Advances in CRTM Aerosol Component With v2.4.1 and v3 Releases

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Overview of JCSDA and CRTM

Joint Center for Satellite Data Assimilation (JCSDA)

A multi-agency research center to improve the use of satellite data for analyzing and predicting the weather, the ocean, the climate and the environment.

- Scope of activities of JCSDA: Collaborative, inter-dependent activities inside AOP
- Approach: The formation of a *project-based structure* targeting science frontiers jointly pursued among partners.
- Metric of success = *added* value for Partners of doing work *jointly* via the JCSDA

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)

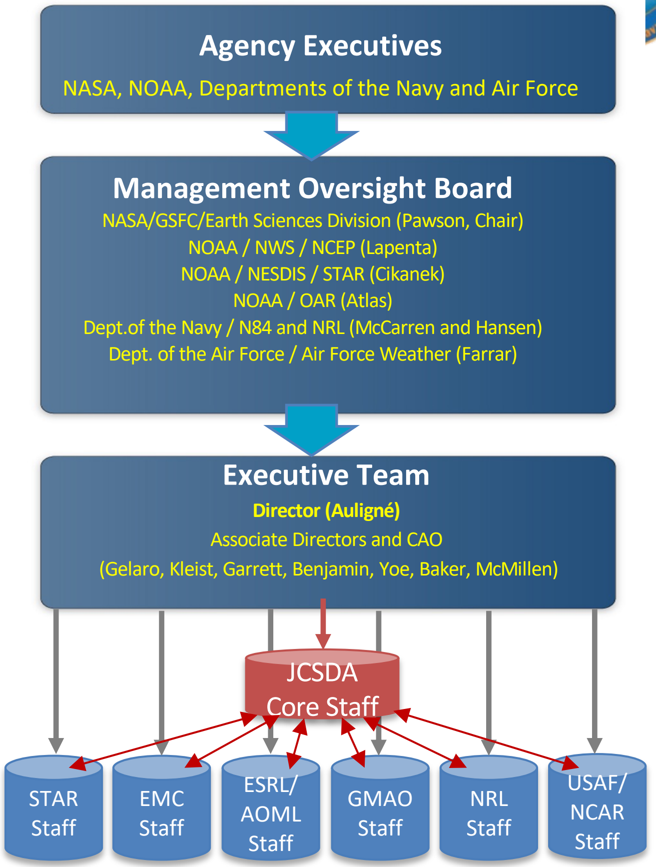
Monitor impact of observations and provide guidance for improvements

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



Slide from Tom Aulignè

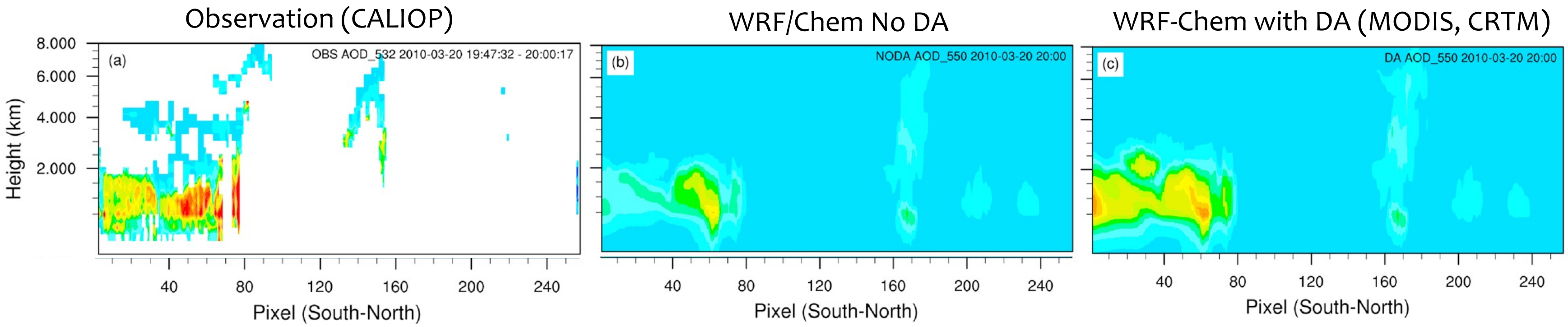
Community Radiative Transfer Model (CRTM)

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.
- **Components**: aerosol, cloud, precipitation, gas, atmosphere and surface.
- **History:** originally developed 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).

Data Assimilation

"Provided the atmospheric/surface conditions, what radiance/AOD value do we expect to observe from a particular satellite sensor?"



Data Assimilation

Estimate the optimal atmospheric states

Model State **Observations**

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x_b})^{\mathbf{T}}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_b}) + \frac{1}{2}[H(\mathbf{x})-\mathbf{y}]^{\mathbf{T}}\mathbf{R}^{-1}[H(\mathbf{x})-\mathbf{y}]$$

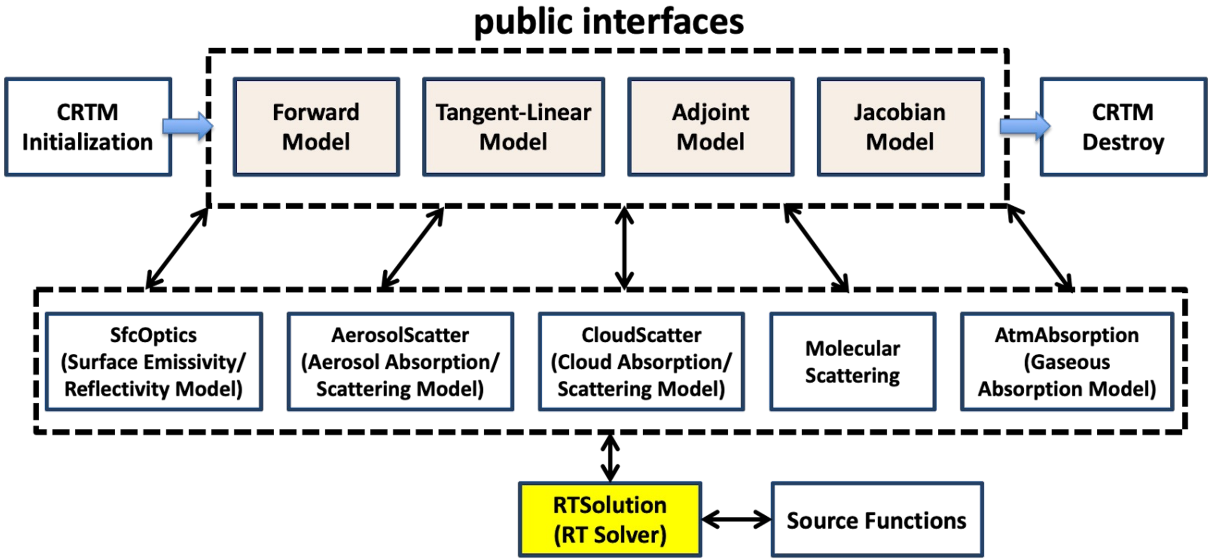
$$\nabla J_{\delta x} = \mathbf{B}^{-1}\delta\mathbf{x} + \mathbf{H}^{\mathbf{T}}\mathbf{R}^{-1}(\mathbf{H}\delta\mathbf{x}-\mathbf{d}) = 0$$

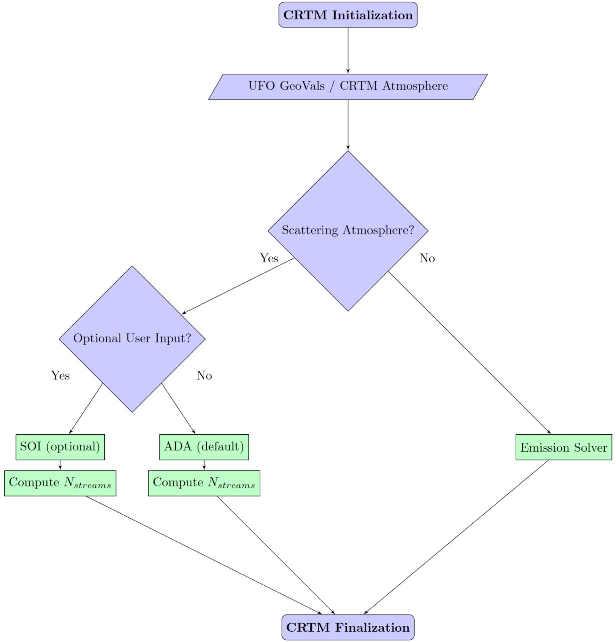
Observation Operator

Community Radiative Transfer Model (CRTM)

(Liu et al., 2011)

Community Radiative Transfer Model (CRTM)





CRTM radiative transfer solver initialization flow chart. The presence of a scattering atmosphere in the input data decides whether a scattering or emission solver is used. Optional user input can specify either the Successive-Order-of-Interaction (SOI) or Advanced Doubling Adding (ADA) solver [**Default**]. The number of scattering solver streams is computed automatically from the characteristic size parameter of the particle size distribution.

A Brief History of CRTM Releases

Version 1.0 (2006)
- absorption and scattering from various types of hydrometeors and aerosols.
- a comprehensive set of models for computing surface emissivity and reflectivity over land, ocean, ice and snow surfaces for both the microwave and infrared spectral regions.
- standard Fortran 95, module based.

Version 2.0 (2010)
- ODAS (Optical Depth in Absorber Space) and ODPS (Optical Depth in Pressure Space) transmittance algorithm for gaseous absorption and emission.
- Specular surface reflection option; Ocean emissivity.

Version 2.1 (2012)
- Clear sky RT simulations.
- Surface emissivity: Ocean (FASTEM1~6 over the years) and land.
- Successive Order of Interaction (SOI) radiative transfer algorithm.
- Non-LTE simulations applied to infrared sensors.

Version 2.2 (2015)
- Overcast radiances in fully cloud-covered conditions.
- Snow emissivity.
- Cloud optical property.

Version 2.3.0 (2017)
- Cloud fraction/all sky radiance capabilities.
- Sea ice emissivity.

Version 2.4.0 (2020)
- Aerosol coefficient table based on CMAQ specifications.
- WSM-6, Thompson, and GFDL cloud microphysics schemes.
- Updated/Released sensor coefficient files, including ABI G-17, AMSUA-Metop-C, Metop-C, etc.
- netCDF modules for cloud and aerosol coefficients.

CRTM transmittance and spectral coefficient generation package, Version 1 (2021)

Version 2.4.1 and 3.0 under development.

Johnson et al., 2022

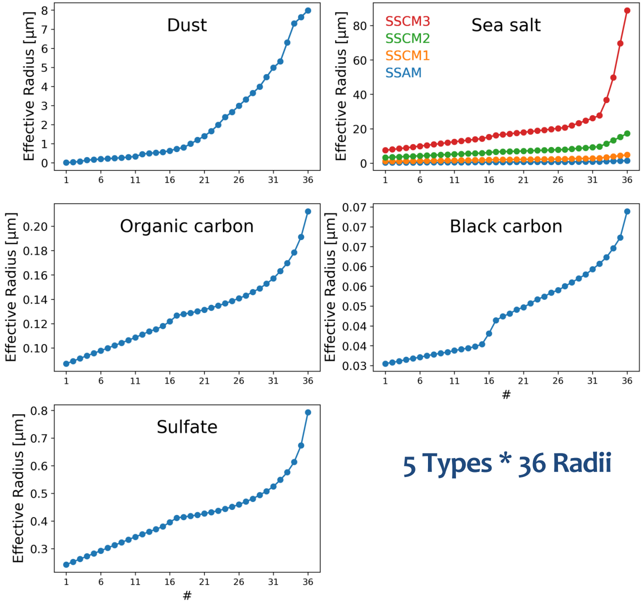
Development on CRTM Aerosol Component

CRTM Version 2.3 and before

Sensor information

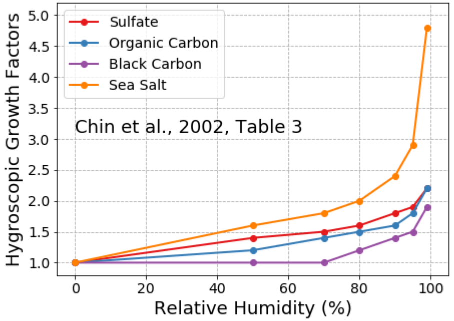
CRTM_Init(SENSOR_ID, & chinfo, …) → Binary I/O → Default look-up table → CRTM calculation

Given aerosol profiles



5 Types * 36 Radii

Aerosol effective radius



- Binary format.
- Effective radii for hydrophilic aerosols.

Interpolate optical properties based on:
aerosol types, effective radius

CRTM Version 2.4

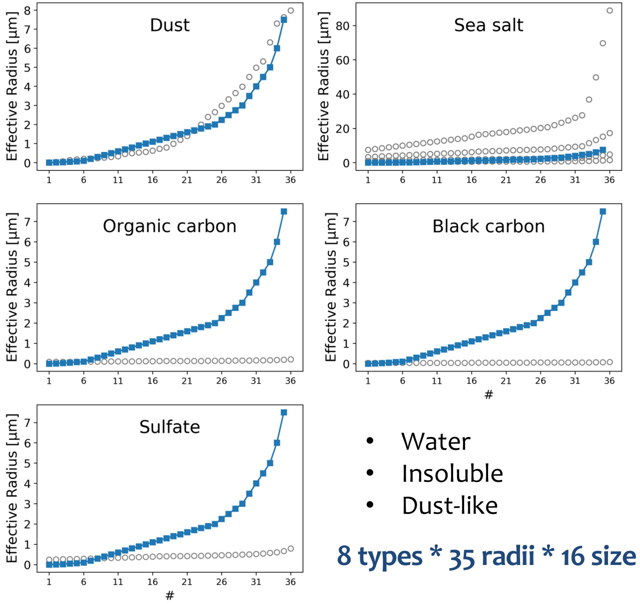
Oct. 2020
https://www.jcsda.org/crtm-release

Sensor information

CRTM_Init(SENSOR_ID, &
chinfo, &
Aerosol_Model, &
AerosolCoeff_Format, &
AerosolCoeff_File, &…)

→ Binary I/O / Net CDF I/O → Default look-up table / CMAQ look-up table → CRTM calculation

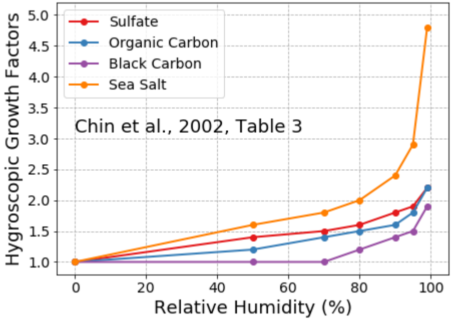
Given aerosol profiles



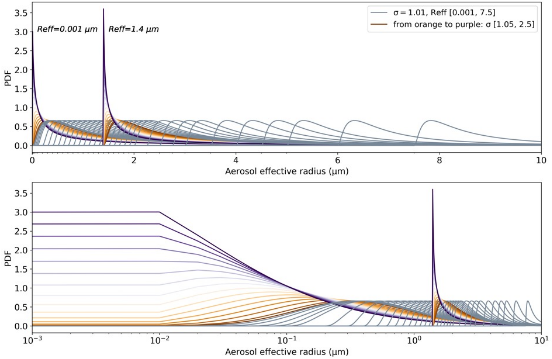
- Water
- Insoluble
- Dust-like

8 types * 35 radii * 16 size variances

Aerosol effective radius



Aerosol size distribution



- CMAQ aerosol size specifications.
- Require mapping of specific aerosols to the CRTM categories.

CMAQ Table

Oct. 2020
https://www.jcsda.org/crtm-release

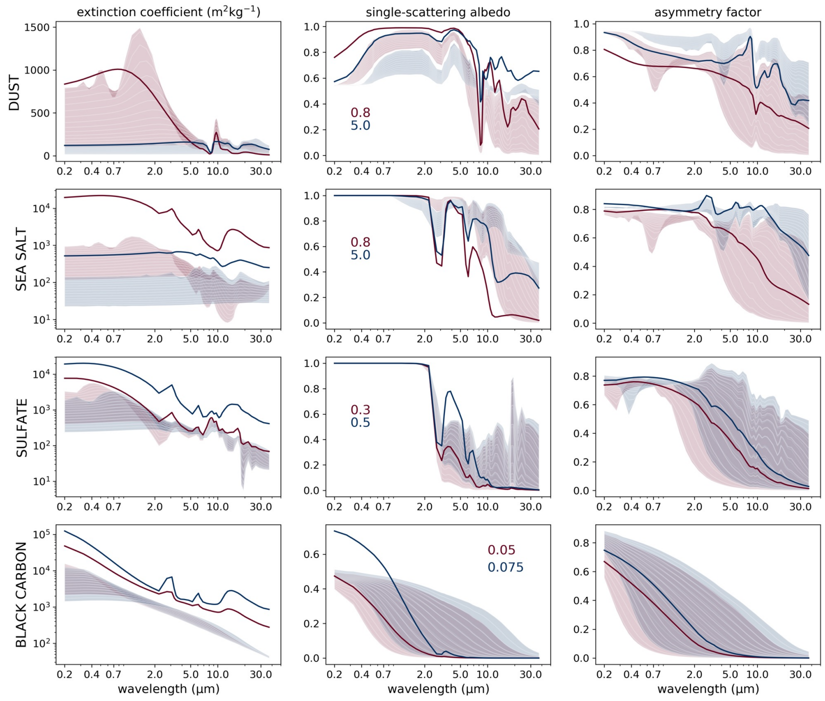


Table from Yingtao Ma, NOAA STAR

C1	CMAQ v4.x Aerosol Type	CRTM v2.0.2 Type	C2	C3
1	ASO4J Accumulation mode sulfate	SULFATE_AEROSOL	4	2
2	ASO4I Aitken mode sulfate	SULFATE_AEROSOL	4	1
3	ANH4J Accumulation mode ammonium	WATER_SOLUBLE_AEROSOL	3	2
4	ANH4I Aitken mode ammonium	WATER_SOLUBLE_AEROSOL	3	1
5	ANO3J Accumulation mode nitrate	WATER_SOLUBLE_AEROSOL	3	2
6	ANO3I Aitken mode aerosol nitrate	WATER_SOLUBLE_AEROSOL	3	1
7	AORGAJ Accumulation mode anthropogenic secondary organic	INSOLUBLE_AEROSOL	7	2
8	AORGAI Aitken mode anthropogenic secondary organic	INSOLUBLE_AEROSOL	7	1
9	AORGPAJ Accumulation mode primary organic	INSOLUBLE_AEROSOL	7	2
10	AORGPAI Aitken mode mode primary organic	INSOLUBLE_AEROSOL	7	1
11	AORGBJ Accumulation mode secondary biogenic organic	INSOLUBLE_AEROSOL	7	2
12	AORGBI Aitken mode biogenic secondary biogenic organic	INSOLUBLE_AEROSOL	7	1
13	AECJ Accumulation mode elemental carbon	BLACK_CARBON_AEROSOL	2	2
14	AECI Aitken mode elemental carbon	BLACK_CARBON_AEROSOL	2	1
15	A25J Accumulation mode unspecified anthropogenic	INSOLUBLE_AEROSOL	7	2
16	A25I Aitken mode unspecified anthropogenic	INSOLUBLE_AEROSOL	7	1
17	ACORS Coarse mode unspecified anthropogenic	INSOLUBLE_AEROSOL	7	3
18	ASOIL Coarse mode soil-derived	DUST_AEROSOL	1	3
19	AH2OJ Accumulation mode water	WATER_AEROSOL	6	2
20	AH2OI Aitken mode water	WATER_AEROSOL	6	1
21	ANAJ	SEASALT_AEROSOL	5	2
22	ANAI	SEASALT_AEROSOL	5	1
23	ACLJ	SEASALT_AEROSOL	5	2
24	ACLI	SEASALT_AEROSOL	5	1
25	ANAK	SEASALT_AEROSOL	5	3
26	ACLK	SEASALT_AEROSOL	5	3
27	ANO3K	SULFATE_AEROSOL	4	3
28	ASO4K	WATER_SOLUBLE_AEROSOL	3	3
29	AH2OK	WATER_AEROSOL	6	3

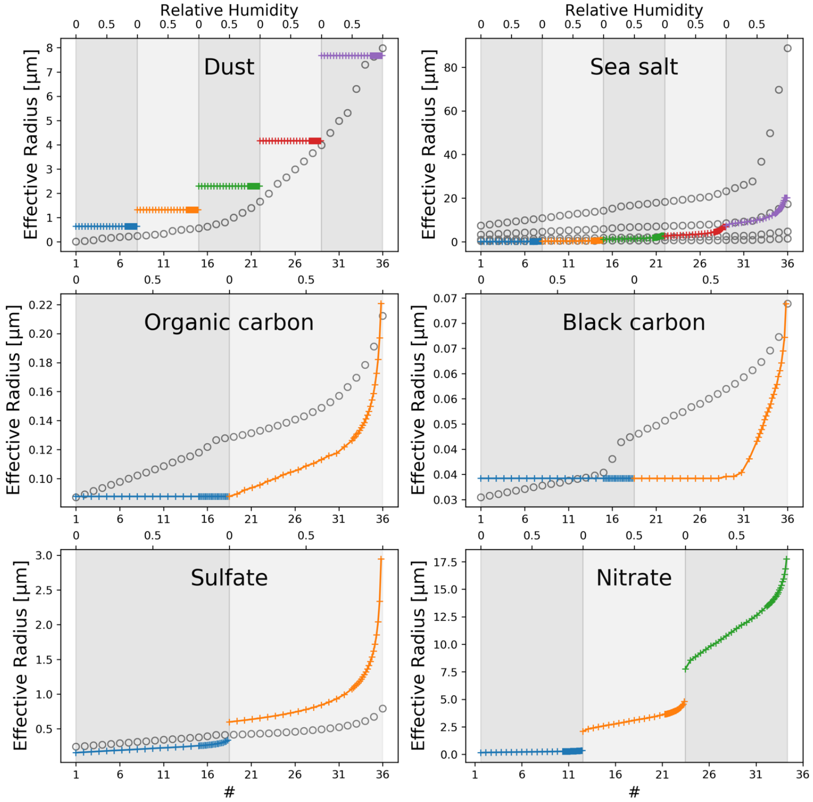
```
cmaq_type_mapping =[ 4,4, 3,3,3,3, 7,7,7,7,7,7, 2,2, 7,7,7, 1, 6,6, 5,5,5,5,5,5, 4, 3, 6 ]
cmaq_size_mapping =[ 2,1, 2,1, 2,1, 2,1, 2,1, 2,1, 2,1, 2,1, 3,3, 2,1, 2,1, 2,1, 3,3,3,3,3 ]
```

CMAQ aerosol species mapping to CRTM v2.0.2_CMAQ aerosol types

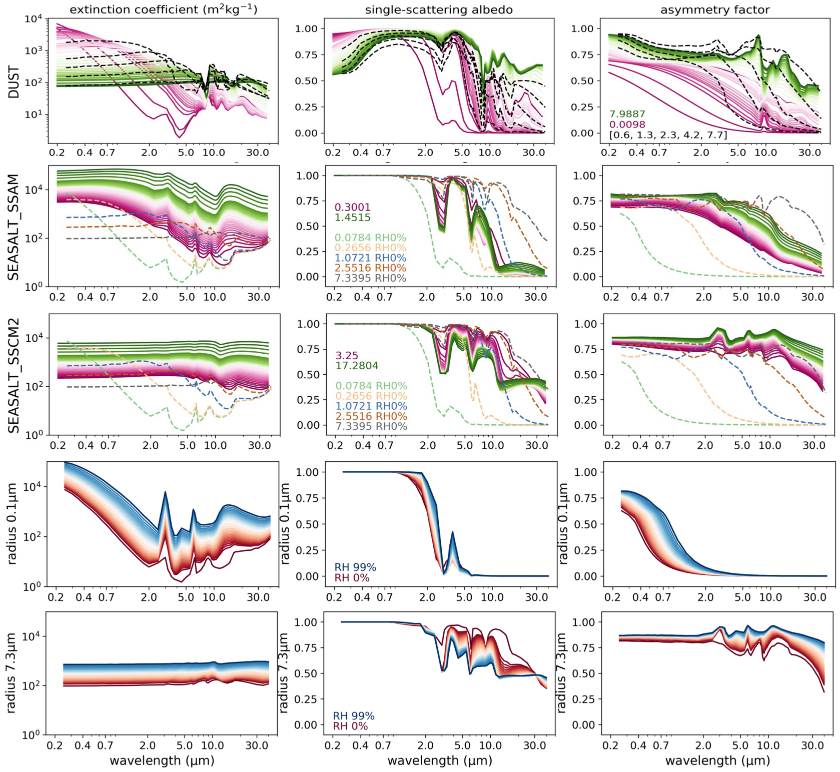
C1: CMAQ aerosol type ID
C2: CMAQ-to-CRTM type mapping
C3: CMAQ-to-CRTM size mapping
(1. Aikten, 2. Accumulation, 3. Coarse)

Intercomparison of select aerosol single-scattering properties between the CRTM default and CMAQ LUTs. The numbers listed in the figures are aerosol effective radii.
[Curves] the default LUT. **[Shade]** CMAQ LUT with the same effective radii but different size distribution.

GOCART-GEOS5 Table



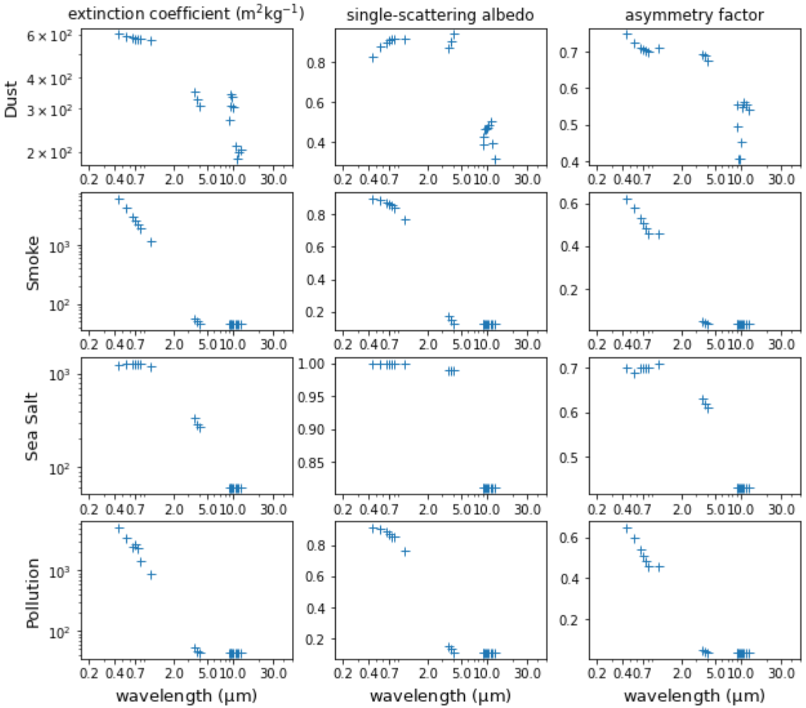
Default vs. GOCART-GEOS5



[Pink to green] the default LUT with increasing radius. [Dashed] GOCART-GEOS5.
[Red to blue] GOCART-GEOS5 Sea salt with increasing relative humidity.

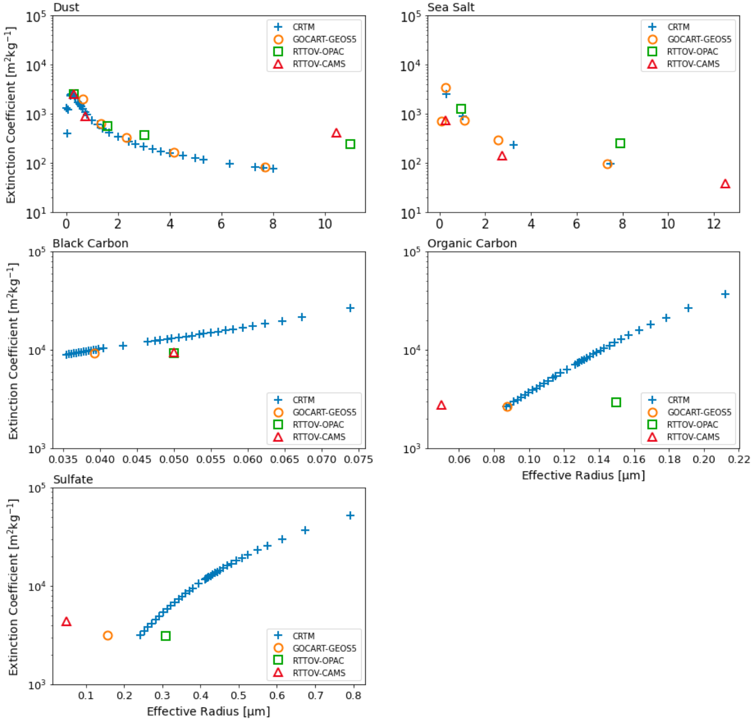
NAAPS and RTTOV Tables

NAAPS



Single-scattering properties of NAAPS aerosols.

RTTOV



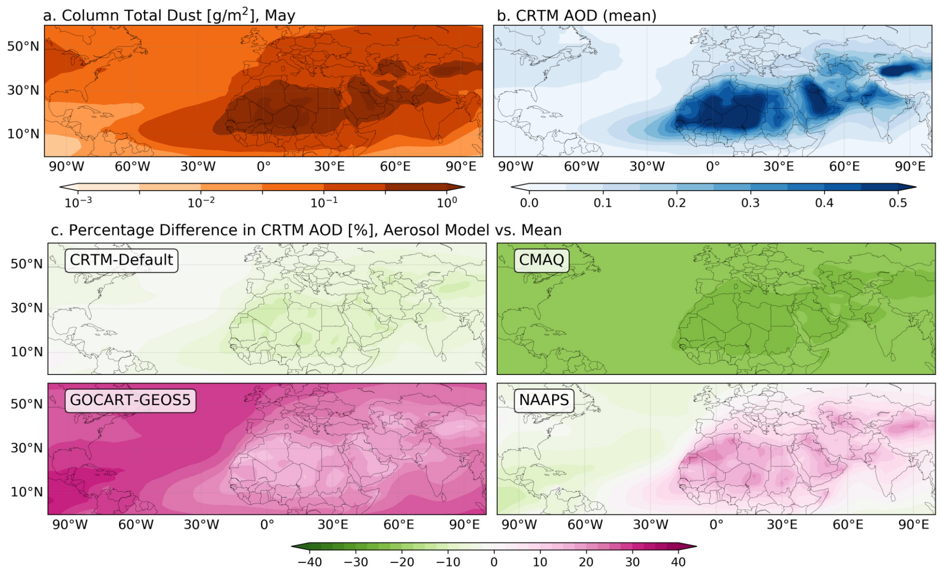
Intercomparison of select aerosol extinction coefficient across the CRTM default, GOCART-GEOS5, and RTTOV LUTs. [550nm]

CRTM Version 2.4.1 and Version 3

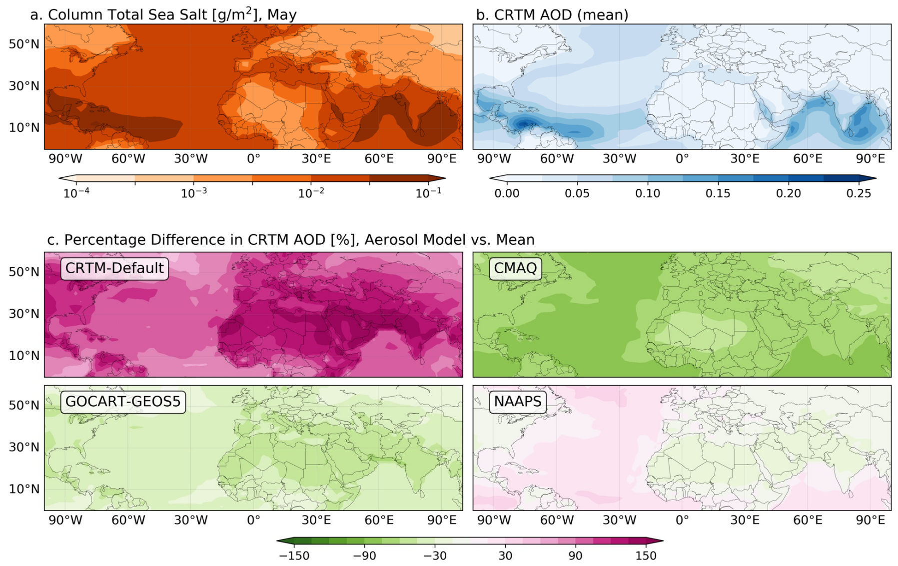
CRTM Version	Aerosol model	Aerosol species	Aerosol properties	References
All versions	CRTM (Default)	dust, sea salt, organic carbon, black carbon, sulfate	effective radius, hygroscopicity	Chin et al., 2002; Han, 2006
v2.4 – v3.0	CMAQ	dust, sea salt, water-soluble, soot, sulfate, water, insoluble, dust-like	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

Aerosol Optical Depth

Dust



Sea Salt



Figure, ***a.*** Column total aerosol concentration of May (MERRA-2 climatology) and ***b.*** the corresponding AOD simulated using CRTM, averaged over four aerosol schemes. ***c.*** percentage differences in AOD computed using each aerosol scheme.

Summary of CRTM Aerosol Capabilities

Table 4.10: The default CRTM `Aerosol` structure valid `Type` definitions and effective radii. SSAM ≡ Sea Salt Accumulation Mode, SSCM ≡ Sea Salt Coarse Mode.

Aerosol Type	Index Parameter	Name Parameter	r_{eff} Range (μm)
Dust	1	DUST_AEROSOL	0.01 - 8
Sea salt SSAM	2	SEASALT_SSAM_AEROSOL	0.3 - 1.45
Sea salt SSCM1	3	SEASALT_SSCM1_AEROSOL	1.0 - 4.8
Sea salt SSCM2	4	SEASALT_SSCM2_AEROSOL	3.25 - 17.3
Sea salt SSCM3	5	SEASALT_SSCM3_AEROSOL	7.5 - 89
Organic carbon	6	ORGANIC_CARBON_AEROSOL	0.09 - 0.21
Black carbon	7	BLACK_CARBON_AEROSOL	0.036 - 0.074
Sulfate	8	SULFATE_AEROSOL	0.24 - 0.8

Table 4.11: CRTM `Aerosol` structure valid `Type` definitions, effective radii (0.01 -7.5 μm), and radius standard deviations (1.05 - 2.5 μm), based on the aerosol size specification in CMAQ model.

Aerosol Type	Index Parameter
Dust	1
Soot	2
Water soluble	3
Sulfate	4
Sea salt	5
Water	6
Insoluble	7
Dust-like	8

Table 4.12: The CRTM `Aerosol` structure valid `Type` definitions and effective radii, based on the aerosol specification in GOCART-GEOS5 model. The optical properties of hydrophobic aerosols are constant with relative humidity (RH).

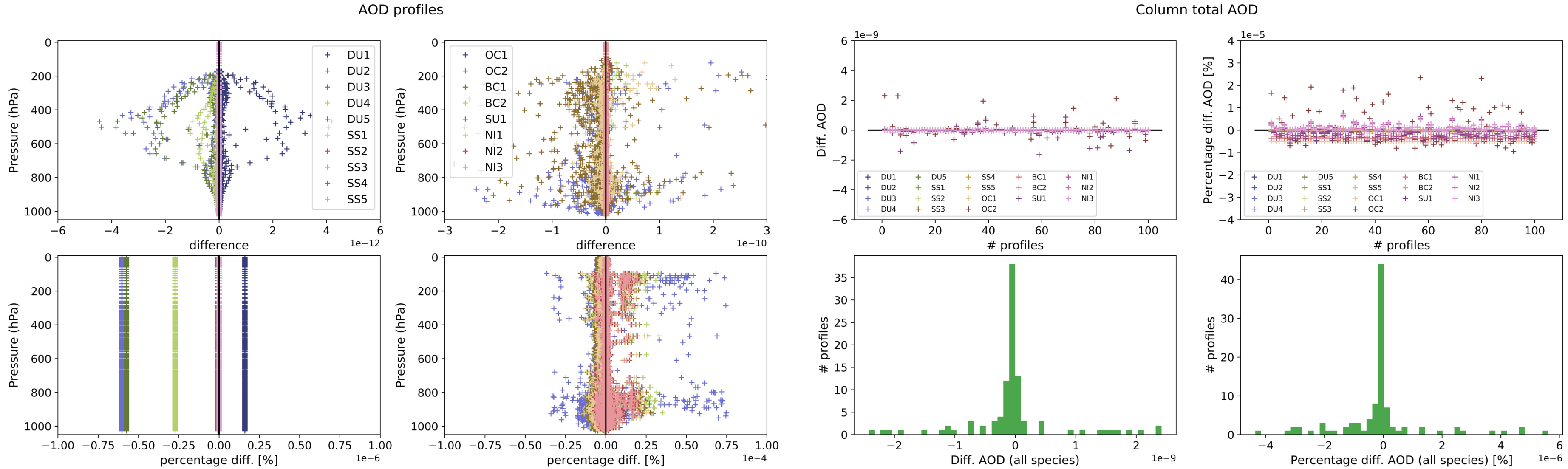
Aerosol Type	Index Parameter	r_{eff}(μm)	RH
Dust 1,2,3,4,5	1,2,3,4,5	0.64, 1.32, 2.30, 4.17, 7.67	0-1, Dummy
Sea salt 1,2,3,4,5	6,7,8,9,10	0.08, 0.27, 1.07, 2.55, 7.34	0-1
Organic Carbon 1	11	0.09	0-1, Dummy, (hydrophobic OC)
Organic Carbon 2	12	0.09	0-1
Black carbon 1	13	0.04	0-1, Dummy, (hydrophobic BC)
Black carbon 2	14	0.04	0-1
Sulfate 1, 2	15,16	0.16, 0.60	0-1
Nitrate 1, 2, 3	17,18,19	0.16, 2.10, 7.75	0-1

Table 4.13: The CRTM `Aerosol` structure valid `Type` definitions, based on the aerosol specification in NAAPS model. The optical properties of hydrophobic aerosols are constant with relative humidity (RH).

Aerosol Type	Index Parameter	RH
Dust	1	0-1, Dummy
Smoke	2	0-1
Sea Salt	3	0-1
Anthropogenic and Biogenic Fine Particles	4	0-1

Is such approach accurate?

Merged CRTM table versus the original tables



Offline tests with 100 aerosol profiles/geovals (aod_geoval_2018041500_m.nc4)
Differences in AOD profiles and column total AOD.
GOCART-GEOS5

Why CRTM?

Radiance Assimilation

Wei et al., 2022

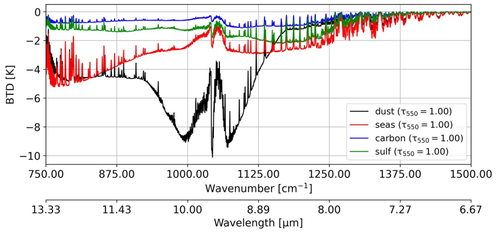


Figure 3. The brightness temperature differences between clear sky and hazy sky for IASI between 750 to 1500 cm-1.

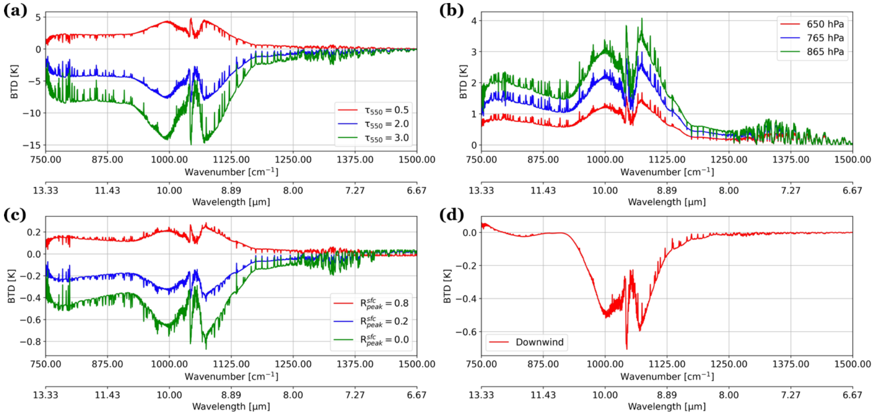


Figure 4. The relative change in simulated BT of IASI against the reference dust profile for each sensitivity test: (a) column mass density, (b) altitude of peak dust layer, (c) thickness, and (d) bins partition.

Lu et al., 2022

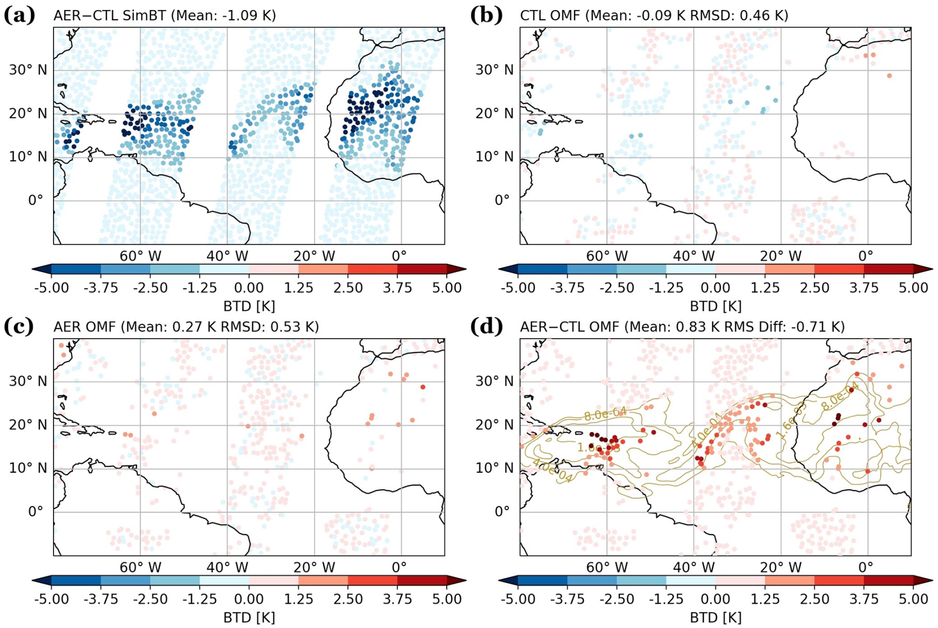


Figure 3. (a) Simulated BT differences (AER-CTL), (b) bias-corrected OMF from the CTL experiment, (c) bias-corrected OMF from the AER experiment, and (d) OMF differences (AER-CTL) for 10.39 μm channel of IASI on board METOP-A. All the data are from the analysis cycle at 12:00 Z on 22 June 2020. Contours of total column mass density from MERRA-2 are plotted in panel (d).

JEDI-SkyLab: Next Generation Earth System DA

Quarterly releases

Skylab 1.0, released in August with CRTM 2.3

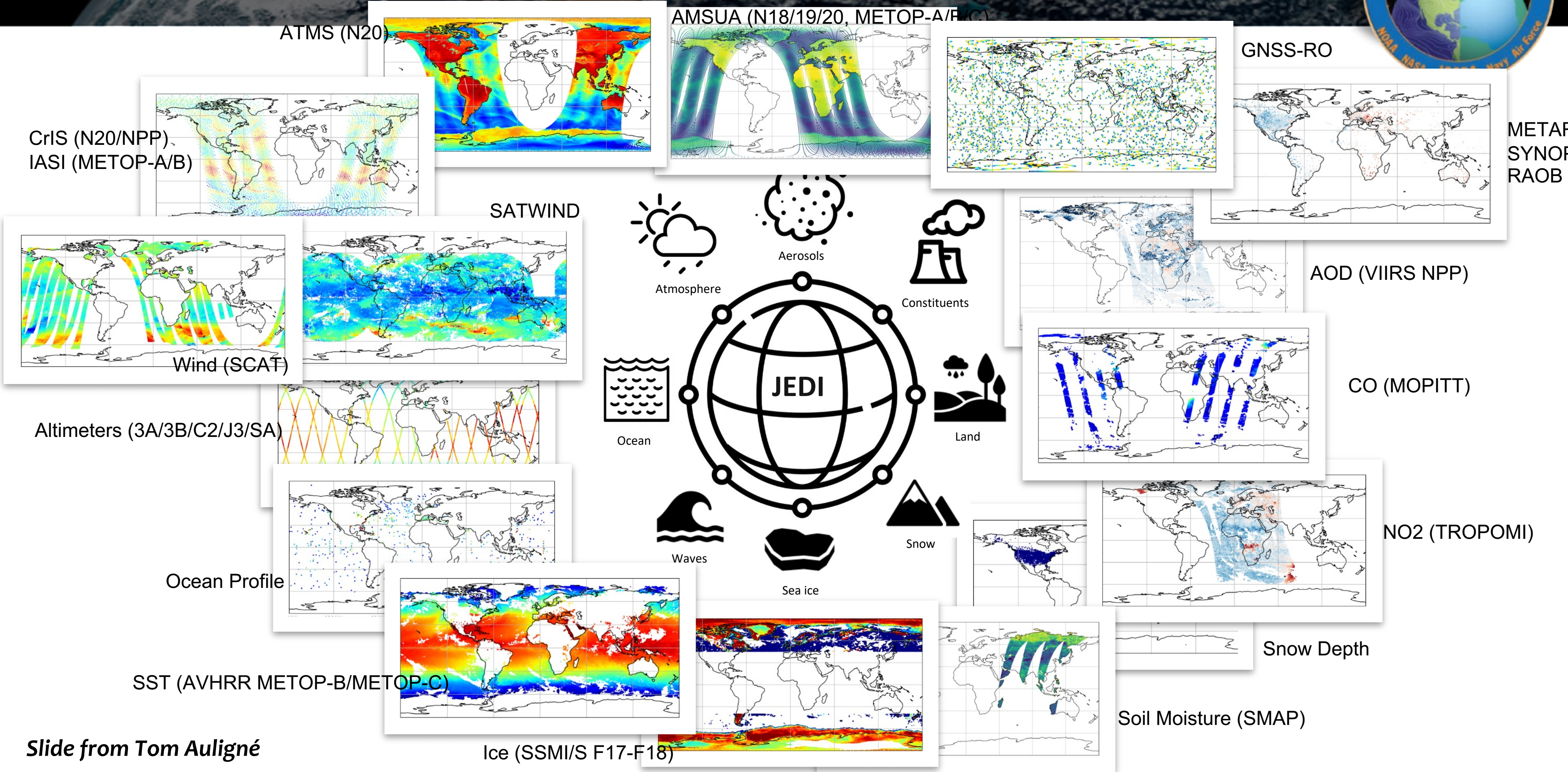
Skylab 2.0, released in October with CRTM 2.4

- Digital twin of the Earth system
  - Live and reanalysis
  - Emphasis on comprehensive observations
  - Coupled, continuous DA across scales
  - Stretched grid model(s) + AI/ML surrogates

- Showcase + channel **joint** science and tech. achievements
- Community access to *real-world* experimental testbed + rapid validation (e.g. obs. impact, new algo., performance)
- Deliver continuously functioning default configuration for downstream operational applications

Slide from Tom Aulignė

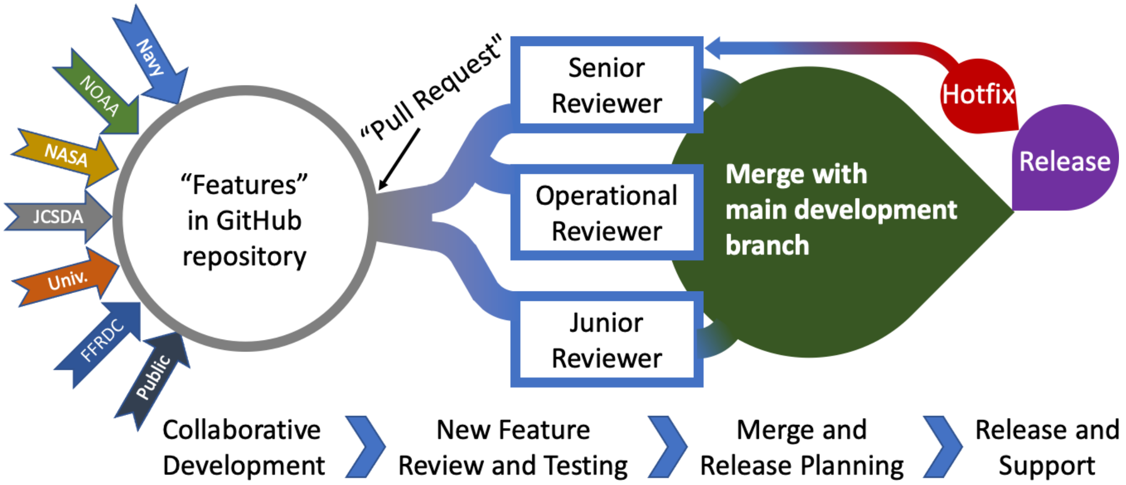
JEDI-SkyLab: Next Generation Earth System DA



Slide from Tom Auligné

Community Radiative Transfer Model

- Open source on GitHub.
- Collaborative development, testing, review, and release workflow.
- As part of the build process and the automated CI pipeline, the CRTM offers a comprehensive range of tests.
- In conjunction with the JCSDA JEDI project repositories, the CRTM repository has an integrated continuous integration / continuous delivery (CI/CD) workflow in support of its agile development approach.
- Standalone radiative transfer model.



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Useful links

- CRTM release note: https://www.jcsda.org/crtm
- CRTM public repository: https://github.com/JCSDA/crtm
- CRTM Internal developer repository: https://github.com/JCSDA-internal/crtm (please email us for access)
- PyCRTM: https://github.com/JCSDA/pycrtm
- CRTM transmittance/spectral coefficient generation package: https://github.com/JCSDA-internal/CRTM_coef (please email us for access)

- JCSDA: https://www.jcsda.org/
- Skylab releases: https://www.jcsda.org/jediskylab

Thank you!