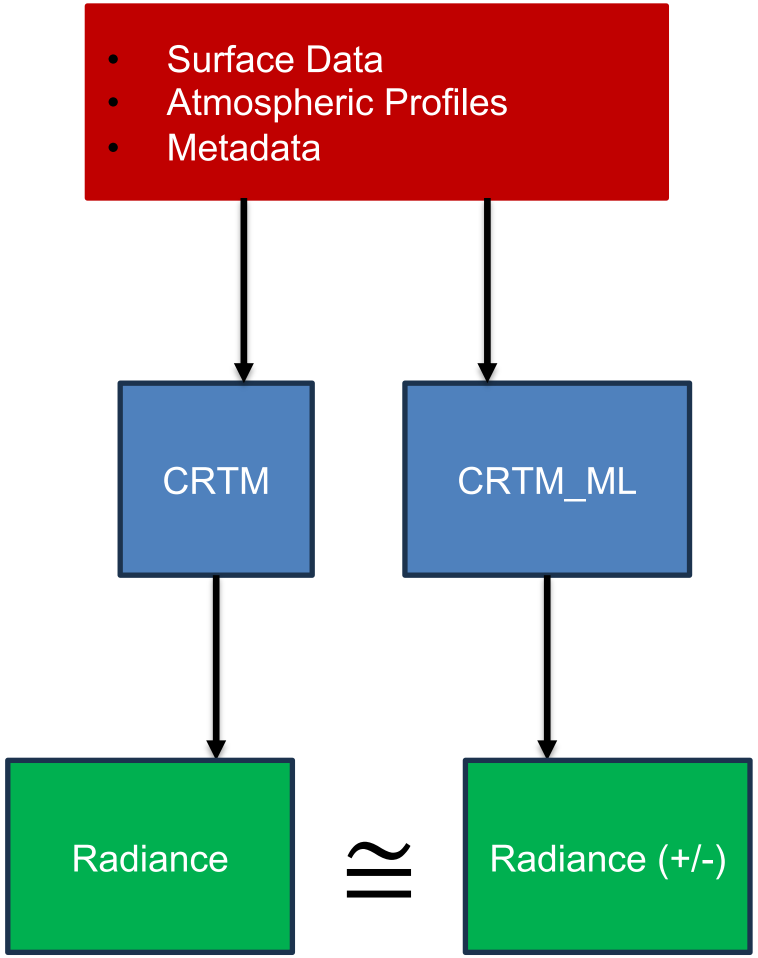
AI Jac. vs CRTM Jac. for ResNET

(single profile)



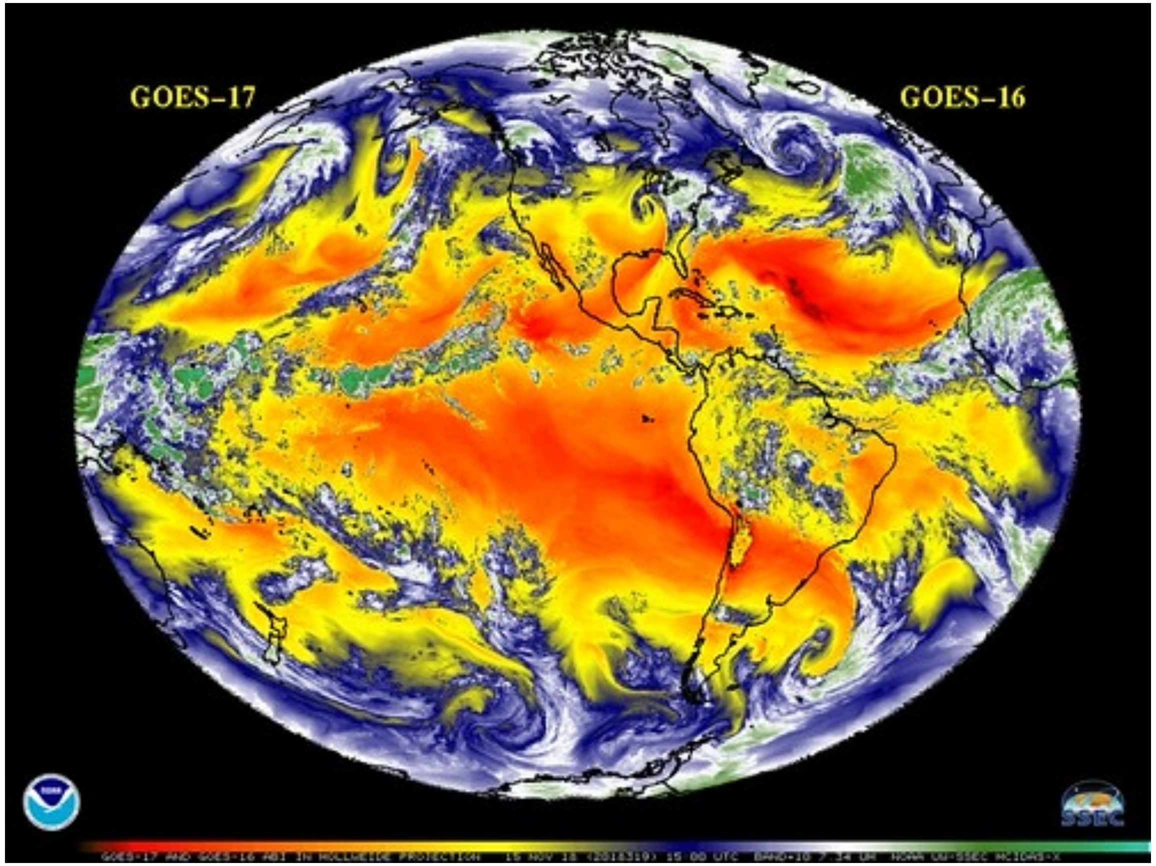
ML Emulator Approach (L. Howard/CU)

- **Question: can a neural network be trained to accurately emulate CRTM and reliably predict its own error?**
- Target platform: GOES Advanced Baseline Imager (ABI)
  - Only IR channels (7-16)
- All inputs are identical to CRTM
- Output is predicted CRTM-computed brightness temperature
  - Mean and error standard deviation

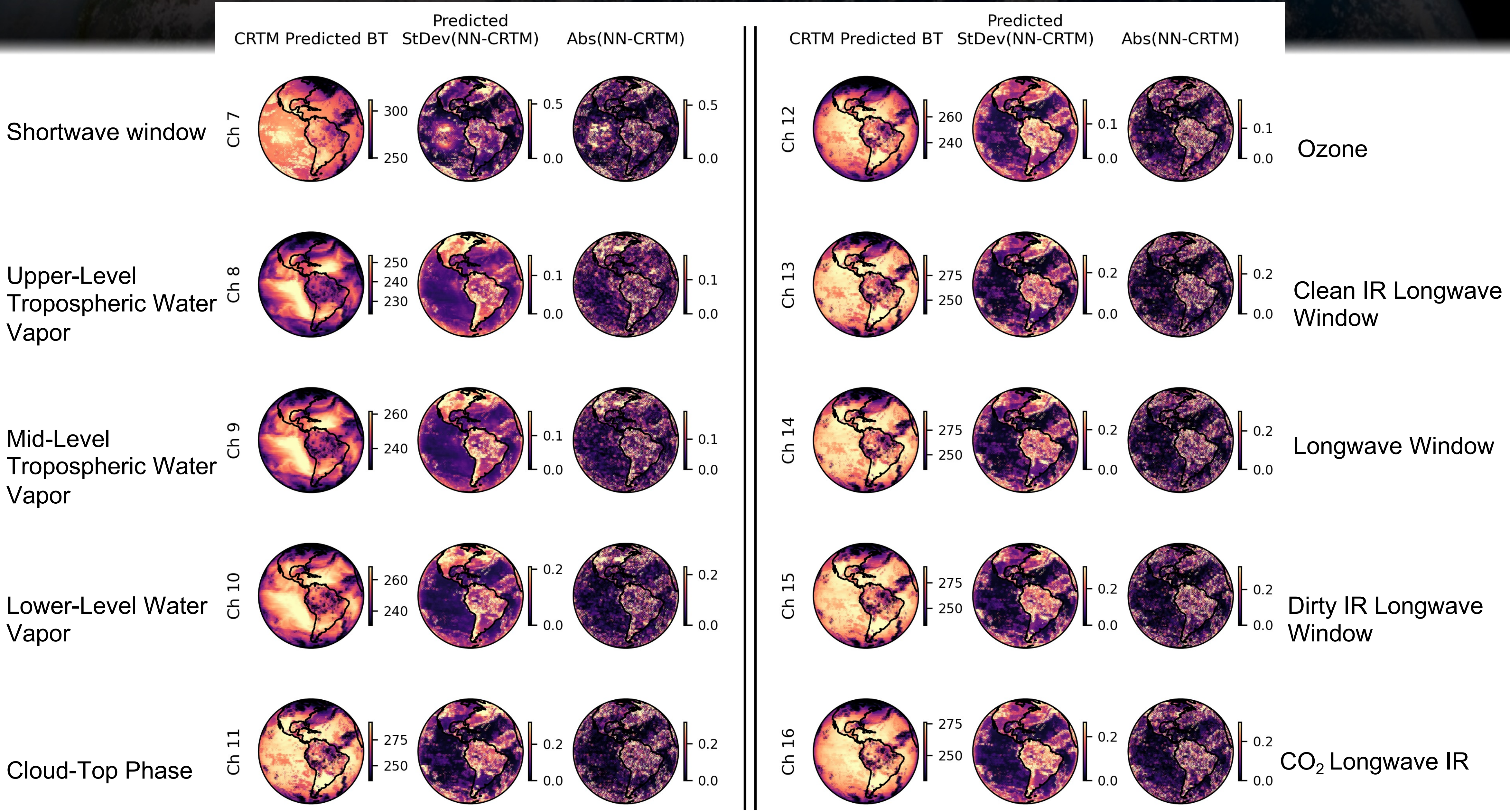


Training, Validation, and Testing

- Fully connected neural network
- Cost function: Continuous Rank Probability Score (CRPS)
- 30 days of GOES-17 and GOES-16 scans
  - 6-hr, 64 km resolution
  - Physical input variables from GFS forecasts
- Train/Validate/Test split:
  - 151/19/19 scans randomly chosen
  - 3.4E6/4.3E5/4.3E5 data points

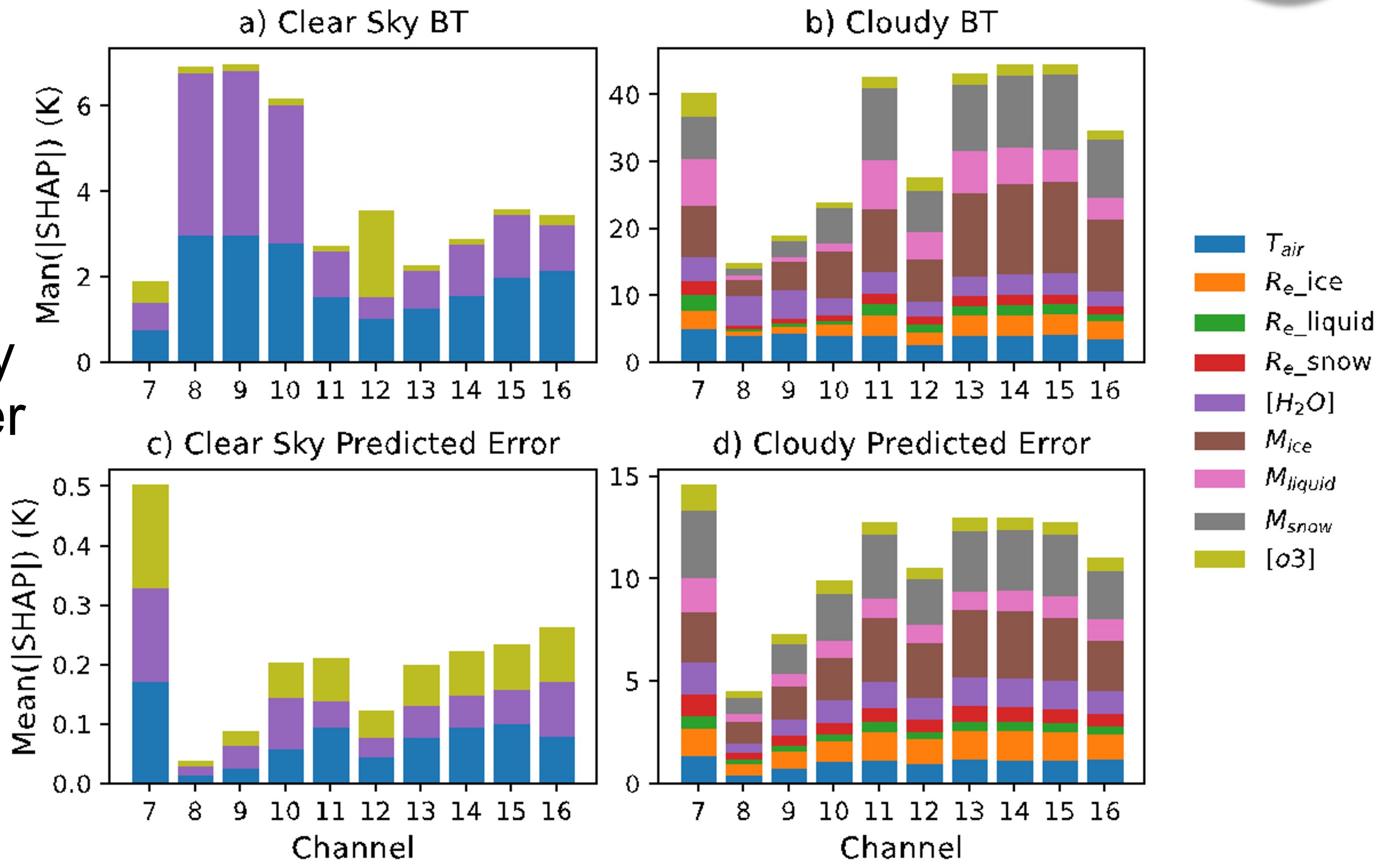


Spatial Distribution of Results for Single Scan



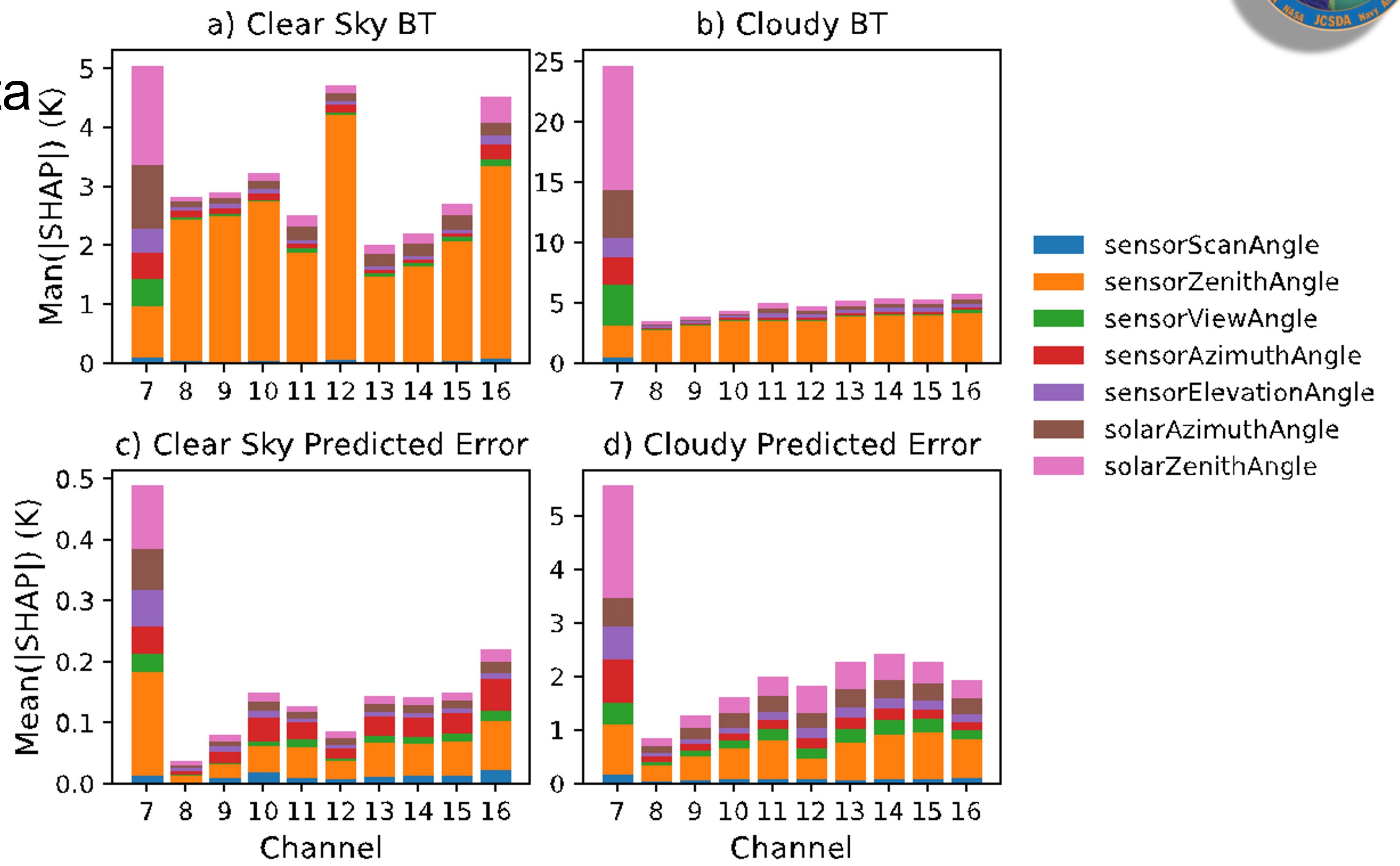
Howard et al, in review

- Impact of all atmospheric variables on all channels
- Summed vertically and averaged over samples



CRTM AI training data and plots courtesy of Lucas Howard, CU-

- Impact of all meta variables on all channels



CRTM AI training data and plots courtesy of Lucas Howard, CU-

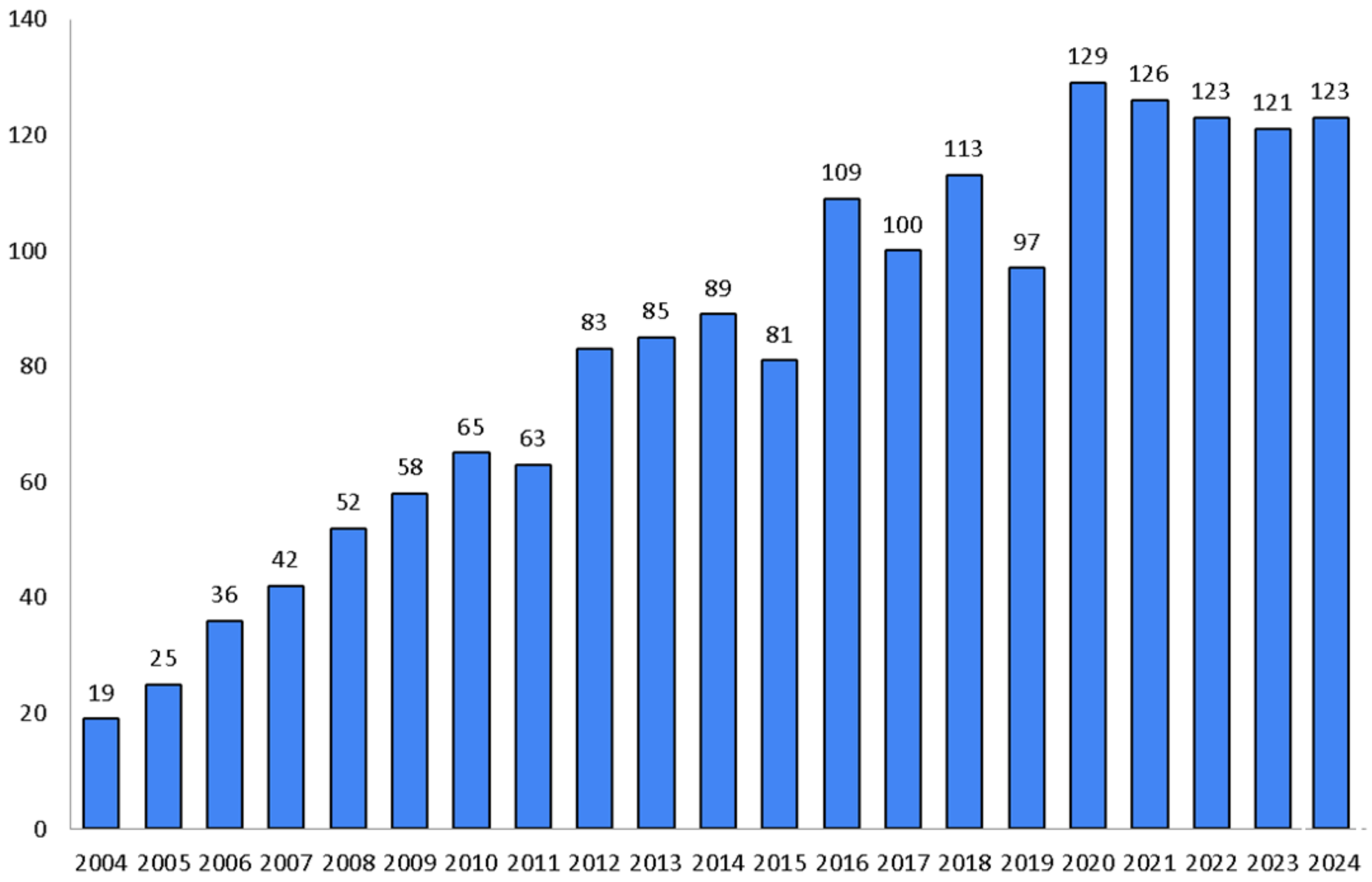
Future Tasks (Team)

General work plan for CRTM

- Standardize and improve the NetCDF interface for all coefficient LUTs (version #, release #, generic I/O modules)
- Aerosol: TAMU 2020, experimental table for Asian aerosols (for GEMS AOD DA)
- Surface: UV/Visible/IR reflectance models for snow/ice.   Improved IR/MW thermal emission models
- Solver:
  - add and test TOA reflectance in support of DA of solar sensors.
  - Full pol support for MW/IR, work with UFO support for pol. radiance simulation
- Offline packages in support of CRTM development and tests.
- Aerosol coefficient generation package.
- Exploratory: Genericization of surface and optical property interfaces, separation of concerns
- Initial pivot toward AI front-end development for CRTM (CRTM v4.x).   Coordinated effort with JCSDA partners, CU-Boulder.

CRTM Publications

Unique citations of the CRTM model by year
(citations from previous years take about 3 months to filter in)



Recent Publications

Johnson, Benjamin T., Cheng Dang, Patrick Stegmann, Quanhua Liu, Isaac Moradi, and Thomas Auligne. "The Community Radiative Transfer Model (CRTM): Community-focused collaborative model development accelerating research to operations." Bulletin of the American Meteorological Society 104, no. 10 (2023): E1817-E1830.

Moradi, I., Johnson, B., Stegmann, P., Holdaway, D., Heymsfield, G., Gelaro, R. and McCarty, W., 2023. Developing a Radar Signal Simulator for the Community Radiative Transfer Model. *IEEE Transactions on Geoscience and Remote Sensing*.

Nalli, N.R., Dang, C., Jung, J.A., Knuteson, R.O., Borbas, E.E., Johnson, B.T., Pryor, K. and Zhou, L., 2023. Physically Based Thermal Infrared Snow/Ice Surface Emissivity for Fast Radiative Transfer Models. *Remote Sensing*, *15*(23), p.5509.

Liu, Q. and Liang, X., 2023. Physics constraint Deep Learning based radiative transfer model. *Optics Express*, *31*(17), pp.28596-28610.

Jung, J., Nalli, N.R., Dang, C., Lim, A.H., Liu, E.H., Johnson, B. and Kalluri, S., Reduced Global Sea Surface Temperature Biases from Upgrades to the CRTM Infrared Sea Surface Emissivity Model.

Stegmann, P.G., Johnson, B., Moradi, I., Karpowicz, B. and McCarty, W., 2022. A deep learning approach to fast radiative transfer. Journal of Quantitative Spectroscopy and Radiative Transfer, 280, \
p.108088.

AOP24+ Future Tasks (Team)

General work plan for CRTM (1-5 years)

- Standardize and improve the NetCDF interface for all coefficient LUTs (version #, release #, generic I/O modules
- Aerosol: TAMU 2020, experimental table for Asian aerosols (for GEMS AOD DA)
- Surface: UV/Visible/IR reflectance models for snow/ice. Improved IR/MW thermal emission models
- Solver:
  - add and test TOA reflectance in support of DA of solar sensors.
  - Full polarization support for MW/IR, work with UFO support for pol. radiance simulation
- Offline packages in support of CRTM development and tests.
- Cloud / Aerosol coefficient generation package.
- Exploratory: Genericization of surface and optical property interfaces, separation of concerns
- Initial pivot toward AI front-end development for CRTM (CRTM v4.x). Coordinated effort with JCSDA partners, CU-Boulder.
- Melting layer simulation improvements (Moradi / Johnson 2025+)
- (Marine) boundary layer resolution improvements (NASA partners, TBD)
- Ocean Color integration (OASIM? VLIDORT w/SOCA team)
- And to maximize confusion: PCRTM integration in CRTM (STAR, Xu Liu/NASA)

Support / Contact

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

Github:https://github.com/JCSDA/CRTMv3
Please feel free to create an issue with questions, comments, feature requests, etc.

CRTM User/Developer Tutorials: https://github.com/JCSDA/crtm-tutorial

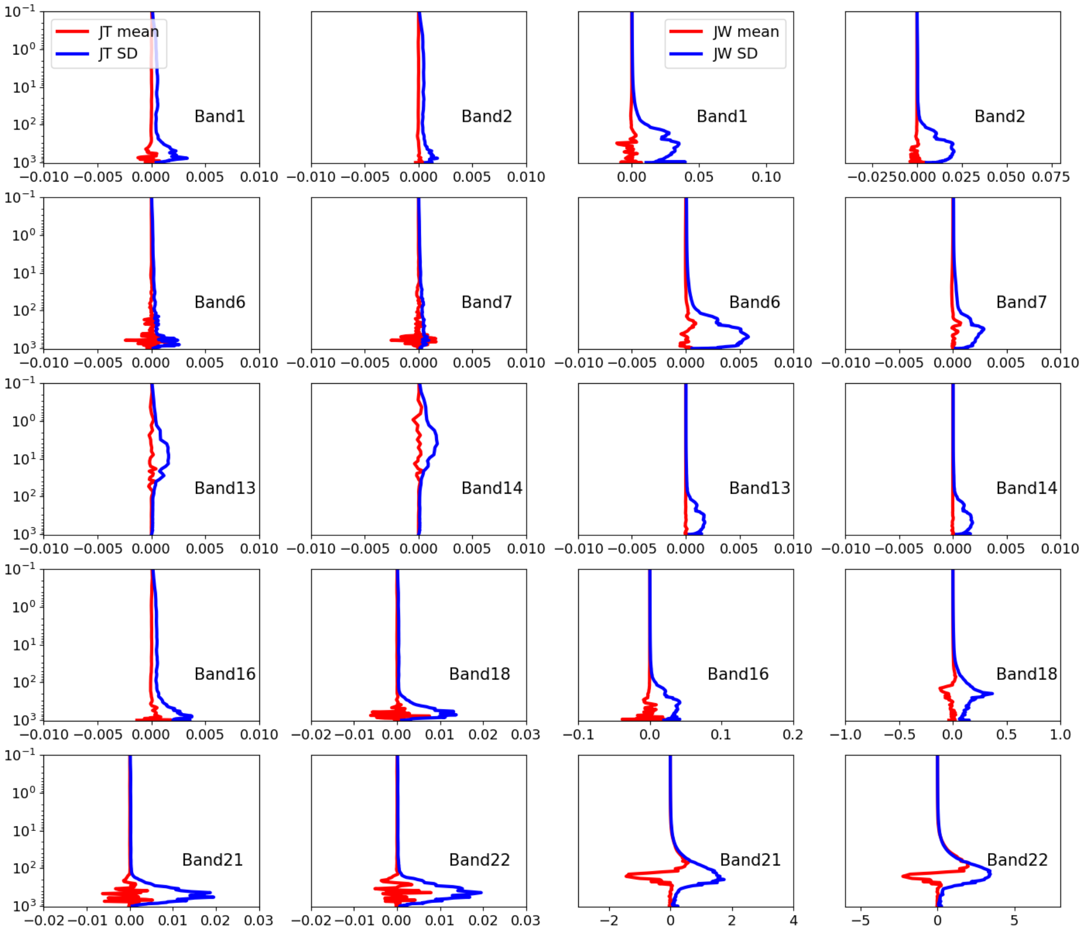
CRTM Python Interface (v. 2.4.x): https://github.com/JCSDA/pycrtm

Improving AI_CRTM by Combination of ResNET and Physical Constraints

Cooperative Institute for Satellite Earth System Studies

Xingming Liang, UMD; Quanhua Liu, STAR/NOAA; and Christopher

Mean and STD of AI Jac. Minus CRTM Jac. For ResNET (20000 profiles samples)

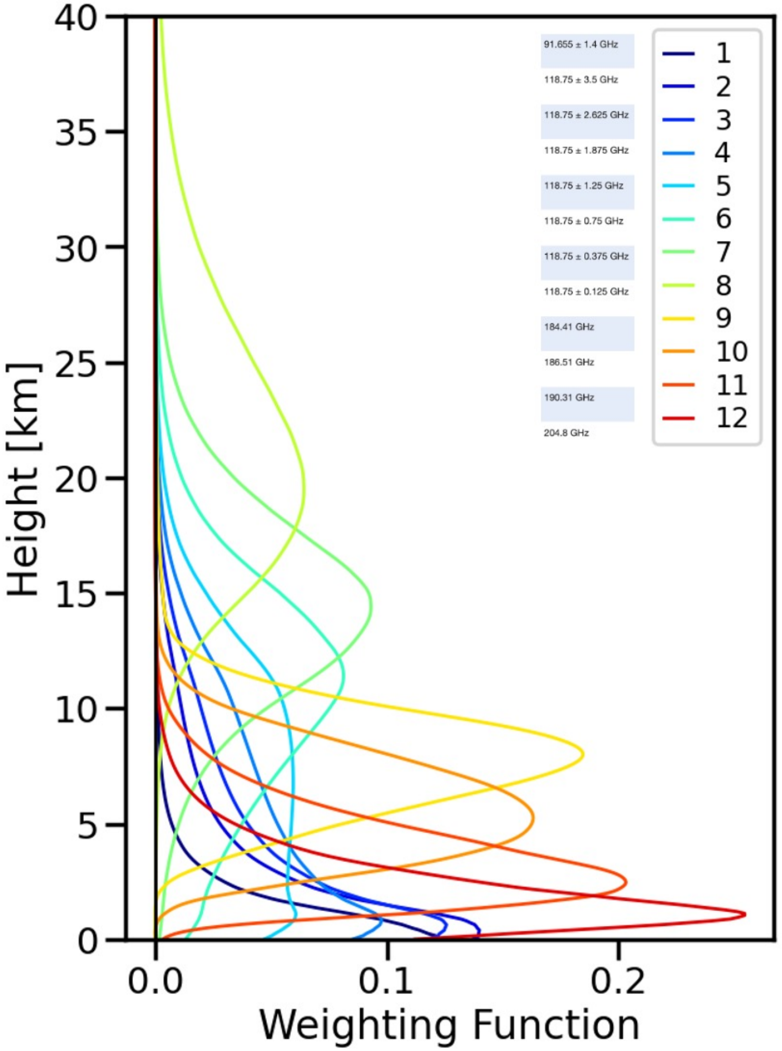


Results and Future Works

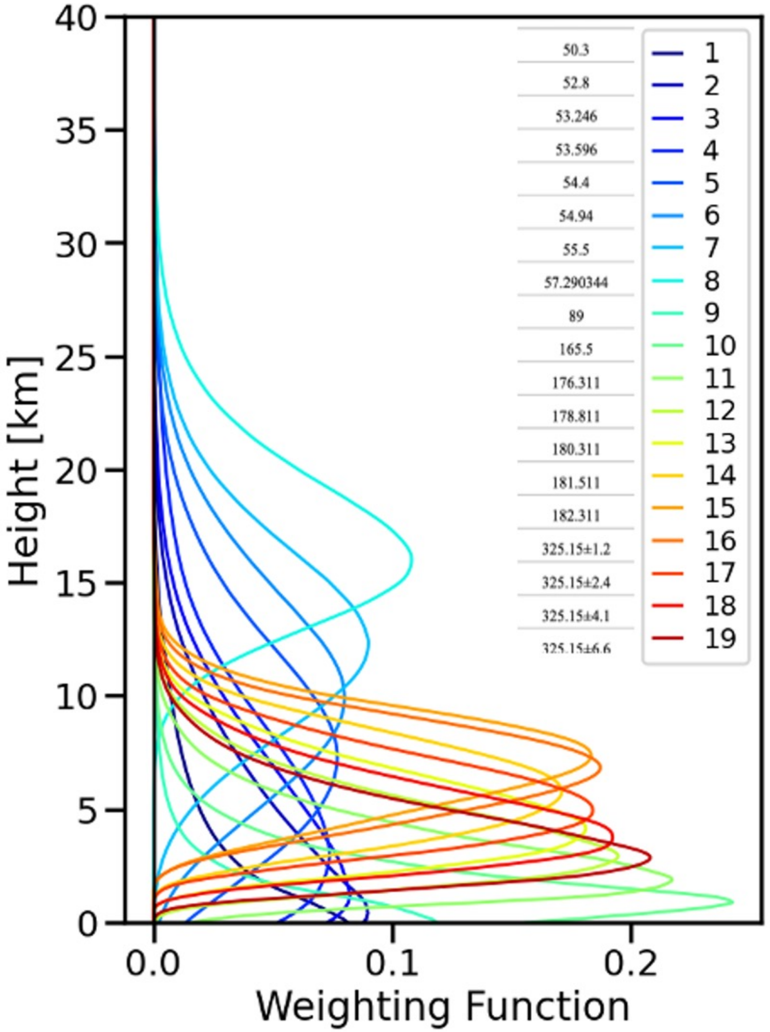
- Two AI_CRTM models are designed to meet requirements of CRTM, NOAA retrieval systems, and data assimilation processes: Ocean model and user-defined-emissivity (UDE) model
- Introducing ResNET and a custom loss function with normalization and weighted physical constraints improved AI_CRTM accuracy for both BTs and Jacobians.
- AI_CRTM BT predictions are more than 20 times faster than CRTM, AI Jacobian calculations for both DNN and ResNET models are faster than CRTM.
- AI_CRTM in all-sky conditions, with cloud Jacobians is under development.
- AI_CRTM will be tested within the NOAA Microwave Integrated Retrieval System (MiRS)
- The functionality of AI_CRTM for BT and Jacobian predictions will be extended to include IR and hyperspectral sensors in the future.

Instrument Weighting Functions (CRTM)

TMS



AWS



ATMS