



RTTOVpy v1.0: A Python framework for automated radiative-transfer simulations for satellite remote sensing using ERA5 and WRF atmospheric data

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Abstract. Satellite observations provide an essential reference for evaluating atmospheric models, but meaningful comparisons require model variables to be transformed into the radiometric quantities measured by satellite instruments. This transformation commonly involves substantial preprocessing, configuration, radiative-transfer execution, and post-processing. We present RTTOVpy, an open-source Python application that provides an automated and reproducible interface between atmospheric datasets and the Radiative Transfer for TOVS (RTTOV) model. RTTOVpy supports atmospheric input from ERA5 reanalysis and Weather Research and Forecasting (WRF) model output. It extracts atmospheric and surface variables, constructs vertically consistent RTTOV profiles, defines surface and satellite-viewing geometries, executes simulations for configurable sensors and channels, and reorganizes the results into georeferenced NetCDF files and satellite-like imagery. Solar-reflectance calculations and aerosol simulations using WRF-Chem dust profiles can also be enabled when supported by the selected RTTOV coefficient files. An integrated verification workflow remaps satellite observations to the model grid and provides statistical comparisons and Taylor diagrams.

The application is demonstrated through an ERA5-based simulation for the MODIS instrument and WRF-based simulations for the SEVIRI instrument, including a dust event simulated with WRF-Chem. The latter experiment evaluates the sensitivity of simulated infrared brightness temperatures to atmospheric dust by comparing dust-free and dust-aware simulations against satellite observations. For three SEVIRI infrared channels (8.7, 10.8, and 12.0 μm), spatial correlations range from 0.72 to 0.76. Including dust reduces the normalized centered root-mean-square difference at 8.7 μm from 0.727 to 0.691, while the other channels exhibit negligible or slightly unfavorable changes, indicating a channel-dependent response rather than a uniform improvement. These experiments demonstrate RTTOVpy's capability to generate satellite-equivalent model fields and quantify the radiometric effects of atmospheric constituents within a reproducible simulation and verification workflow. The current implementation primarily targets clear-sky conditions, with cloudy-sky support and more efficient multi-profile RTTOV execution identified for future development. RTTOVpy provides a practical observation-operator framework for satellite-based model evaluation, radiative-transfer experimentation, and the generation of synthetic satellite products from atmospheric model and reanalysis datasets.



1 Introduction

25 Satellite observations provide essential information on the state of the atmosphere and the Earth's surface and are widely used in weather forecasting, climate monitoring, atmospheric retrievals, and model evaluation. However, satellite instruments do not directly measure most geophysical variables; instead, they record radiances within specific spectral channels. Interpreting these measurements therefore requires radiative-transfer models (Stamnes and Stamnes, 2015) that describe how atmospheric composition, temperature, clouds, aerosols, surface properties, and viewing geometry influence the radiation received by the sensor.

30 Forward radiative-transfer simulations consequently provide an important link between atmospheric-model or reanalysis fields and satellite observations, enabling the generation of observation-equivalent radiances and brightness temperatures for direct comparison with measured data (Sekertekin, 2019; Chen et al., 2008). Such comparisons are particularly valuable for evaluating modelled atmospheric conditions in the observational space of satellite instruments, thereby reducing the dependence on retrieved geophysical products and their associated assumptions.

35 Among fast radiative-transfer models, the Radiative Transfer for TOVS (RTTOV) model (Saunders et al., 2018) is widely used to simulate radiances for satellite instruments operating in the infrared, microwave, and visible spectral regions. Developed within the EUMETSAT Numerical Weather Prediction Satellite Application Facility, RTTOV provides computationally efficient forward, tangent-linear, adjoint, and Jacobian calculations for applications including satellite data assimilation, atmospheric retrievals, instrument evaluation, and the generation of synthetic satellite observations (Geer et al., 2021). Its use

40 of precomputed sensor-specific coefficient files enables simulations for numerous current and historical satellite platforms while maintaining the computational efficiency required for large atmospheric-profile datasets. RTTOV has therefore become an established component of operational and research workflows that connect numerical weather prediction, reanalysis, and atmospheric-model output with satellite measurements (Bani Shahabadi et al., 2016).

Despite the computational efficiency and broad sensor support provided by RTTOV, constructing complete simulations from

45 atmospheric-model or reanalysis datasets remains a technically demanding task (Zhou et al., 2025). Multidimensional fields from sources such as ERA5 and the Weather Research and Forecasting (WRF) model must be converted into vertically ordered atmospheric profiles with the variables, units, pressure coordinates, and metadata expected by RTTOV. Surface characteristics, near-surface conditions, sensor geometry, simulation time, gas concentrations, and instrument-specific coefficient files must also be prepared consistently (Geer and Vidot, 2022). These requirements are complicated by differences in data structures,

50 vertical-coordinate systems, variable conventions, and available atmospheric quantities among input datasets. Furthermore, scientifically meaningful comparisons with satellite observations require consistency in spectral-channel selection, simulation time, viewing geometry, and spatial representation. Large gridded simulations additionally require systematic processing of individual atmospheric columns and subsequent reconstruction of the radiative-transfer outputs into georeferenced products. An end-to-end application therefore involves substantial preprocessing, execution control, and post-processing beyond the

55 radiative-transfer calculation itself (De Angelis et al., 2016).

Existing software addresses different aspects of these requirements. RTTOV provides an official Python interface, `pyrttov`, which enables direct access to the compiled radiative-transfer model through Python and supports the processing of multiple



atmospheric profiles within a single execution. However, the preparation of model-specific atmospheric and surface inputs, including vertical-coordinate conversion and satellite viewing geometry, remains the responsibility of the application using the interface. Similarly, pyCRTM (Karpowicz et al., 2022) provides a Python interface to the Community Radiative Transfer Model (CRTM), exposing its underlying Fortran structures and procedures for atmospheric radiative-transfer applications. Although these interfaces facilitate the integration of radiative-transfer calculations into scientific Python workflows, they primarily provide access to the forward models rather than complete processing pathways for heterogeneous atmospheric-model and reanalysis datasets.

Other developments integrate radiative-transfer simulations more directly with atmospheric modelling systems. The RTTOV-WRF-MPAS package (Ikugler, 2025) generates synthetic satellite observations from WRF and Model for Prediction Across Scales (MPAS) output. Its WRF implementation is configured for selected Spinning Enhanced Visible and Infrared Imager (SEVIRI) channels, whereas its MPAS implementation also supports calculations at prescribed observation locations using externally supplied observation information. At the Earth system modelling scale, the CFMIP Observation Simulator Package coupled with RTTOV (COSP-RTTOV) (Shaw et al., 2025) enables the simulation of satellite-like spectral radiation fields within Earth system models. COSP-RTTOV supports instrument-specific spectral channels, satellite sampling, and both clear- and cloudy-sky radiances, primarily facilitating climate-model evaluation and related scientific applications. These approaches demonstrate the usefulness of integrating radiative-transfer models with atmospheric simulations, but differ in their target applications and coupling strategies. In particular, inline integration with an Earth system model and offline processing of previously generated regional-model or reanalysis output represent distinct approaches with different requirements for model interfaces, input preparation, and workflow control.

These developments highlight the continuing need for an offline framework that systematically connects heterogeneous atmospheric datasets with satellite radiative-transfer simulations. Such a framework should minimize the model-specific programming required to construct radiative-transfer inputs, provide consistent treatment of atmospheric and surface quantities, accommodate different satellite instruments and viewing geometries, and preserve sufficient configuration and intermediate information for reproducible experiments. It should also support model-to-observation comparisons and sensitivity studies without requiring modifications to the underlying atmospheric model or radiative-transfer solver. These requirements are particularly relevant to regional atmospheric modelling, where satellite-equivalent radiances can provide complementary information about simulated temperature, moisture, surface conditions, and aerosol effects.

To address these requirements, this study introduces RTTOVpy v1.0, an open-source Python framework for automated preparation, execution control, and post-processing of RTTOV simulations from ERA5 reanalysis and WRF model output. RTTOVpy does not modify the radiative-transfer algorithms of RTTOV. Instead, its contribution lies in the development and integration of methods that transform heterogeneous atmospheric datasets into consistently configured satellite-equivalent simulations. The principal scientific and technical contributions of the framework are as follows:

1. A unified atmospheric-data processing methodology for ERA5 and WRF, including extraction and conversion of atmospheric and surface variables, reconstruction of RTTOV-compatible vertical profiles, and systematic processing of



independent atmospheric columns. This enables the application of a common radiative-transfer workflow to datasets with different coordinate systems and variable conventions.

2. An integrated satellite-geometry and instrument configuration methodology that supports user-defined satellite positions, geostationary viewing configurations, and historical orbital information derived from two-line element (TLE) data. Together with configurable instrument coefficients and spectral-channel selection, this enables satellite-specific simulations across different observational geometries without modifying the source code.

3. A WRF-Chem aerosol-processing capability that converts modelled mineral-dust size-bin concentrations into the aerosol representation required by RTTOV. This provides a framework for investigating the radiative influence of simulated dust distributions and for comparing dust-affected and aerosol-free satellite-equivalent simulations.

4. A reproducible, configuration-driven simulation architecture that integrates input preparation, RTTOV execution scripts, georeferenced NetCDF output generation, visualization, and optional verification against satellite observations. The separation of preprocessing, radiative-transfer execution, and post-processing facilitates inspection of intermediate results and repeatable experiments across different model domains and satellite configurations.

The framework uses YAML configuration files to specify atmospheric inputs, RTTOV installations and coefficient files, satellite geometry, spectral channels, simulation settings, and output processing. Radiative-transfer calculations are performed using the compiled RTTOV forward-model programs, preserving the original model implementation while avoiding a direct dependency on the pyrttov interface. This design favors modularity and transparent processing, although execution of individual atmospheric profiles introduces additional file input/output and computational overhead relative to batched in-process approaches.

The remainder of this paper describes the RTTOV input requirements, the architecture and methodology of RTTOVpy, and its application to ERA5- and WRF-based satellite simulations. The simulation examples and verification analyses are used to examine the framework's practical applicability, while the discussion addresses its methodological advantages, computational characteristics, current limitations, and opportunities for further development.

2 RTTOV radiative-transfer model

The Radiative Transfer for TOVS (RTTOV) model is a fast radiative-transfer model developed within the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Numerical Weather Prediction Satellite Application Facility. RTTOV simulates top-of-atmosphere radiances observed by passive downward-viewing satellite radiometers, spectrometers, and interferometers in the visible, infrared, and microwave spectral regions. It is widely used as an observation operator in satellite-data assimilation, atmospheric retrieval, instrument simulation, and model-evaluation applications.

For a given atmospheric and surface state vector x , RTTOV represents the forward radiative-transfer calculation as



$$\mathbf{y} = \mathcal{H}(\mathbf{x}; \mathbf{c}), \quad (1)$$

where $\mathbf{y}$ denotes the vector of simulated channel radiances, $\mathcal{H}$ is the RTTOV forward operator, and $\mathbf{c}$ represents the coefficients associated with the selected satellite instrument and channels (Scheck, 2021). The atmospheric state generally includes vertical profiles of temperature and water vapour and may additionally include ozone and other trace gases, depending on the coefficient file and simulation configuration. Surface pressure, surface temperature, near-surface meteorological variables, surface type and emissivity, and satellite and solar viewing geometries are also required as appropriate for the selected spectral region.

The computational efficiency of RTTOV is achieved through channel-specific parameterisations of atmospheric optical depth. These parameterisations are derived from reference calculations performed using accurate line-by-line radiative-transfer models and are distributed in sensor-specific coefficient files (Silveira et al., 2024). The coefficient files account for the spectral characteristics of individual satellite instruments and therefore determine the platforms, sensors, and channels that can be simulated. This approach allows large numbers of atmospheric profiles and satellite channels to be processed substantially faster than would be possible through direct line-by-line calculations.

In addition to clear-sky simulations, RTTOV provides options for representing cloud- and aerosol-affected radiances and for treating scattering in supported spectral regions. The availability and configuration of these calculations depend on the selected RTTOV version, coefficient files, cloud or aerosol optical-property tables, and the atmospheric inputs supplied by the user. RTTOV also provides tangent-linear, adjoint, and Jacobian models for applications requiring radiance sensitivities to atmospheric and surface variables (Lupu and Geer, 2015). RTTOVpy currently uses the direct forward model because its main purpose is to generate synthetic satellite observations from reanalysis and numerical weather prediction data.

RTTOVpy v1.0 contains version-specific interfaces for RTTOV versions 12, 13, and 14. RTTOV version 14 is recommended for the current RTTOVpy release and was used for the simulations presented in this study. RTTOVpy does not alter the RTTOV source code, radiative-transfer equations, optical-depth parameterisations, or instrument coefficients. Instead, it prepares the required atmospheric, surface, and geometrical inputs, invokes the original RTTOV executables, and post-processes the resulting outputs. Differences among the supported RTTOV versions, particularly those related to the representation of pressure levels and layer boundaries, are handled by the corresponding RTTOVpy input-processing workflows described in Sect. 2.1.

2.1 RTTOV Atmospheric input data

RTTOV requires atmospheric profiles and associated surface and geometrical information for each simulated location. RTTOVpy obtains these inputs from gridded atmospheric datasets and converts each horizontal grid point into an independent RTTOV profile. The current version supports data from the ERA5 reanalysis and the Weather Research and Forecasting (WRF) model.

The atmospheric inputs required by RTTOVpy include three-dimensional fields of air temperature, water-vapour concentration, and pressure or the variables needed to derive pressure. Depending on the selected simulation, additional three-



dimensional fields may include ozone, cloud variables, hydrometeor concentrations, and aerosol concentrations. Surface and
155 near-surface inputs may include surface pressure, skin temperature, 2 m temperature and humidity, 10 m wind components,
surface elevation, land–sea classification, and other surface properties required by RTTOV.

The exact set of required variables depends on the RTTOV simulation mode, satellite instrument, spectral region, and selected
treatment of clouds and aerosols. RTTOVpy therefore distinguishes between mandatory atmospheric fields, mandatory surface
fields, and optional variables used by specific simulation configurations. The procedures used to transform these variables into
160 RTTOV-compatible profiles are described in Sect. 3.3.

2.1.1 ERA5 reanalysis data

ERA5 is the fifth-generation global atmospheric reanalysis produced by the European Centre for Medium-Range Weather
Forecasts. It combines numerical weather prediction with a wide range of assimilated observations to provide temporally
and spatially consistent estimates of the atmospheric state. RTTOVpy supports ERA5 as a source of atmospheric and surface
165 information for the generation of synthetic satellite observations.

The ERA5 workflow uses three-dimensional atmospheric variables together with two-dimensional surface and near-surface
fields. Atmospheric inputs generally include temperature and specific humidity on pressure levels or model levels. Additional
trace-gas, cloud, and aerosol variables may be supplied when they are available and required by the selected RTTOV configura-
tion. Surface and near-surface inputs include fields such as surface pressure, skin temperature, 2 m temperature, 2 m dew-point
170 temperature, 10 m wind components, surface geopotential, and land–sea mask.

ERA5 pressure-level data provide atmospheric variables directly on prescribed pressure surfaces and can therefore be
mapped relatively directly to the vertical coordinate required by RTTOV. ERA5 model-level data retain the native vertical
structure of the reanalysis and require the corresponding surface pressure and hybrid-coordinate information to determine the
pressure of the individual atmospheric levels. RTTOVpy provides separate processing workflows for these two data organisa-
175 tions.

ERA5 data may be supplied to RTTOVpy as NetCDF files containing one or more time steps over a selected geographical
domain. The files must preserve the coordinate information required to identify time, latitude, longitude, and vertical level.
Input files may contain the atmospheric and surface variables in separate datasets, provided that their temporal and horizontal
coordinates are mutually consistent. The retrieval and preprocessing of ERA5 data used in the demonstration experiments are
180 described in Sect. 4.1.

2.1.2 WRF model output

The Weather Research and Forecasting model is a limited-area numerical atmospheric modelling system used for research
and operational applications. WRF produces four-dimensional atmospheric fields over one or more nested model domains and
can represent meteorological, cloud, land-surface, chemical, and aerosol processes at a wide range of spatial and temporal
185 resolutions. RTTOVpy uses WRF output to simulate satellite observations corresponding to the atmospheric state represented
by a WRF simulation.



The standard WRF output file contains the atmospheric and surface variables required for profile generation, although several quantities are stored as prognostic or perturbation variables rather than as the physical variables expected by RTTOV. Relevant three-dimensional fields include perturbation and base-state pressure, perturbation potential temperature, water-vapour mixing ratio, geopotential, and optional cloud, hydrometeor, chemical, or aerosol variables. Surface and near-surface fields include surface pressure, skin temperature, 2 m temperature and moisture, 10 m wind components, terrain height, land-use information, and land-sea classification.

WRF employs a terrain-following vertical coordinate, and the vertical position and pressure of each model layer vary horizontally and temporally. Consequently, WRF output cannot be passed directly to RTTOV without reconstructing the physical pressure, temperature, humidity, and height profiles. RTTOVpy reads the geographical coordinates, simulation times, and model-domain dimensions directly from the WRF output. Each model column is then associated with the corresponding atmospheric profile, surface state, and observation geometry. Support for optional WRF cloud and aerosol fields depends on the physical parameterisations and output variables enabled in the WRF simulation. The WRF configurations and datasets used in the demonstration experiments are described in Sect. 4.2.

3 RTTOVpy software and methodology

RTTOVpy is a Python-based application designed to automate the preparation, execution, and post-processing of simulations performed with the Radiative Transfer for TOVS (RTTOV) model. The application connects atmospheric-model and reanalysis data with RTTOV by converting multidimensional meteorological fields into the atmospheric, surface, and geometrical inputs required for radiative-transfer calculations. It subsequently executes the selected RTTOV simulation and reorganizes the resulting radiances, brightness temperatures, transmittances, and related quantities into structured NetCDF products and satellite-like images.

The RTTOVpy workflow was developed to reduce the manual processing normally required when numerical weather prediction or reanalysis output is used as input to RTTOV. In particular, the application handles the extraction of atmospheric columns, preparation of pressure and thermodynamic profiles, assignment of surface properties, configuration of satellite instruments and channels, generation of RTTOV input files, execution of the radiative-transfer model, and spatial reconstruction of the simulation results. The current implementation supports atmospheric data obtained from ERA5 and the Weather Research and Forecasting (WRF) model, while its modular structure permits the addition of further input-data sources and satellite instruments.

RTTOVpy does not modify the radiative-transfer equations or numerical solvers implemented in RTTOV. Instead, it provides a reproducible processing and workflow layer around RTTOV. Consequently, the scientific results produced by RTTOVpy depend both on the physical and numerical formulation of the selected RTTOV version and on the transformations applied by RTTOVpy to the original atmospheric data. The following subsections therefore describe the complete processing chain, with particular attention to unit conversions, interpolation procedures, atmospheric-profile construction, instrument configuration, and other implementation decisions that can influence the simulated satellite quantities.



220 3.1 Configuration and workflow control

RTTOVpy simulations are controlled through YAML configuration files, with separate configurations provided for ERA5- and WRF-based applications. The configuration specifies the atmospheric input data, target simulation time, RTTOV installation and coefficient files, satellite instrument and channel selection, viewing geometry, optional physical processes, output-generation settings, and verification options. This configuration-driven design allows simulations to be reproduced or adapted
225 without modifying the source code.

Figure 1 illustrates the organization of the WRF configuration file and its relationship to the principal RTTOVpy workflow stages. The required configuration blocks define the RTTOV environment, WRF input file and simulation time, and satellite instrument and viewing geometry. Optional blocks enable additional calculations and processing steps, including solar-reflectance simulation, WRF-Chem dust-aerosol radiative effects, generation of NetCDF and image products, and verification
230 against satellite observations.

The configuration parameters are parsed at the beginning of a simulation and propagated to the relevant workflow components. Input data and satellite-geometry settings control the construction of atmospheric and surface profiles and the calculation of pixel-specific viewing angles. The RTTOV version, sensor coefficient file, selected channels, and optional aerosol settings determine the forward-model configuration. Post-processing and verification settings subsequently control the reconstruction
235 of the RTTOV outputs on the original WRF grid, the generation of single-band and RGB imagery, the remapping of satellite observations, and the production of statistical comparison results.

3.2 Design rationale and methodological trade-offs

The architecture of RTTOVpy is guided by the objective of providing a reproducible and configurable pathway from heterogeneous atmospheric datasets to satellite-equivalent radiative-transfer simulations. Several methodological decisions distinguish
240 this approach from direct integration with RTTOV through its Python interface and involve trade-offs between computational efficiency, flexibility, and transparency.

First, RTTOVpy processes atmospheric columns independently and interfaces with the compiled RTTOV forward-model executables rather than relying on the pyrttov Python bindings. This approach separates atmospheric-data preparation from radiative-transfer execution, allowing intermediate input profiles to be inspected and individual simulations to be reproduced
245 or diagnosed. It also facilitates adaptation to different RTTOV versions without requiring the Python interface to be compiled and configured for each installation. However, independent profile execution introduces file input/output overhead and repeated model initialization, including coefficient loading, making it computationally less efficient than batched in-process simulations. The approach therefore prioritizes modularity and traceability over maximum computational throughput.

Second, atmospheric profiles are constructed from the native vertical structure of the input datasets, with the pressure coordinates and atmospheric variables transformed as necessary to satisfy RTTOV input requirements. Avoiding unnecessary
250 interpolation onto an additional prescribed vertical grid helps retain the vertical information represented by the original atmospheric model or reanalysis. Nevertheless, the accuracy of the resulting radiative-transfer calculations remains dependent on

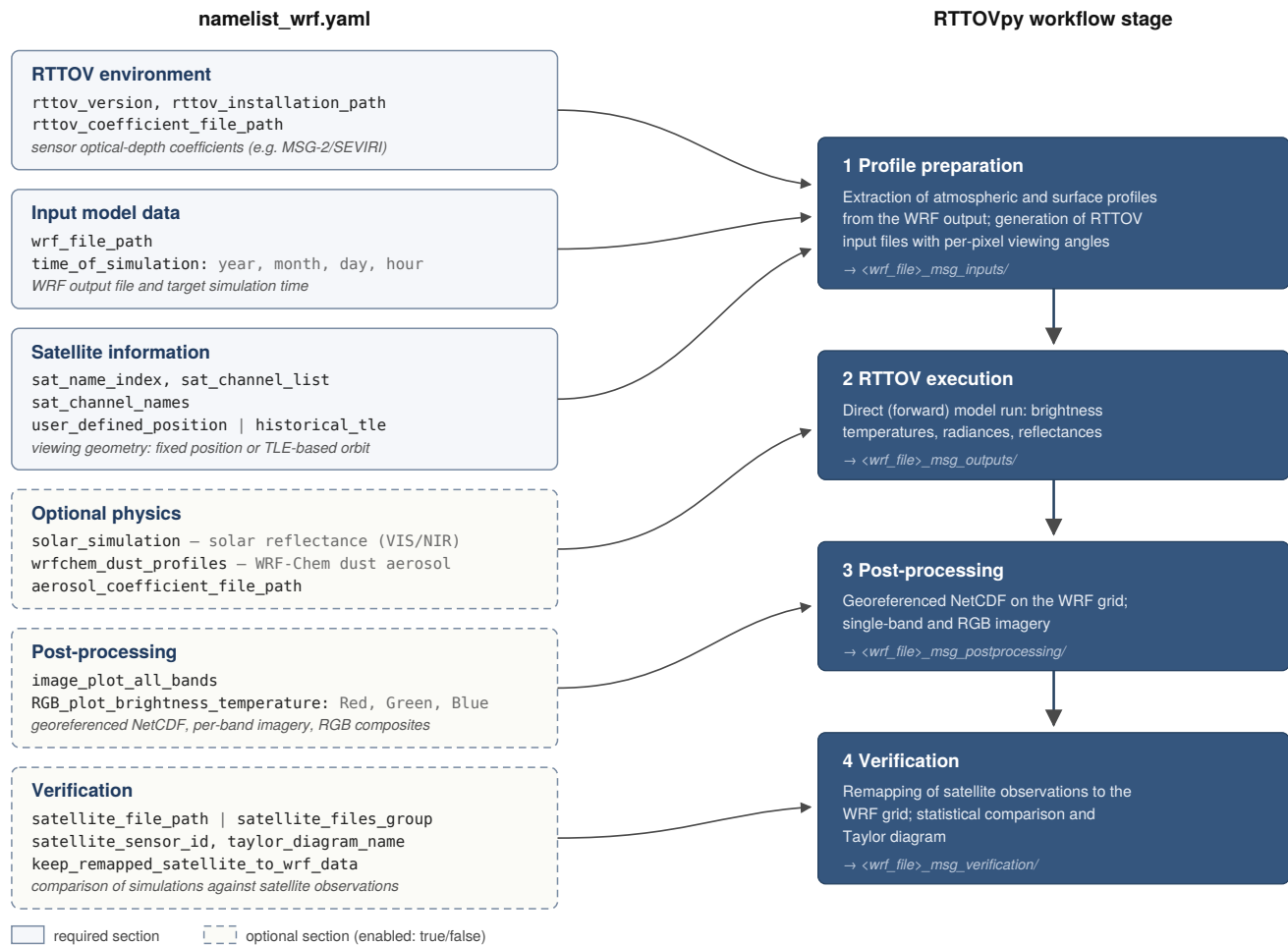


Figure 1. Structure of the RTTOVpy WRF YAML configuration file and its relationship to the principal workflow stages. Required configuration blocks define the RTTOV environment, atmospheric input, and satellite configuration, whereas optional blocks enable additional physical processes, post-processing, and verification. The workflow produces stage-specific directories containing RTTOV input profiles, forward-model outputs, georeferenced simulation products, and verification results.

the vertical resolution, physical consistency, and availability of the input atmospheric variables. Differences between model vertical coordinates and RTTOV version-specific profile requirements must therefore be handled explicitly.

255 Third, the treatment of mineral dust from WRF-Chem is implemented through a mapping between the model’s dust size-bin representation and the aerosol categories supported by RTTOV. This provides a practical means of incorporating modelled dust distributions into satellite radiance simulations without modifying the underlying radiative-transfer model. The mapping necessarily involves assumptions regarding the correspondence between dust size distributions and the optical properties asso-



ciated with RTTOV aerosol types. Consequently, uncertainties in aerosol representation and optical properties may influence
 260 the simulated radiances and should be considered when interpreting dust-related results.

Finally, satellite and simulation settings are managed through a declarative YAML configuration rather than being embedded
 in the processing code. Instrument selection, spectral channels, simulation time, and satellite viewing geometry can therefore
 be changed independently of the atmospheric-data processing implementation. Support for user-defined satellite positions and
 orbital information derived from historical two-line element (TLE) data enables experiments involving different observational
 265 geometries. The resulting configuration provides a record of the simulation settings, while full reproducibility additionally
 requires preservation of the input datasets, RTTOV version, coefficient files, and relevant orbital information.

Together, these design decisions establish RTTOVpy as an offline model-to-satellite simulation framework whose primary
 methodological contribution is the systematic integration of atmospheric-data preparation, satellite geometry, radiative-transfer
 execution, and output generation, rather than modification of the underlying RTTOV radiative-transfer algorithms.

270 3.3 Atmospheric-profile generation

RTTOVpy converts the three-dimensional atmospheric fields at a selected simulation time into a collection of independent one-
 dimensional atmospheric profiles. Each horizontal grid point in the ERA5 or WRF domain is treated as a separate atmospheric
 column, and the profiles are processed sequentially in the same order as the original horizontal grid. The resulting profile files
 are assigned zero-padded numerical identifiers, which are subsequently used to reconstruct the RTTOV output on the original
 275 ERA5 or WRF grid.

The principal atmospheric variables supplied to RTTOV are pressure, temperature, and water vapour. Temperature is ex-
 pressed in kelvin, pressure in hectopascals, and water vapour in kilograms per kilogram over moist air, corresponding to
 RTTOV gas-unit option 1. The vertical profiles are reordered from the top of the atmosphere towards the surface, as required
 by the RTTOV profile format. Very small or negative water-vapour values are replaced by a lower limit of $10^{-5} \text{ kg kg}^{-1}$, pre-
 280 venting zero or non-physical humidity values from being passed to RTTOV. For WRF output, the native water-vapour mixing
 ratio is first converted to specific humidity according to

$$q = \frac{r}{1 + r}, \quad (2)$$

where r is the water-vapour mixing ratio and q is the corresponding specific humidity.

The pressure-profile construction depends on the RTTOV version. For RTTOV versions using conventional full-level pro-
 285 files, RTTOVpy supplies pressure, temperature, and water vapour on the same vertical levels. In the WRF workflow, full pres-
 sure is obtained as the sum of the perturbation and base-state pressures, $P + P_B$, and converted from pascals to hectopascals.
 For ERA5 pressure-level input, the pressure coordinate supplied with the data is used directly.

$$p_{k+\frac{1}{2}} = a_{k+\frac{1}{2}} + b_{k+\frac{1}{2}} p_s, \quad (3)$$

where $a_{k+\frac{1}{2}}$ and $b_{k+\frac{1}{2}}$ are the ERA5 hybrid-coordinate coefficients and p_s is the surface pressure. Because the uppermost
 290 ERA5 half-level pressure is zero, RTTOVpy assigns it a small positive value obtained by logarithmic extrapolation from the



following two half levels. The resulting pressure boundaries and the corresponding layer temperature and humidity values are then ordered from the top of the atmosphere to the surface.

For WRF input to RTTOV 14, pressure at the staggered layer boundaries is reconstructed from the WRF mass-level pressure and geopotential fields. Full pressure is first calculated from $P + P_B$. Geopotential height at the staggered levels is calculated from $(PH + PH_B)/g$, and mass-level heights are obtained by averaging the adjacent staggered heights. Pressure is then interpolated to the staggered heights linearly in $\ln p$, which better represents the approximately exponential decrease of pressure with altitude than direct linear interpolation. The upper boundary is estimated by logarithmic extrapolation, while the lowest boundary is replaced by the WRF surface pressure. This produces $N + 1$ pressure boundaries for the N WRF temperature and humidity layers.

When WRF-Chem dust processing is enabled, RTTOVpy also constructs an aerosol profile associated with each atmospheric column. The five WRF-Chem dust size bins are mapped to the mineral nucleation, accumulation, and coarse aerosol modes used by RTTOV. Specifically, `DUST_1` is assigned to the mineral nucleation mode, the sum of `DUST_2`, `DUST_3`, and `DUST_4` is assigned to the accumulation mode, and `DUST_5` is assigned to the coarse mode. The remaining RTTOV aerosol categories are set to zero. These aerosol profiles are written separately from the atmospheric profiles and are used only when an aerosol optical-property coefficient file is selected.

3.4 Surface and geometrical inputs

In addition to the vertical atmospheric state, RTTOV requires near-surface meteorological variables, surface characteristics, geographical information, and satellite and solar viewing geometry. RTTOVpy extracts or derives these quantities separately for every atmospheric column and appends them to the corresponding RTTOV profile.

$$q_{2m} = \frac{\epsilon e}{p_s - (1 - \epsilon)e}, \quad (4)$$

where e is the water-vapour partial pressure and $\epsilon = 0.622$ is the ratio of the gas constants for dry air and water vapour. For WRF, in the absence of a directly available 2 m humidity field, RTTOVpy approximates near-surface humidity using the water-vapour value from the lowest model layer. The wind fetch is currently assigned a constant value of 100000 m for all profiles.

Surface temperature is obtained from the ERA5 skin-temperature field or the WRF `TSK` variable. The skin-input record also contains the salinity and the five FASTEM parameters required by the RTTOV example-profile format. RTTOVpy currently assigns a salinity of 35 and FASTEM parameter values of 3, 5, 15, 0.1, and 0.3. These fixed values ensure that the generated profiles remain compatible with RTTOV, although their influence depends on the simulated spectral region, surface category, and emissivity configuration.

The land–water classification is derived from the surface masks provided by the atmospheric dataset and converted to the RTTOV convention, in which 0 denotes land, 1 denotes sea, and 2 denotes sea ice. For ERA5, the fractional land–sea mask is converted to a binary classification using a threshold of 0.5 before being mapped to the RTTOV flag convention. WRF land and water points are classified from the corresponding model surface masks. The water-type flag is currently set to ocean water.



Sea-ice surfaces are not diagnosed separately in the present implementation and therefore require additional preprocessing
when simulations over sea ice are considered.

Surface elevation is expressed in kilometres above mean sea level. For WRF, it is obtained from the model terrain-height field. For ERA5, the surface geopotential is divided by gravitational acceleration and converted to kilometres. The latitude and longitude associated with each grid point are retained without horizontal interpolation, so that every RTTOV profile remains directly associated with its original ERA5 or WRF column.

RTTOVpy determines satellite position either from orbital information or from a user-defined position. For polar-orbiting and other non-geostationary platforms, Two-Line Element data are used to propagate the satellite orbit to the selected simulation time. Recent element sets can be obtained from CelesTrak, while historical element sets can be requested from Space-Track when user credentials are provided. If historical retrieval fails, RTTOVpy can fall back to the corresponding CelesTrak data. Geostationary satellites are represented by their nominal subsatellite longitude, zero latitude, and an altitude of approximately 35 786 km, because their fixed positions do not require TLE-based propagation. A user may alternatively prescribe the satellite latitude and longitude in the configuration file.

For each atmospheric column, the satellite azimuth and elevation are calculated relative to the grid-point location and elevation. The satellite zenith angle is then obtained as 90° minus the elevation angle. Solar zenith and azimuth angles are calculated for the same location and UTC simulation time. These four angles are written to the RTTOV profile and are therefore allowed to vary across the atmospheric-model domain. This is particularly important for wide WRF domains and for polar-orbiting instruments, for which the viewing angle can change substantially between neighbouring parts of the simulated swath.

3.5 RTTOV execution

The RTTOV simulation is controlled through separate YAML configuration files for ERA5 and WRF input. The configuration specifies the RTTOV major version and installation directory, the atmospheric input file or ERA5 acquisition settings, the simulation time, the satellite platform, the coefficient file, the requested RTTOV channel numbers, user-defined channel labels, the treatment of solar radiation, and the optional aerosol and post-processing settings.

Before generating the executable workflow, RTTOVpy checks the consistency of several configuration elements. The selected simulation time must be available in the atmospheric input data, the coefficient file must exist, and the numbers of requested channels and output channel labels must agree. RTTOVpy also compares the selected satellite name with the coefficient-file name and reports a warning when they appear inconsistent. The channel central wavenumbers are read from the RTTOV coefficient file and converted to wavelengths. When one or more selected channels have wavelengths shorter than $4\mu\text{m}$, the solar-radiation option is enabled automatically if it was not already activated by the user.

After the profile files have been created, RTTOVpy generates an executable shell script from a version-specific template. The script is populated with the selected coefficient-file path, RTTOV installation directory, number of atmospheric levels, number and identifiers of the simulated channels, and solar-radiation setting. For aerosol simulations, the aerosol optical-property coefficient file is inserted into the corresponding aerosol-enabled script. The compiler architecture supplied when launching the script must match the architecture with which RTTOV was compiled.



The generated script processes the profiles sequentially. Each profile is linked temporarily into the RTTOV test directory and passed to the RTTOV `example_fwd` executable with one profile per model invocation. The number of vertical levels and requested channels is therefore constant within a simulation, whereas the atmospheric, surface, and geometrical inputs vary among grid points. The current scripts use one execution thread, although RTTOV installations compiled with OpenMP can be configured to use additional threads.

The text output generated by RTTOV is renamed using the identifier of the corresponding atmospheric profile and moved to a dedicated output directory. If an RTTOV invocation terminates unsuccessfully, for example because a profile lies outside the supported zenith-angle range, RTTOVpy writes a missing-value marker instead of a normal RTTOV output file. This ensures that the original profile ordering is retained and that unsuccessful simulations can subsequently be represented as missing grid cells rather than shifting the remaining output values.

RTTOVpy does not alter the RTTOV executable, coefficient files, predictors, optical-depth calculations, or radiative-transfer solver. Its role in this stage is limited to validating the configuration, generating the execution script, supplying the prepared profiles, invoking the selected RTTOV forward model, and organizing the resulting text files.

3.6 Output post-processing

The native output of the RTTOV example forward model consists of one formatted text file for each simulated atmospheric profile. RTTOVpy parses these files and extracts the channel-dependent quantities reported after the `CHANNELS PROCESSED` section. The currently extracted quantities are brightness temperature, calculated radiance, overcast radiance, surface-to-space transmittance, and surface emissivity.

The numerical profile identifiers are used to place the extracted values back into their original horizontal positions. For ERA5, the results are reconstructed on the regular latitude–longitude grid. For WRF, the results are reconstructed on the native two-dimensional model grid using the WRF latitude and longitude coordinates. The channel order in every output product follows the channel list given in the configuration file, while the user-defined channel labels are used as NetCDF variable names. Profiles carrying the missing-value marker are assigned a fill value of -9999 for every requested channel and output quantity.

Each simulated quantity is stored in a separate NetCDF file. Brightness temperatures are expressed in kelvin and radiances in $\text{mW m}^{-2} \text{sr}^{-1} (\text{cm}^{-1})^{-1}$. Transmittance, emissivity, and the currently reported overcast-radiance quantity are stored as dimensionless values. The files contain the geographical coordinates, one variable for each selected satellite channel, descriptive variable attributes, and the fill-value definition. Separating the output quantities into individual files permits users to load only the products required for a particular analysis.

RTTOVpy can additionally generate a georeferenced PNG image for every simulated channel and output quantity. The images are plotted on a latitude–longitude map with coastlines, political boundaries, coordinate labels, and a colour bar showing the corresponding physical units. An optional RGB facility allows mathematical combinations of simulated brightness-temperature channels to be assigned to the red, green, and blue components. This functionality can be used to construct qual-



itative satellite-style composites, although the resulting products should not be interpreted as standardized operational RGB recipes unless the configured channel combinations and normalization reproduce the definition of the relevant satellite product.

For WRF applications, the post-processing workflow may optionally be extended to comparison with observed satellite data. RTTOVpy reads supported satellite products through Satpy (Raspaud et al., 2018), remaps the observations to the WRF grid, and compares the observed and simulated radiances or brightness temperatures. The resulting evaluation products can include the remapped satellite fields, channel-wise statistical measures, tabulated results, and Taylor diagrams. This optional stage does not modify the RTTOV simulation results; it provides a consistent framework for assessing whether the WRF atmospheric state produces satellite-equivalent quantities that agree with the corresponding observations.

4 Applications, verification, and discussion

This section demonstrates the application of RTTOVpy to atmospheric data from ERA5 and WRF. The ERA5-based case is presented as an illustrative application of the complete RTTOVpy workflow, including automatic data acquisition, atmospheric-profile generation, RTTOV execution, and output post-processing. The WRF-based case, described subsequently, is additionally used to evaluate the simulated satellite quantities against corresponding observations. The ERA5 example should therefore be interpreted primarily as a demonstration of the radiative-transfer products that can be generated with RTTOVpy, rather than as an observational verification experiment.

4.1 ERA5-based illustrative simulation

An illustrative Terra MODIS simulation was performed for 12 April 2022 at 12:00 UTC over a domain extending from 45 to 50° N and from 0 to 7° E. ERA5 data were retrieved on their 0.25° horizontal grid, resulting in a domain of 21×29 grid cells and therefore 609 atmospheric profiles. For this example, the satellite position was prescribed by the user at 47.5° N and 3.5° E. The prescribed position was used to construct the viewing geometry over the simulation domain. Consequently, the case is intended to illustrate the RTTOVpy workflow and the spatial variation of simulated radiative-transfer quantities, rather than to reproduce the exact geometry of a particular Terra overpass.

When ERA5 is selected as the atmospheric input source, RTTOVpy automatically downloads the required data according to the date, time, and geographical bounds specified in the configuration file. The user therefore does not need to obtain and preprocess the ERA5 files separately. For the present case, the three-dimensional atmospheric input consisted of air temperature and specific humidity on the 137 ERA5 hybrid model levels. Surface and near-surface fields included surface pressure, 2 m temperature, 2 m dew-point temperature, the 10 m zonal and meridional wind components, skin temperature, land–sea mask, soil type, and surface geopotential.

RTTOVpy combines the ERA5 hybrid-coordinate information with surface pressure to construct the pressure coordinates required by RTTOV. Each ERA5 column was converted into a profile containing 138 pressure half-levels and 137 atmospheric layers, together with the corresponding layer temperature and specific-humidity values. The surface and near-surface ERA5



fields were then used to construct the remaining RTTOV profile variables, including skin temperature, near-surface atmospheric conditions, surface classification, elevation, and viewing geometry.

The RTTOV coefficient file for Terra MODIS, `rtcoef_eos_1_modis_o3co2.dat`, contains coefficients for 36 spectral channels. Two channels with contrasting radiative characteristics were selected for the example. MODIS band 18 has a representative wavelength of $0.936\mu\text{m}$ and is treated as a solar near-infrared channel, whereas MODIS band 27 has a representative wavelength of $6.766\mu\text{m}$ and is a thermal-infrared water-vapour channel. This selection demonstrates that the same RTTOVpy workflow can process both reflected solar radiation and thermally emitted atmospheric radiation.

RTTOVpy reads the spectral metadata from the selected coefficient file and identifies whether solar calculations are required for the requested channels. In the present case, the RTTOV solar option was activated automatically because band 18 is a solar channel, even though solar simulation was not explicitly enabled in the user configuration. For band 18, the most relevant simulated quantities are therefore top-of-atmosphere radiance and bidirectional reflectance factor. For band 27, radiance and brightness temperature provide the more physically meaningful outputs. Because band 27 lies within a strong water-vapour absorption region, its simulated brightness temperature primarily represents emission from the moist atmosphere rather than direct emission from the underlying surface.

The current RTTOVpy release supports clear-sky simulations. Although RTTOV itself provides several cloudy-sky and scattering options, these capabilities have not yet been incorporated into the RTTOVpy workflow. The ERA5 total-cloud-cover field downloaded for this case was therefore not used to perform a cloudy-sky radiative-transfer calculation. The outputs presented here should accordingly be interpreted as clear-sky results. Support for cloud and hydrometeor inputs is planned as a possible extension of future RTTOVpy versions.

Following completion of the RTTOV calculations, RTTOVpy reorganized the profile-based output into two-dimensional fields on the original ERA5 grid. The post-processing procedure generated NetCDF files containing brightness temperature, radiance, surface-to-space transmittance, and surface emissivity, together with corresponding PNG maps for each selected MODIS channel. Additional RTTOV return quantities were also retained where available. This output organization allows the simulated quantities to be inspected immediately as spatial fields while preserving them in analysis-ready NetCDF format for more detailed subsequent evaluation.

Figure 2 shows the simulated brightness temperature for MODIS band 27. The spatial structure reflects variations in atmospheric temperature and water vapour across the domain. Corresponding radiance and reflectance products were generated for band 18, demonstrating the application of RTTOVpy to a solar channel within the same simulation.

This application demonstrates the complete ERA5-based RTTOVpy processing chain, beginning with a compact user configuration and automatic ERA5 data retrieval and ending with spatially structured NetCDF and graphical radiative-transfer products. It also illustrates how channels in different spectral regions can be selected to investigate distinct atmospheric and surface contributions to satellite-observed radiances.

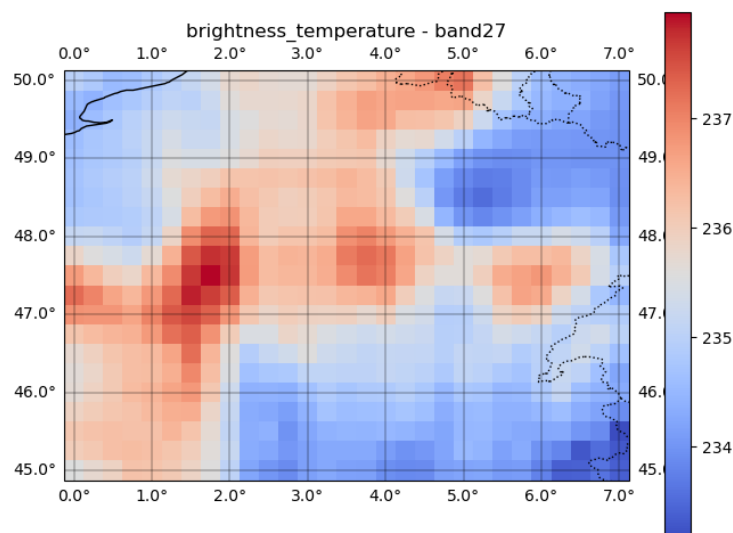


Figure 2. Simulated top-of-atmosphere brightness temperature for Terra MODIS band 27 ($6.766\ \mu\text{m}$) at 12:00 UTC on 12 April 2022. The 21×29 simulation domain extends from 45 to 50°N and from 0 to 7°E . The clear-sky simulation was generated by RTTOVpy from automatically retrieved ERA5 atmospheric and surface data using a user-defined satellite position.

4.2 WRF-based simulation

455 A WRF-based experiment was conducted to demonstrate the application of RTTOVpy to three-dimensional numerical weather prediction output, including mineral-dust fields, and its comparison with satellite observations. Atmospheric and surface inputs were obtained from a WRF-Chem version 4.6.0 simulation over a domain centred near Kuwait. The model employed a Lambert conformal projection with a horizontal grid spacing of 30 km and 62×62 unstaggered horizontal grid points. The atmosphere was represented by 44 vertical layers extending from the surface to approximately 50 hPa. The radiative-transfer calculations
 460 were performed for 12:00 UTC on 16 May 2022.

The WRF-Chem output supplied pressure, temperature, water-vapour mixing ratio, surface pressure, skin and near-surface air temperatures, 10 m wind components, terrain elevation, and land–water classification, together with mineral-dust fields. The experiment used RTTOV v14 and the coefficient file `rtcoef_msg_2_seviri_o3co2.dat` for the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) aboard Meteosat Second Generation (MSG). Three thermal-infrared channels were
 465 selected: channel 7 (IR_087), channel 9 (IR_108), and channel 10 (IR_120). RTTOVpy extracted the WRF-Chem atmospheric columns, prepared the atmospheric, surface, and satellite-viewing inputs, and executed RTTOV for the selected grid points and channels. Hydrometeor scattering was disabled in both configurations; hence, the calculations did not represent cloud radiative effects.

Two otherwise equivalent configurations were examined: a reference calculation without aerosol radiative effects (dust-off)
 470 and a calculation incorporating WRF-Chem mineral-dust profiles into the aerosol treatment (dust-on). The meteorological input fields, satellite channels, simulation time, and satellite-observation comparison procedure were kept the same. This comparison

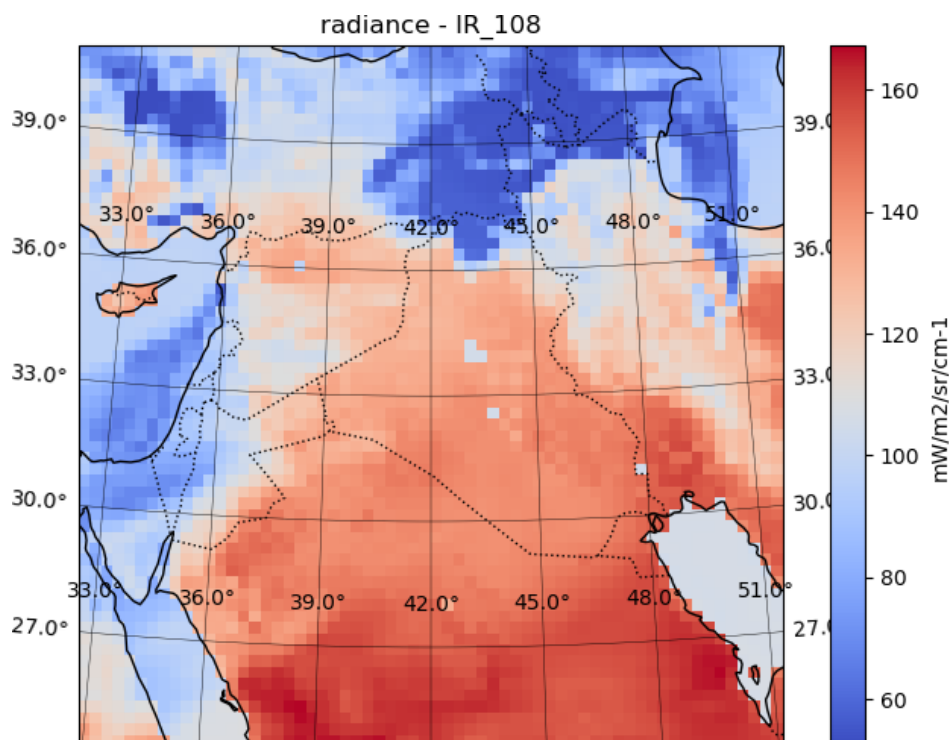


Figure 3. RTTOVpy-simulated MSG SEVIRI IR_108 radiance at 12:00 UTC on 16 May 2022, derived from WRF-Chem atmospheric and surface fields with aerosol radiative effects disabled (dust-off configuration).

was designed to assess the sensitivity of the RTTOVpy outputs to the inclusion of modelled mineral dust, rather than to validate the WRF-Chem dust simulation independently.

4.2.1 Dust-off reference simulation

475 The dust-off experiment excluded aerosol radiative effects. For an example model column at approximately 30.96° N and 40.27° E, RTTOVpy generated a 44-layer atmospheric profile extending from approximately 50 to 927 hPa. The simulated brightness temperatures for IR_087, IR_108, and IR_120 were 314.34, 317.01, and 315.41 K, respectively. The corresponding radiances were 94.60, 142.63, and 157.02 mW m⁻² sr⁻¹ (cm⁻¹)⁻¹, and the surface-to-space transmittances were 0.8556, 0.9263, and 0.8868, respectively. These quantities illustrate the channel-dependent response to the same atmospheric and
 480 surface state.

Following the grid-point radiative-transfer calculations, RTTOVpy assembled the outputs into spatially structured NetCDF products for radiance, brightness temperature, surface-to-space transmittance, surface emissivity, and overcast radiance diagnostics. The software also generated graphical representations of the selected quantities. Figure 3 presents the dust-off IR_108 radiance field as an example of the resulting satellite-like spatial products.



Table 1. Spatial verification statistics for dust-off and dust-on RTTOVpy radiance simulations against collocated MSG SEVIRI observations. R is the spatial correlation coefficient, $\sigma_{\text{sim}}/\sigma_{\text{obs}}$ is the ratio of simulated to observed standard deviations, and CRMSD is the centred root-mean-square difference normalised by the observed standard deviation. All reported quantities are dimensionless.

Channel	Configuration	R	$\sigma_{\text{sim}}/\sigma_{\text{obs}}$	CRMSD
IR_087	Dust-off	0.750	1.053	0.727
	Dust-on	0.724	0.755	0.691
IR_108	Dust-off	0.756	0.913	0.674
	Dust-on	0.745	0.641	0.675
IR_120	Dust-off	0.764	0.852	0.651
	Dust-on	0.749	0.590	0.681

485 For comparison with observations, RTTOVpy read the available MSG SEVIRI data and remapped the observational fields to the WRF horizontal grid. The collocated fields were saved as `msg_to_wrf_IR_087.nc`, `msg_to_wrf_IR_108.nc`, and `msg_to_wrf_IR_120.nc`. These files support subsequent spatial-difference analyses, regional selections, and user-defined verification statistics. The dust-off evaluation provided the reference against which the dust-on results were compared (Fig. 5; Table 1).

490 4.2.2 Dust-on simulation and comparison with observations

A second RTTOVpy experiment was performed with mineral-dust radiative effects enabled, using the dust profiles derived from the same WRF-Chem output. Figure 4 displays the modelled total dust mass mixing ratio at 850 hPa for the radiative-transfer simulation time. The field shows a heterogeneous distribution, with pronounced maxima over parts of Iraq and surrounding areas and substantially lower values elsewhere in the domain. This pattern provides context for the aerosol-sensitive radiative-transfer calculation, although the 850 hPa field represents only one level of the three-dimensional dust distribution supplied to RTTOVpy. Consequently, the spatial magnitude of the dust-induced radiance response cannot be inferred directly from this map alone.

The dust-on simulation was evaluated against the same MSG SEVIRI observational fields remapped to the WRF grid. Figures 5 and 6 show the Taylor diagrams for the two configurations. In addition to spatial correlation, these diagrams characterise the simulated-to-observed standard-deviation ratio and the normalised centred root-mean-square difference (CRMSD). The standard-deviation ratio measures the simulated spatial variability relative to the observed variability, with a value of unity indicating equal standard deviations. The normalised CRMSD quantifies differences in the spatial anomalies after removal of their respective means; it is therefore distinct from an uncentred RMSE or a mean radiance bias.

The statistics in Table 1 reveal a channel-dependent response to the inclusion of mineral dust. For IR_087, the normalised CRMSD decreased from 0.727 to 0.691, a reduction of approximately 5%. In contrast, the CRMSD was nearly unchanged for IR_108 (0.674 versus 0.675) and increased for IR_120 (0.651 to 0.681). The spatial correlations decreased in all three

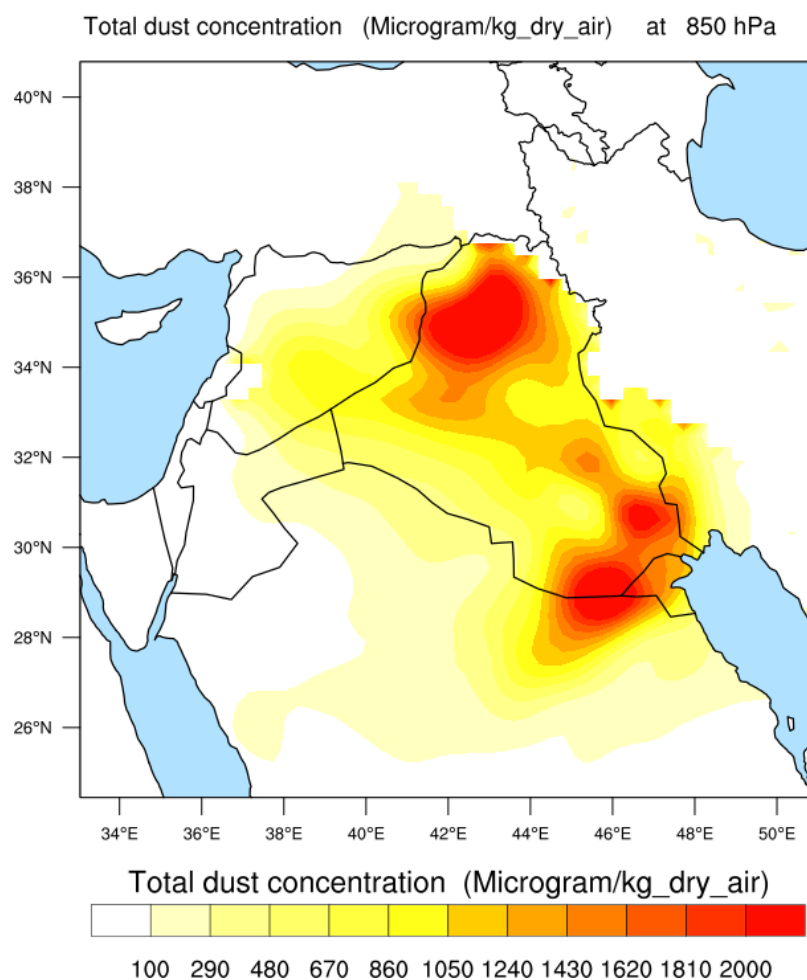


Figure 4. WRF-Chem total mineral-dust mass mixing ratio at 850 hPa ($\mu\text{g kg}^{-1}$ of dry air), valid at 12:00 UTC on 16 May 2022. The map illustrates the spatially varying dust field available to the RTTOVpy dust-on simulation.

channels, from 0.750 to 0.724, 0.756 to 0.745, and 0.764 to 0.749, respectively. Thus, the inclusion of dust did not produce a consistent improvement across the evaluated channels and statistics.

A larger change occurred in the simulated spatial variability. The simulated-to-observed standard-deviation ratios decreased from 1.053 to 0.755 for IR_087, from 0.913 to 0.641 for IR_108, and from 0.852 to 0.590 for IR_120. In the dust-on configuration, the simulated radiances therefore exhibited lower spatial standard deviations than the observations in all three channels. Although the dust-on calculation improved the normalised CRMSD for IR_087, this result did not coincide with improved spatial correlation or agreement in spatial variability. The contrasting responses highlight why several complementary metrics are needed to assess the effect of the aerosol treatment.

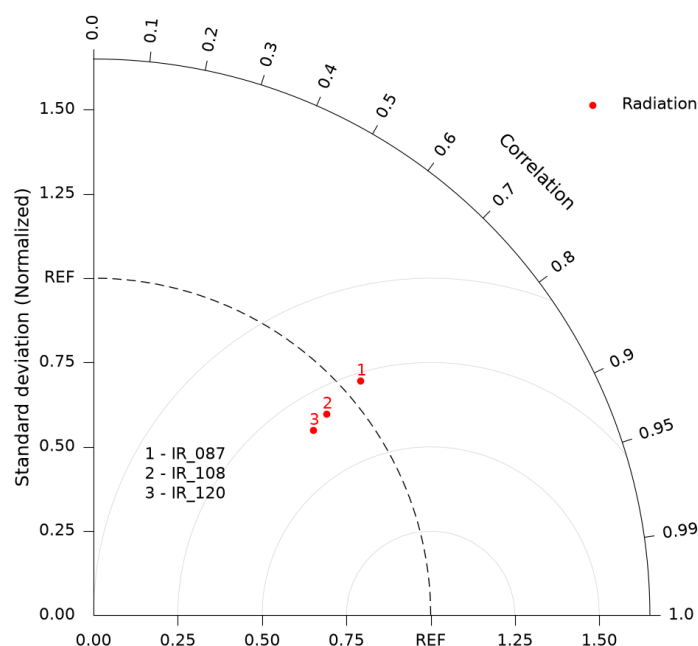


Figure 5. Taylor diagram comparing the dust-off RTTOVpy radiances with colocated MSG SEVIRI observations for the IR_087, IR_108, and IR_120 channels. Standard deviations and centred root-mean-square differences are normalised by the observational standard deviation.

515 The heterogeneous dust distribution in Fig. 4 also indicates that interpretation of domain-wide statistics requires care. Errors in the simulated location, magnitude, or vertical distribution of dust may influence satellite-radiance agreement. Potential sources of uncertainty in WRF-Chem include the specification of dust emission source functions, meteorological forcing, dust transport, and removal processes. These mechanisms offer plausible explanations for discrepancies, but the present experiments do not isolate or quantify their individual contributions. Other limitations include the omission of cloud radiative effects
 520 despite the possible presence of clouds in the observations, uncertainties in surface temperature and emissivity, satellite-model temporal matching, and the remapping of satellite observations onto the coarser model grid.

The results should therefore be viewed primarily as a demonstration of RTTOVpy's ability to incorporate WRF-Chem dust profiles and to compare alternative radiative-transfer configurations with satellite observations. The dust-on experiment produces measurable changes in the radiance-field statistics, particularly in spatial variability, but the present evaluation does not
 525 establish an overall improvement in agreement with MSG SEVIRI observations. A more conclusive assessment of dust-related simulation skill would require additional case studies and analyses stratified by dust loading, together with independent constraints on aerosol abundance and cloud conditions. Nevertheless, the experiment illustrates the integrated RTTOVpy workflow

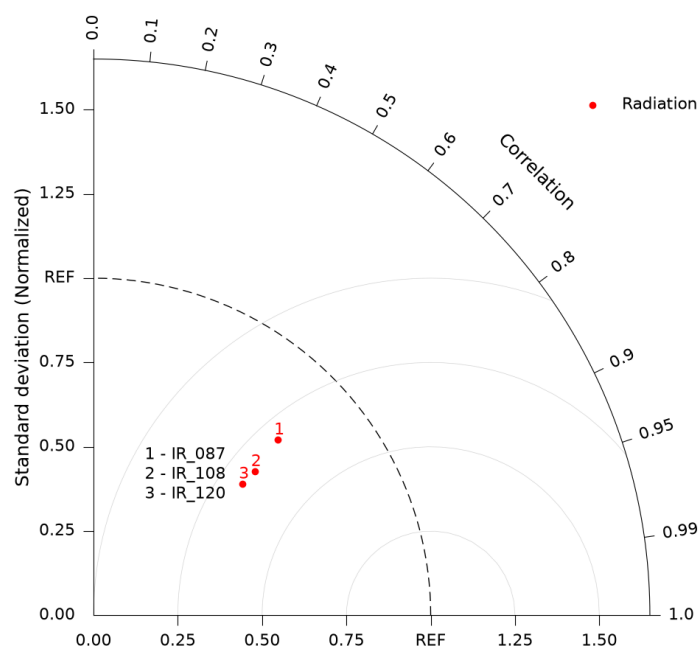


Figure 6. As in Fig. 5, but for RTTOVpy simulations incorporating mineral-dust radiative effects (dust-on configuration).

for generating satellite-channel radiances, writing analysis-ready NetCDF products, collocating observations, and performing quantitative intercomparisons.

530 4.3 Future development

The current version of RTTOVpy is primarily designed for clear-sky radiative-transfer simulations. Although RTTOV itself provides dedicated capabilities for cloudy-sky calculations, these options are not yet exposed through the RTTOVpy workflow. This limitation is particularly relevant for comparisons with satellite observations because clouds strongly affect measured radiances across infrared, microwave, and solar-reflective channels. The present application examples therefore either rely
 535 on clear-sky conditions or require cloud-contaminated observations to be excluded during the comparison procedure. Consequently, the simulated satellite fields should not be interpreted as complete representations of all observed scenes.

Adding cloudy-sky radiative-transfer capability is therefore a major priority for future development. Such an extension would require the extraction and conversion of cloud-related variables from ERA5 and WRF outputs into the cloud inputs required by RTTOV. Depending on the selected RTTOV configuration, these inputs may include cloud fraction, cloud liquid-
 540 water content, cloud ice-water content, and information describing the vertical distribution of clouds. Integrating these variables into RTTOVpy would allow simulations of both clear and cloudy atmospheric columns and would improve the applicability



of the software to realistic satellite-scene reconstruction, numerical-weather-prediction evaluation, and radiance-based model assessment.

The current WRF-Chem interface is also limited to mineral-dust profiles. This functionality enables the influence of simulated dust particles on radiances and brightness temperatures to be investigated, but other aerosol species represented by atmospheric-chemistry models are not yet supported by RTTOVpy. Future extensions could introduce more general mappings between WRF-Chem aerosol variables and the aerosol optical-property configurations available within RTTOV. Such development would broaden the use of RTTOVpy for studying smoke, sea salt, sulfate, and other aerosol types, provided that the required optical properties and compatible RTTOV input configurations are available.

A further limitation concerns observational verification. RTTOVpy uses external libraries, particularly Satpy, to read and process satellite observations when suitable readers are available. However, not all satellite instruments supported by RTTOV are supported by Satpy. For example, dedicated Satpy readers are not currently available for some hyperspectral instruments, including AIRS and CrIS. Verification of simulations for these sensors therefore requires instrument-specific preprocessing workflows or additional reader implementations. This limitation does not affect the forward RTTOV simulations themselves, but it reduces the degree to which a common observational-verification workflow can presently be applied across all supported instruments.

More generally, agreement between simulated and observed radiances depends not only on RTTOVpy but also on the accuracy of the atmospheric input data and on the spatial, temporal, spectral, and geometrical matching between simulations and observations. Differences in model resolution, satellite footprint size, observation time, viewing geometry, cloud screening, and unresolved atmospheric variability may all contribute to discrepancies. The verification presented in this study should therefore be regarded as an evaluation of the complete modelling and comparison workflow rather than as an isolated test of the RTTOV radiative-transfer calculations.

Future RTTOVpy development will consequently focus on cloudy-sky simulations, broader aerosol support, and additional observational readers and preprocessing workflows. These extensions would enable the software to represent a wider range of atmospheric conditions and satellite instruments while retaining the configuration-driven workflow demonstrated in the present study.

5 Conclusions

This study introduced RTTOVpy, a Python-based application developed to automate the preparation, execution, and post-processing of radiative-transfer simulations with RTTOV. The software connects multidimensional atmospheric datasets with the profile-based input structure required by RTTOV and provides a configuration-driven workflow for generating atmospheric, surface, and geometrical inputs, executing the selected simulations, and reorganizing the results into structured NetCDF products and satellite-like visualizations.

RTTOVpy currently supports atmospheric input from ERA5 reanalysis and WRF model output, enabling the same general workflow to be applied to both global gridded datasets and regional numerical simulations. The software can simulate channels



575 from different satellite platforms and spectral regions when suitable RTTOV coefficient files are available, including solar-reflective and thermal-infrared channels. It also provides an interface for incorporating mineral-dust profiles from WRF-Chem simulations into aerosol-aware radiative-transfer calculations.

The ERA5-based example demonstrated the use of RTTOVpy for preparing atmospheric profiles and producing spatially distributed radiance and brightness-temperature fields from reanalysis data. The WRF-based application further demonstrated the generation of synthetic satellite products from regional model output and their comparison with corresponding satellite observations. The statistical evaluation and Taylor-diagram analysis showed that RTTOVpy can support model-to-observation comparisons while preserving the spatial structure of the simulated satellite fields. Differences between simulations and observations nevertheless reflect the combined influence of atmospheric-model uncertainty, surface conditions, cloud screening, observation geometry, spatial and temporal matching, and the assumptions used in the radiative-transfer configuration.

585 By integrating data preparation, RTTOV execution, output processing, and visualization within a unified Python workflow, RTTOVpy reduces the amount of instrument-specific and repetitive processing normally required to apply RTTOV to atmospheric model and reanalysis datasets. The configuration files and documented application examples also facilitate the reproducibility and adaptation of simulations for different datasets, instruments, channels, and study regions.

The current implementation is primarily limited to clear-sky simulations, and the WRF-Chem interface presently supports mineral dust only. In addition, observational verification for instruments not supported by general-purpose satellite-reading libraries requires dedicated preprocessing workflows. Future development will therefore focus particularly on cloudy-sky radiative-transfer simulations, broader aerosol support, and additional interfaces for reading and comparing satellite observations. These developments would further extend the applicability of RTTOVpy to satellite simulator generation, numerical-model evaluation, atmospheric-composition studies, data assimilation support, and the production of synthetic datasets for emerging data-driven applications.

Code availability. The current development version of RTTOVpy is publicly available from GitHub at <https://github.com/anikfal/rttovpy> under the MIT License. The version of RTTOVpy used to produce the results presented in this study, including the associated configuration files and example workflows, is archived on Zenodo at <https://doi.org/10.5281/zenodo.21298079>. RTTOV and its coefficient files are distributed separately by the EUMETSAT Numerical Weather Prediction Satellite Application Facility (NWP SAF) and are therefore not included in the RTTOVpy archive.

Video supplement. Video tutorials demonstrating the installation, configuration, and application of RTTOVpy are available in the YouTube playlist at <https://youtube.com/playlist?list=PL93HaRiv5QkAL-EzzCXIKaAfkclWuYyyH>.

Author contributions. AN conceptualized the study, designed and developed the RTTOVpy software, developed the methodology, performed the simulations and verification, analysed and visualized the results, and wrote and revised the manuscript.



605 *Competing interests.* The author declares that there are no competing interests.

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