

The Community Radiative Transfer Model (CRTM): Community-Focused Collaborative Model Development Accelerating Research to Operations

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Abstract:

The Joint Center for Satellite Data Assimilation (JCSDA) Community Radiative Transfer Model (CRTM) is a fast, 1-D radiative transfer model used in numerical weather prediction, calibration/validation, etc. across multiple federal agencies and universities. The key benefit of the CRTM is that it is a satellite simulator. It provides a highly accurate representation of satellite radiances by using the specific sensor response functions convolved with a line-by-line radiative transfer model (LBLRTM). CRTM covers the spectral ranges consistent with all present operational and most research satellites, from visible to microwave. The capability to simulate ultraviolet radiances and support space-based radar sensors is being added over the next two years in CRTM Version 3.0.

In addition to simulated radiances, the CRTM also provides Jacobian outputs needed to interpret satellite observations for numerical weather prediction. The Jacobian estimates how changes in geophysical parameters affect simulated measurements from satellite sensors. Using the Jacobian in modeling and weather prediction improves the accuracy and efficiency of data analysis, leading to better weather predictions.

The CRTM model's success and growth depend on community contributions and evaluation. To facilitate this, we have made the CRTM highly accessible through modular programming, clear documentation and tutorials, public domain licensing, unfettered public access via Github, and a

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clear path to operational implementation for innovative research. We encourage and welcome contributions from the community to help us continue to improve the CRTM.

Introduction

Timely and accurate weather forecasting is increasingly important in decision-making across a broad range of human pursuits (Uccellini and Ten Hoeve 2019). Such forecasts rely on a series of complex and computationally intensive models combined with the interpretation of increasingly diverse and voluminous input data sources (Bauer et al., 2015; Gettelman et al., 2022). This effort ultimately culminates in a relatively simple answer to the following question: "what's the weather going to be like?" (Brunet et al., 2022)

Generally, the accurate extraction and application of information from such observation data sources has the potential to provide critical adjustments to the model's atmospheric and surface states (Kleist et al., 2009; Dee et al., 2011; Lorenz, 2006). Without this information, a weather model quickly loses its capability to accurately predict weather due to rapidly increasing errors (Lorenz, 1969; Orrell, 2002). With the advent of low cost-to-orbit terrestrial observation satellites and a profusion of interconnected devices via the internet, routine and efficient exploitation of the relevant information content of these "observations" provides critical updates to the knowledge of the atmospheric and surface state in various weather prediction models (Eyre et al., 2022).

Data assimilation (DA) methodologies, such as 4DVAR (Le Dimet and Talagrand, 1986; Talagrand and Courtier, 1987; Bannister 2016), provide formalisms for combining information derived from observation interpretation with model states (Takens, 1980) and updating prior information. Such DA formalisms also preserve and propagate knowledge of the combined errors coming from both the model and observations and are usually implemented in systems of various scales for data products or operational weather forecasting. Examples of such systems are the Global Data Assimilation System (GDAS) (Kleist et al., 2009), ERA5 reanalysis by ECMWF Integrated Forecasting System (IFS) (Hersbach et al., 2020), and Japan Meteorological Agency (JMA) reanalysis system (Kobayashi et al., 2015).

A firehose of potential information

Even with the lower cost-to-orbit launch capabilities, satellites in low earth orbit still represent substantial risks due to high development costs, short lifetimes, and the inherent risks of

operating in a space environment (National Academies of Sciences, Engineering, and Medicine, 2018; Stephens et al., 2020). Despite these costs, atmospheric and surface observations made by space-based sensors remain highly underutilized in operational data assimilation contexts. While studies have shown that all-sky observations provide up to 20% of short-range forecast skill improvements (e.g., Geer et al., 2017), illustrating the benefit of accurately assimilating satellite-based observations, some models only use 0.1% of satellite observations for any given sensor. Typically, up to 80% of available mid-tropospheric observations in cloud-affected scenes are discarded (Geer et al., 2018) due to computational limitations imposed, in part, by the data assimilation framework's ability to rapidly and accurately interpret the radiances being observed.

Interpretation of radiances

Weather satellites typically host sensors that are sensitive to scattered/reflected light and/or thermally emitted wavelengths such as infrared, submillimeter, and microwaves (Thies and Bendix, 2011; Rani et al., 2016). For DA systems to exploit the information from such sensors, it requires a relationship between the observed radiances - typically expressed in terms of a "brightness temperature" (T_B), a measure of the equivalent temperature a perfect emitter would have to produce the intensity of the observed radiance. The model that provides such a relationship is called a Forward Operator (or Forward Model), which provides an answer to the question: "Provided the atmospheric and surface conditions, what radiance value do we expect to observe from a particular satellite sensor?" (Takens, 1980; Bannister 2016; Gettelman et al., 2022)

The Community Radiative Transfer Model (CRTM), developed and maintained by the Joint Center for Satellite Data Assimilation (JCSDA), fulfills this role in several mission-critical satellite data assimilation frameworks. In development since 2004, the model has been designed to operate as a fast, accurate radiance interpreter and satellite simulator, providing simulated radiances for all-weather and all-surface conditions.

Enabling all-weather all-surface all-sensor capabilities

From the beginning, CRTM's design centered around the core concepts of modularity and consistency. As Fig. 1 below demonstrates, the CRTM consists of a series of modules and

interfaces, with each module representing a central element of radiative transfer model requirements. The public interface to the CRTM consists of the Forward Model, which produces sensor-specific simulated radiances given the state of the surface and atmosphere (i.e., the state vector). The “Jacobian” provides the transpose of the derivative of the radiance with respect to the state vector by instrument channel. It can be thought of as a “sensitivity” of a given sensor channel’s simulated radiance to changes in the surface or atmospheric properties.

The primary scientific modules within the CRTM are as follows: surface optics, aerosol scattering, cloud scattering (including precipitation), molecular scattering, and atmospheric absorption/transmission. This modularity facilitates collaboration with expert researchers without requiring them to fully understand irrelevant portions of the code.

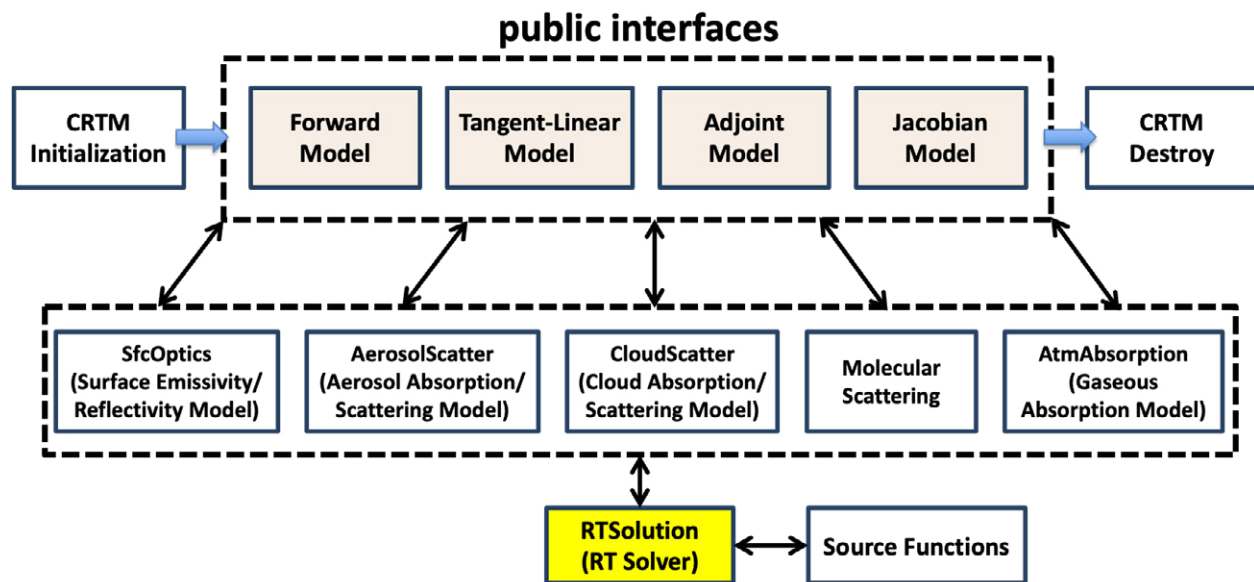


Figure 1. CRTM Public Interfaces

The CRTM is designed to be a library for users to link to from other models, rather than supplying a graphical user interface. However, CRTM can be readily run in "stand-alone" mode using existing test codes as an example of interfacing.

The CRTM user interface provides the forward model function to compute radiances and the Jacobian interface to compute sensitivities of radiance to user-specified atmospheric/surface parameters and relevant sensor geometry information.

Each of the physical models depicted in Fig. 1, such as Surface, Aerosol, Cloud, and Gaseous Absorption rely on pre-computed lookup-tables (LUTs for short). The use of LUTs allows for much faster interpretation of large amounts of satellite data, which can be critical for time-sensitive applications like weather forecasting. Second, it can reduce the computational resources required to run the model, making it more accessible to a wider range of users. Third, it can improve the accuracy of the model by allowing for more detailed and precise calculations to be made offline and then subsequently imported into the CRTM.

An Overview of the CRTM Scientific Model Elements

The CRTM was designed to meet users' needs, consequently, many options are available for users to choose from: input surface emissivity; select a subset of channels for a given sensor; inclusion of scattering calculations; computation of upwelling radiance at aircraft altitudes; computation of aerosol optical depth only; and threading of the CRTM via openMP.

The need for speed: fast atmospheric radiative transfer modeling

In general, computer modeling of radiative transfer (RT) invokes a series of approximations surrounding these more complex elements and seeks to elucidate the explicit relationship between the physical state and the radiance being simulated. Of relevance to atmospheric radiative transfer, many radiative transfer models (including CRTM) are one-dimensional (1-D), typically oriented in the vertical coordinate to approximate the view a downward-looking satellite-based sensor would have without encountering the computational burden of 3-D RT models.

Satellite-based sensors typically measure not only the intensity of radiation, but also the polarization state of that radiance. Thermal emission from the ocean surface is typically polarized (Erdem et al., 2012.; English et al., 2020), and the degree of polarization observed by a sensor depends on various surface parameters, the angle of emission and, consequently, the sensor viewing angle and polarization basis (e.g., Meissner and Wentz, 2012).

When simulating clear skies (no clouds), the way that photons move and interact with the atmosphere usually does not change their polarization state. So, to accurately simulate clear skies, a surface function that includes the full polarization state is enough. However, when there are clouds present, the polarization state of the photons must be considered. There are several

methods available to keep track of the polarization state, depending on the model assumptions and requirements (e.g., Battaglia and Mantovani, 2005).

The CRTM addresses these computational challenges associated with radiative transfer in different atmospheric scenarios by employing two internal solvers. One solver is optimized for clear-sky simulations and accurately calculates radiative emission (ADA, Han, 2006; Liu and Cao, 2019). The other solver is designed for scenarios involving scattering, known as the successive orders of interaction solver (SOI, Heidinger et al., 2006). The reason for this distinction is that scattering situations require more complex data structures and algorithms for scalar and polarized radiative transfer, which significantly increases the computational time and memory requirements compared to clear-sky simulations involving only absorption and emission.

Gaining efficiency by parameterizing the Line-by-Line Radiative Transfer Model

Accurate modeling of radiative transfer processes is essential for interpreting and analyzing measurements of atmospheric radiation. For this purpose, the Line-by-Line Radiative Transfer Model (LBLRTM) was developed to compute radiative transfer in clear-sky atmospheres with high precision (Clough et al., 2005). It solves the complex absorption and emission processes of atmospheric trace gases by treating each individual absorption line, hence the name "line-by-line." This approach provides the most rigorous and accurate modeling of atmospheric radiative transfer, but it is computationally expensive. LBLRTM is considered the gold standard for clear-sky radiative transfer modeling, and it has been extensively validated against observations (Matricardi, 2007). It serves as the foundation for other fast radiative transfer models, including the CRTM (Chen et al, 2010; Stegmann et al., 2022), RTTOV (Hocking et al., 2021), and the ARMS model (Kan et al., 2020).

As demonstrated in McMillin et al. (2006) and Stegmann et al. (2022), CRTM uses these precomputed LBLRTM calculations of representative atmospheric training profiles to generate a database of transmittance predictands and atmospheric state predictors. The subsequent statistical regression or neural network training uses this database to predict transmittance for new atmospheric conditions.

Temperature, moisture, and trace gases like CO₂, O₃, N₂O, CO, and CH₄ in the atmosphere are supported. Depending on the instrument type, the CRTM can account for different numbers of variable gases. For microwave instruments, the CRTM can tell the difference between moist and dry air. For conventional infrared instruments, it can account for water vapor, CO₂, and O₃, while for interferometers, it can account for the full range of variable gases.

Simulating sensor channel responses

When satellite instruments measure the radiation from the Earth's atmosphere, they don't detect radiation at a single, exact wavelength or frequency. Instead, the instruments measure the radiation over a range of wavelengths, called spectral bandwidth. Additionally, the instruments are subject to random variations during construction, which can cause irregularities in their sensitivity to different wavelengths. Once the instrument's sensitivity is experimentally determined by the instrument team – this is called the “spectral response function” (SRF). Using the previously described LBLRTM predictors, this information is convolved with the SRF to obtain a unique and representative ability to simulate the various channels on a given instrument. Each instrument added to the CRTM requires its own set of coefficients to accurately account for its specific response to different wavelengths.

Figure 2 shows an example of the clear-sky vertical temperature Jacobian (a partial derivative of brightness temperature with respect to the Temperature) for each channel of the "Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats" (TROPICS) instrument.

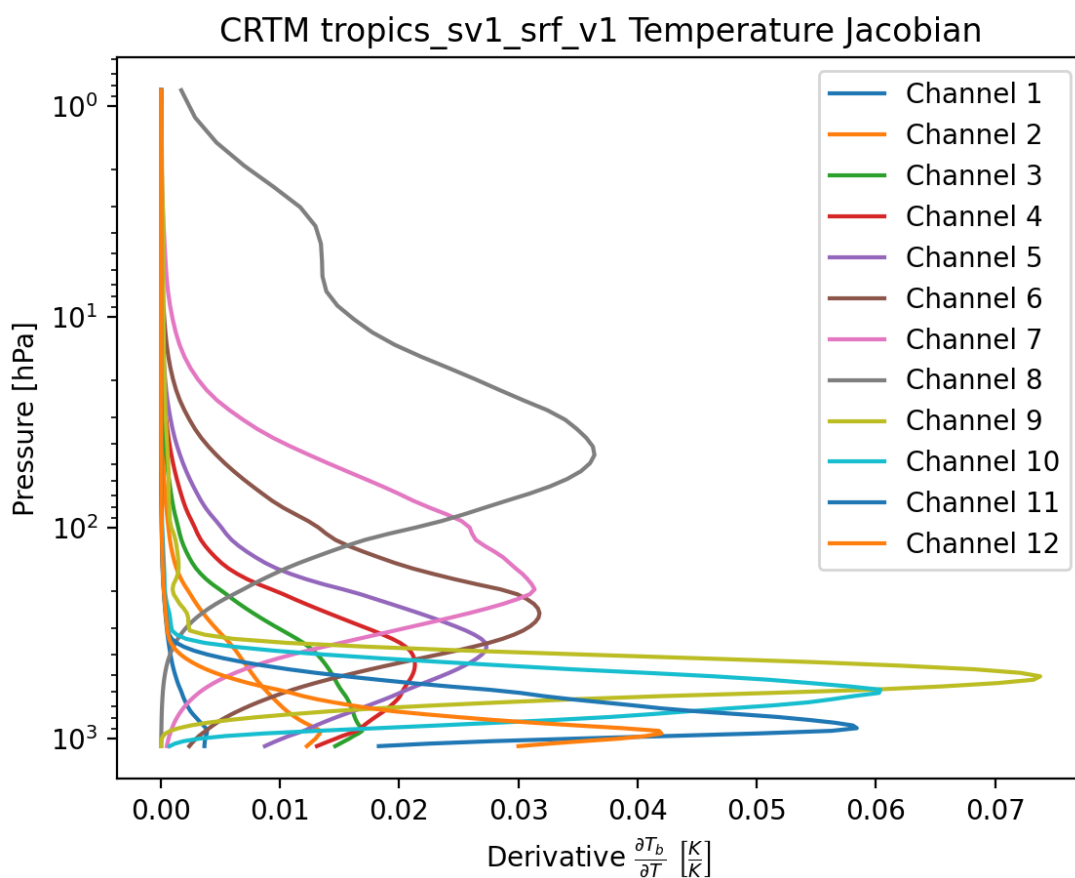


Figure 2. Example of the clear-sky Temperature Jacobian (partial derivative of brightness temperature with respect to the Temperature) for various TROPICS instrument channels, indicating the vertical sensitivity to changes in radiance with respect to changes in temperature for each sensor channel.

For a new sensor, the CRTM team and collaborators regularly generate and update spectral and transmittance coefficient files. Once the spectral and transmittance coefficient files are created, the CRTM is ready for the new sensor.

Aerosols

The aerosol module is fundamental to acquire aerosol type and concentration for studying air quality. CRTM supports numerous aerosols species simulated by aerosol transport models, including GOCART (Colarco et al., 2010), CMAQ (Liu and Lu 2016), and NAAPS (Lynch et al., 2016), with optical properties (0.2 - 40 μm) of dust, sea salt, organic carbon, black carbon,

sulfate, nitrate, volcanic ash, smoke, and anthropogenic and biogenic fine particles as a group. These coefficients are assembled based on measurements of bulk aerosol properties, or computed offline using aerosol scattering theories (e.g., Mie theory) (see e.g., Mishchenko, 1999), and stored in multiple aerosol coefficient lookup tables for efficient CRTM calculation. The associated aerosol optical properties are necessary for accurate scattering and extinction calculations in support of radiance calculations and aerosol optical depth (AOD) computations.

Clouds and Precipitation

The cloud module contains optical properties of six cloud types, providing radiative forcing information for weather forecasting and climate studies. Clouds and precipitation play an important role in the modification of upwelling and scattered radiances as would be observed from a given satellite sensor. CRTM supports "cloudy radiance" simulations from visible to microwave by interpolation of pre-computed cloud optical properties stored in a LUT, which are indexed by the wavelength of radiation, the effective radius of the particles, hydrometeor phase, temperature, and density of the particles. This includes precipitation-sized particles as well. The optical properties are linearly interpolated from the LUT and applied to each cloud type on a per atmospheric layer basis.

These cloud optical properties, computed offline using Mie Theory (Yi et al., 2016), Invariant Imbedding T-Matrix (Bi and Yang, 2014), and Discrete Dipole Approximation (Stegmann et al, 2018), are integrated into the included Cloud Coefficient LUT. The use of the netCDF file format enables ease of use and modification of these LUTs.

Surface Properties

The CRTM surface model includes surface emissivity/reflectivity for various surface types, including snow, ice, land, and water/ocean. Part of these coefficients are computed offline, based on surface reflectivity/emissivity models developed over the years. Notable emissivity models include the FASTEM series for microwave ocean surface emissivity (English and Hewison, 1998, Liu et al., 2010, Bormann et al., 2012), and the thermal IR water emissivity model IRSSE (Nalli et al., 2022). In addition, parts of these coefficients are developed based on algorithms employed in satellite systems such as NPOESS. These coefficients are also stored in surface coefficient LUTs for CRTM calculations.

These descriptions provide a cursory introduction to the CRTM modules. For specific implementation details see the CRTM User Guide (Johnson et al., 2023).

Community focused, modern development practices

Our community-focused development model permits non-traditional developers and expert contributors from around the world to contribute to the CRTM project. The only barrier to inclusion is the quality of the code and its impact on the outputs of the CRTM. *Code contributions will not be rejected based on any other criteria.* Furthermore, we work directly with novice developers, minimizing the barriers to entry. We believe that this philosophy promotes the most equitable method for a diverse community to be able to contribute to operational radiative transfer improvements while maintaining the high quality of code that our users are accustomed to.

With the goal of transparency and truly community-based development in mind, the CRTM team has adopted Agile software development principles (Beck et al., 2010) and transitioned the CRTM repository to be hosted on the Github platform (<https://github.com>).

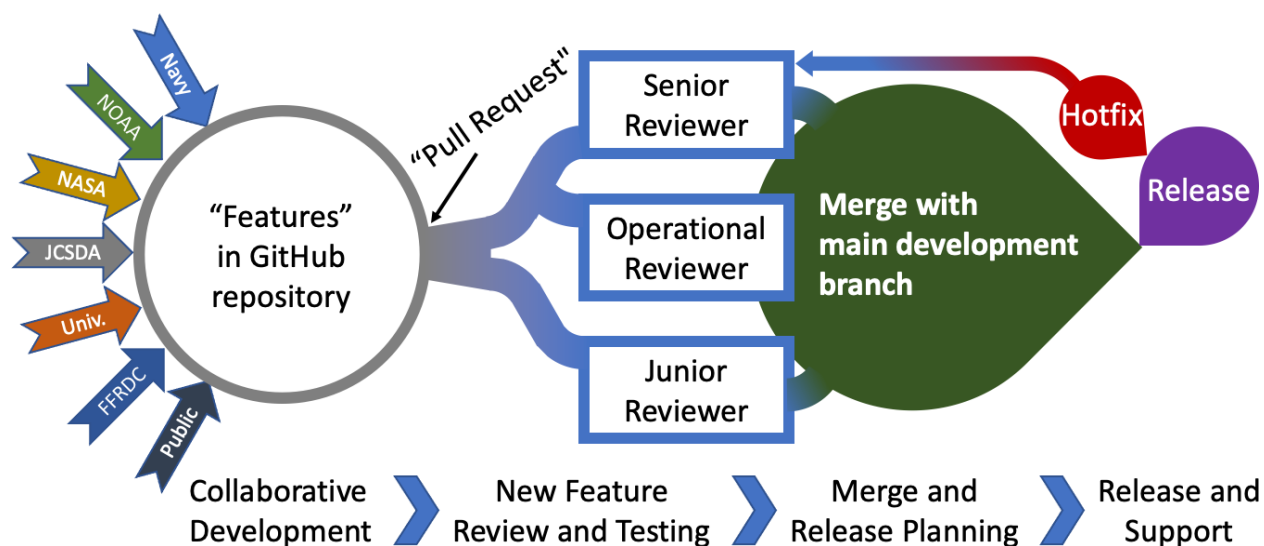


Figure 3. Collaborative development, testing, review, and release workflow, highlighting the role of the community, the JCSDA CRTM team, and operational partners in the development and evaluation of contributions to the CRTM.

The CRTM repository is developed using an agile approach and is integrated with a continuous integration/continuous delivery (CI/CD) workflow to support efficient development. This workflow includes automated testing as part of a pipeline to catch issues early on. There are two types of tests: unit tests and regression tests. Unit tests are designed to check that individual functions of the CRTM are working properly, while regression tests ensure that new code changes do not affect the behavior of the CRTM on larger datasets.

The CRTM also includes a comprehensive unit-testing framework that developers can use to add appropriate tests when developing new features. There are multiple ways to implement the CI/CD pipeline on Github, but the CRTM currently uses Amazon AWS to build and test the code.

Bridging the Research and Operations Gap

Contributing to the CRTM provides a direct path to operational satellite data assimilation and other operational models in which CRTM is used. Traditionally the ability to add new/innovative research to the CRTM required directly contacting the maintainer of the repository and hoping that they would be willing to accept your monolithic code modifications. Using the previously mentioned development practices, innovation through incremental development permits the CRTM maintainers to evaluate code in smaller, easier to manage and test increments. This ensures that the contributors get immediate feedback on their contribution, and also that their time isn't wasted if the proposed contributions aren't consistent with the vision/scope of the CRTM.

As an example of R2O efficiency success: CRTM v2.4.0 was released in October 2020. It was tested and evaluated by NOAA EMC starting in January 2021, and accepted for integration into NOAA GSI in September 2021. This update resulted in measurable improvements in analysis and forecast capability within the GSI system. Additionally, updates to coefficient files and minor code fixes and support are readily handled through the Github repository and other binary storage options, enabling unrestricted access to the model and associated tables.

With more operational centers shifting to a similar continuous integration / continuous development paradigm and making direct use of Github and similar development tools, we expect that the turn-around time for the R2O pipeline will further decrease.

Education and Outreach

As part of the CRTM User & Developer workshops and a general documentation effort, a guided tutorial suite was developed in addition to the existing range of test cases. The tutorial does not assume prior knowledge about using the CRTM and is aimed at the graduate student level. It introduces important concepts in radiative transfer, remote sensing, and inverse methods based on practical examples involving the CRTM.

In addition to the Fortran API of the CRTM, a Python interface also exists (Karpowicz et al., 2022). Due to the dynamic nature and high popularity of the Python language, this simplifies using the CRTM and lowers the barrier of entry for students and the open-source community in general. pyCRTM also comes with a range of example cases in Jupyter notebooks.

Summary and future directions

Accurate interpretation of satellite-based radiances provides a wealth of information regarding the dynamic, thermodynamic, and physical properties of the atmosphere and the surface. The CRTM provides the critical link in this interpretation by relating these properties to simulated radiances as would be observed by a given sensor. However, with the increasing volume and frequency of satellite-based observational data, and the cost of producing such data, the CRTM plays an increasingly critical role in rapidly and accurately interpreting these observations in numerical weather prediction and a variety of remote sensing applications.

Continuous community engagement in the development process provides an equitable and highly effective method for a rapid transition from research to operations. In as little as one month, a new lookup table or research feature can be implemented, tested, and released to the public. The public release model benefits the broader community that uses CRTM and, in turn, provides more opportunities for collaborative development and evaluation under a variety of use cases.

With the increasingly mature applications of artificial intelligence methodologies applied to several physical problems, the CRTM of the future will transition towards a hybrid approach to sensor simulation. The physically based model would become increasingly focused on accuracy (and less on speed), whereas the AI model would be trained against this, resulting in a computationally efficient model radiance interpretation for applications in which execution speed is essential. This will enable a much larger number of observations to be used compared to cases where the forward operator was the limiting factor.

Acknowledgements

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Data Availability Statement

CRTM v2.4.0, including all lookup tables and included binary files, is Public Domain. All datasets and binary assets included in the CRTM v2.4.0 created or used during this study are openly available from the JCSDA CRTM public github repository at <https://doi.org/10.5281/zenodo.7415561> .

Appendix A: Abbreviations

| | |
|--------|---|
| 1D-VAR | One Dimensional Variational (Data Assimilation) |
| ABI | Advanced Baseline Imager |
| AD | Adjoint model |
| ADA | Advanced Doubling Adding method |
| AER | Atmospheric and Environmental Research |
| AIRS | Atmospheric Infrared Sounder |
| AMSU | Advanced Microwave Sounding Unit |
| AOD | Aerosol Optical Depth |
| ARMS | Advanced Radiative Transfer Modeling System |
| CD | Continuous Development |

| | |
|--------|--|
| CI | Continuous Integration |
| CMAQ | Community Multiscale Air Quality (model) |
| CRTM | Community Radiative Transfer Model |
| CrIS | Cross-track Infrared Sounder |
| DA | Data Assimilation |
| ECMWF | European Centre for Medium-range Weather Forecasts |
| EMC | Environmental Modeling Center (NOAA) |
| EPA | Environmental Protection Agency |
| FASTEM | Fast microwave Emissivity Model |
| GeoVal | Geophysical values at locations |
| GFDL | Geophysical Fluid Dynamics Laboratory |
| GOCART | Goddard Chemistry Aerosol Radiation and Transport |
| GSI | Gridpoint-Statistical Interpolation system |
| IASI | Infrared Atmospheric Sounding Interferometer |
| IFS | Integrated Forecast System (EMCWF) |
| IR | Infrared |
| IRSSE | Thermal IR Sea Surface Emissivity Model |
| JCSDA | Joint Center for Satellite Data Assimilation |
| JMA | Japan Meteorological Agency |
| JEDI | Joint Effort for Data Assimilation Integration |
| LBL | Line-by-line |

| | |
|---------|--|
| LBLRTM | Line by Line Radiative Transfer Model |
| LTE | Local Thermodynamic Equilibrium |
| LUT | Lookup Table |
| MetOp | Meteorological Operational satellite |
| MW | Microwave |
| NAAPS | Navy Aerosol Analysis and Prediction System |
| NASA | National Aeronautics and Space Administration |
| netCDF | Network Common Data Form |
| NOAA | National Oceanic and Atmospheric Administration |
| non-LTE | Non-Local Thermodynamic Equilibrium |
| NPOESS | National Polar-orbiting Operational Environmental Satellite System |
| NPP | (Suomi) National Polar-Orbiting Partnership satellite |
| NRL | Naval Research Laboratory |
| ODAS | Optical Depth in Absorber Space |
| ODPS | Optical Depth in Pressure Space |
| OpenMP | Open Multi-Processing |
| OPTRAN | Optical Path Transmittance (model) |
| PR | Pull Request |
| pyCRTM | Python CRTM |
| R2O | Research to Operations |
| RT | Radiative Transfer |

| | |
|---------|---|
| RTTOV | Radiative Transfer for TOVS |
| SOI | Successive-Order-of-Interactions method |
| SRF | Spectral Response Function |
| SSMI | Special Sensor Microwave Imager |
| SSMIS | SSMI / Sounder |
| SSU | Stratospheric Sounding Unit |
| TIROS | Television Infrared Observation Satellite |
| TL | Tangent-Linear model (also TLM) |
| TOVS | TIROS Operational Vertical Sounder |
| TROPICS | Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats |
| UFO | Unified Forward Operator |
| UV | Ultraviolet |
| VIS | Visible |
| WSM-6 | WRF Single-Moment 6-Class Scheme |
| WRF | Weather Research & Forecasting Model |

Appendix B: CRTM Version History

CRTM version 1.0, released in 2006, improved upon the earlier models in both the scientific and software architecture aspects. Specifically, it accounted for the absorption and scattering from various types of hydrometeors and aerosols, as well as including 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.

The CRTM v1 software framework was designed to strike a balance between computational efficiency, code maintenance, and flexibility for future improvements and extensions. The source code was written in standard Fortran 95 and makes extensive use of modules and derived type data structures to achieve these goals.

CRTM version 2.0 was released in March 2010. The primary new capabilities were the addition of the ODAS (Optical Depth in Absorber Space), which is equivalent to the previous Compact OPTRAN algorithm (OPTRAN); and ODPS (Optical Depth in Pressure Space), which is similar to the RTTOV-type of transmittance algorithm that handles more species of gaseous absorption and emission (Chen et al., 2012).

A fast Stratospheric Sounding Unit (SSU) model, based on the ODAS approach, but with elements to account for the time-dependence of the SSU CO₂ cell pressures (Chen et al., 2011) was implemented, as was a fast Zeeman model for SSMI/S upper-peaking channels (Han, 2010).

For the surface properties, a specular surface reflection option was added, replacing the Lambertian surface in calculations of reflected IR downward atmospheric radiation over the ocean. Updates to the ocean emissivity, particularly for infrared, resulted in substantial improvements.

CRTM version 2.1, released in 2012, focused on improving clear-sky simulation capabilities. In particular, the FASTEM series of ocean surface emissivity models were added, starting with FASTEM1 (English and Hewison, 1998), and quickly progressing to FASTEM5 (Bormann et al., 2012). FASTEM is short for FAST microwave Emissivity Model, which was developed by the Met Office, U.K., and has been widely used to compute the surface emissivity for microwave data assimilation and remote sensing.

CRTM implemented the FASTEM ocean emissivity model, which has significantly improved microwave radiance assimilation. Over the years, the CRTM FASTEM module has continued to be enhanced with surface roughness parameterizations, especially on ocean waves and foam (Liu et al., 2010).

Land surface emissivity models were also updated to include more information about the surface characteristics, specifically soil and vegetation types as well as the leaf area index (LAI), to compute the emissivity (Vogel et al., 2011).

A model for non-LTE simulations, applied to infrared sensors, corrected daytime radiances for the non-LTE effects in the shortwave infrared channels. This was applied to the hyperspectral infrared sensors; AIRS (Aqua), IASI (MetOp-A/B), and CrIS (Suomi NPP).

The inclusion of the Successive Order of Interaction (SOI) radiative transfer algorithm provides an alternative RT solution algorithm (Heidinger et al., 2006), and improves performance under appropriate scattering conditions. The default RT solver remained the Advanced Doubling-Adding (ADA) algorithm in v2.1.

Version 2.2, released in 2015, provided the ability to simulate overcast radiances in fully cloud-covered conditions. This necessitated an updated reflection correction to the microwave sea surface emissivity model for non-precipitating clouds. This version also marked early attempts to improve microwave emissivity modeling of snow-covered surfaces. Additionally, to more accurately simulate the impact of clouds on infrared radiances, the cloud optical property coefficient table was updated (Yi et al., 2016).

CRTM version 2.3.0, released in November 2017 continued improvements on all-sky radiance capabilities by providing a cloud fraction option, which permitted users to provide a fractionally cloudy pixel. The resulting simulated radiance of a fractionally cloudy profile represents a mixture of clear sky and overcast radiances. The FASTEM-6 model, as implemented in CRTM, was revised to use all-sky / fractionally cloudy transmittances in the surface reflection correction, along with a key improvement in the downwelling reflection from the surface for scattered radiation (Kazumori and English, 2015).

Like the microwave snow-cover modules developed in v2.2, several sea ice modules were developed to more accurately simulate emission from sea ice.

CRTM version 2.4.0 was released in October 2020. To support air quality prediction and management by the US EPA, an aerosol coefficient table based on CMAQ specifications was added. This permits users to assimilate a larger variety of aerosol size distributions with CRTM. Similar optional coefficient tables have also been released in v2.4.0 alpha for cloud simulations following WSM-6 (Hong et al., 2004), Thompson (Thompson et al., 2004), and GFDL (Chen and Lin, 2013) cloud microphysics schemes.

Version 2.4.0 also updated and released a series of sensor coefficient files, including ABI G-17, Metop-C sensors such as AVHRR, IASI, AMSU-A; and added SMAP and SMOS support.

To improve user experiences and data transparency, this version added, for the first time, netCDF module and released cloud and aerosol coefficients in netCDF format. To improve model efficiency, this version also implemented OpenMP for parallel computing over profile loops.

CRTM version 2.4.1 continues development for aerosol calculations and introduces two more optional aerosol coefficient tables based on GOCART and NAAPS models. This paves the way for more US agencies, such as NOAA, NASA, and NRL to adopt CRTM for aerosol-related simulations.

In this version, we introduced more optional schemes for improving surface-related simulations. Specifically, we added temperature-dependent thermal IR emissivity calculations for water and snow surfaces. In addition, the thermal IR snow emissivity and reflectivity are also interpolated over snow grain sizes. Introductions of these new state variables enable more flexible and accurate calculation of surface-related Jacobians within CRTM and surface DA.

Software-wise, CRTM 2.4.1 continues to expand netCDF interface to surface coefficient tables and implement OpenMP over channel loops to further boost computational efficiency.

CRTM version 3.0 (under active development) represents a major update to the CRTM project. By leveraging the latest updates in v2.4, CRTM v3.0 permits an even more precise simulation capability of satellite observations over cloudy/hazy and precipitating scenes by (i) enabling full polarization simulation and support for UV instruments; (ii) improving over-ocean/snow simulation accuracy; and (iii) up to a factor of 10 improvement in computational speed through code optimization, intelligent openMP support across channels and profiles, and improved LUT accessibility via netCDF interfaces. Additionally, a radar and lidar forward operator is under development, which will permit the direct assimilation of polarized space-based radar/lidar reflectivities.

Sidebar: A History of Community Collaboration

The CRTM was conceived in the early 2000s as a modern and modular framework for atmospheric radiative transfer. Developed around the Compact OPTRAN clear-sky transmittance model (McMillin, 2006), the CRTM builds upon the success of that model by extending the capabilities toward all-sky / all-surface radiance simulation. The impetus for the

development of CRTM arose out of the needs of the growing data assimilation community, sensor calibration and validation needs, and as a U.S. counterpart of the capabilities of the European Radiative Transfer for TOVS (RTTOV) model (Saunders et al., 2018 and references therein).

At the time, cloud-affected satellite radiances had not been assimilated into operational forecast models, although satellite observations contained considerable information content regarding the dynamic and microphysical processes within clouds. Today, it is fully recognized that the assimilation of cloud- and aerosol-impacted radiances provides critical information to numerical weather prediction models (e.g., Geer et al., 2017; Geer et al., 2018).

Early CRTM development implemented newly developed scientific advancements, with the specific aim of improving the modeling of cloudy and aerosol-affected satellite radiance simulations. Another important purpose of developing the new model was to design a modern, modular framework for developer and users, aiming to simplify the implementation of experimental algorithms and permit ease of testing and evaluation in operational environments. Ultimately this approach accelerated the transition from research to operational applications.

The earlier RT models used at the JCSDA were all emission-based, limited to microwave and infrared radiances, and applicable only to clear sky conditions (Kleespies et al., 2004; McMillan et al., 2006). These early models lacked capabilities to accurately simulate surface emission and reflectivity.

From 2004 to the present, the CRTM model advanced through various key stages. See Appendix B for a detailed version history. CRTM version 1 from 2004 through 2010 was primarily focused on clear sky microwave and infrared radiative transfer. CRTM version 2 from 2010 - 2022 focused on cloudy and aerosol-impacted radiance simulations, with substantial improvements in the surface emission. It also saw the addition of a new gaseous transmittance regression model. As of version 2.4, the CRTM was released as a Public Domain model, with no licensing restrictions.

CRTM version 3, under development as of the time of writing, provides a fully polarized solver, and enables ultraviolet support (Liu and Cao, 2019; Liu et al., 2022). Moreover, a radar and lidar forward operator is in progress, which will enable the direct assimilation of space-based radar (e.g., GPM-DPR) and lidar reflectivities. This is expected to provide substantial improvement to cloudy and aerosol-impacted radiance assimilations.

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