

Comparing SRFM and RTTOV Radiance Simulations to Assess Biases in Forward Modelling of Volcanic Ash

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Abstract

This study investigated the biases present in the forward modelling of volcanic ash in the parametric model Radiative Transfer for TOVS (RTTOV v13) by comparing its top of atmosphere radiances with those simulated by the Scattering Reference Forward Model (SRFM). The project aimed to understand the limitations in forward models for volcanic ash to improve the accuracy of satellite retrieval algorithms. RTTOV generated radiances for Spinning Enhanced Visible and Infrared Imager (SEVIRI) channels centred at $8.7\ \mu\text{m}$, $10.8\ \mu\text{m}$, $12\ \mu\text{m}$ and $13.4\ \mu\text{m}$ for varying ash property combinations and atmospheric profiles. For each channel, equivalent band averaged radiances were simulated by SRFM and compared with RTTOV. Comparing SRFM and RTTOV clear sky (ash-free) datasets, discrepancies between the models were found to be grouped by channel, with Channel 11 producing the largest discrepancy (mean % bias 6.8843). In the comparison of the ash datasets, clear trends were identified. The relative difference in radiance between the models was found to be correlated to mass loading, with discrepancies increasing as mass loading increased.

1 Introduction

Accurate representation of volcanic ash in the atmosphere is essential for climate studies and operational forecasting. It is particularly important in aviation, where ash represents a sig-

nificant hazard, since ash particles at flight altitudes can be ingested into jet engines leading to potential damage and risks of engine failure [1].

While satellite radiance measurements are crucial tools to quantify ash in the atmosphere, their interpretation relies on forward models which simulate the interaction of outgoing radiation with atmospheric constituents. Various approaches are employed in the forward modelling of radiative transfer. RTTOV is an operational radiative transfer band model widely used for satellite retrieval which provides fast parametrised calculations. It simulates top of atmosphere radiances for passive visible, infrared and microwave downward-viewing satellite instruments. While they are operationally efficient, the parametrisation used for atmospheric transmittances of fast radiative transfer models like RTTOV is a dominant source of errors. These include biases in regression technique, unrepresentative training set, insufficient layer quantisation and surface emissivity parametrisation [2]. Conversely, LBL models such as the SRFM perform accurate radiance and atmospheric transmittance computations at very high spectral resolution [3] providing a more detailed physical treatment of scattering, clouds, ash, and aerosols. They are however too computationally expensive to be used in a Numerical Weather Prediction (NWP) operational environment. Understanding the limitations of each approach is essential to improve the accuracy of satellite retrieval algorithms.

Saint et al. [4] quantified biases present in satellite volcanic ash retrievals using satellite

data to verify dispersion model ash forecasts. They demonstrated the value in using simulated satellite imagery to assess the performance of a retrieval algorithm with a known truth. This project follows a similar approach, taking a line-by-line model as a known truth to investigate biases in a parametrised model and in this way improve the accuracy of retrieval algorithms. For this, we aim to compare top of atmosphere radiance simulated by RTTOV and SRFM to identify systematic differences between the datasets and determine the origin of the biases. We will simulate radiances for various combinations of ash properties, focusing on the performance of the models under extreme scenarios, specifically high ash mass loading, where model discrepancies are expected to be pronounced.

2 Method

2.1 Generating top-of-atmosphere radiance datasets

Top of atmosphere SRFM and RTTOV radiance datasets were generated using atmospheric compositions from 101 2016 ECMWF profile levels. Temperature, pressure and humidity profiles come from ECMWF 137-level short-range forecasts. All other gases were interpolated to the pressure grid. 10 different atmospheric profiles were generated in this way for the comparison between the models. Spectroscopic data for each gas was obtained using HITRAN 2024 [5].

Radiance spectra were simulated for each profile for a clear sky atmosphere (no ash layer) with a spectral resolution of 0.001 cm^{-1} . The simulations were repeated for an atmosphere containing an ash layer, with varying properties displayed in Table 1. Simulations were produced for varying mass loading, and cloud top altitude/layer thickness. Note that layer thickness is specific to each cloud top altitude, with layer thickness increasing with altitude. Table 2 displays additional ash properties fixed across all simulations. This array of values was selected with the intent of comparing the ash

modelling of SRFM and RTTOV to identify the limits of the sensitivity to each variable. A large range of mass loadings was selected to examine each model's performance in extreme scenarios, testing the models' sensitivity to very low mass loading as well as values at which saturation is reached with high opacity across the spectrum. This is particularly important to examine differences in the saturation threshold of every channel. Cloud top altitudes were selected around the tropopause and in the stratosphere to ensure sufficient visibility from the satellite. Meanwhile, an ash number median radius of $0.62 \mu\text{m}$ was selected because the scattering processes that occur at these particle sizes are more complex. SRFM is hypothesised to better represent these complex scattering processes, suggesting that if discrepancies appear, RTTOV may exhibit important biases in its simulated radiances that should be considered.

RTTOV modelled columns of ash through the atmosphere by inserting ash into specific levels with number concentrations such that the column mass loading was set at the values in Table 3. As RTTOV requires number concentration to be simulated, it was calculated from mass density and mean mass per particle, assuming spherical particles [4]. On the other hand, ash mass loading is an input of the SRFM, and corresponding number densities n were computed to check against the inputted RTTOV number densities using the following:

$$n = \frac{3m}{4\pi\rho \text{ } l r^3 \exp\left[\frac{9}{2}(\ln s)^2\right]} \times 10^6 \quad (1)$$

An important distinction between the datasets is that SRFM uses a lognormal distribution in terms of number, while RTTOV uses a lognormal distribution in terms of volume (or mass). This means that SRFM simulations use an ash median *number* radius while RTTOV simulations use an ash mean *volume* radius, with values shown in Table 2. The following expression was used to convert between the two radii: $r_n = r_V \exp(3 \ln^2 s)$. While column mass loadings were set to be identical for both simula-

Column mass loading m (g m ⁻²)	0.5	7	20	50
Layer index	70	80	-	-
Cloud top altitude h (km)	13.727	16.999	-	-
Layer thickness l (km)	0.312	0.339	-	-

Table 1: Varied ash cloud properties. Note each layer is given an index with corresponding cloud top altitude and layer thickness in the rows beneath.

SRFM ash median number radius r_n (μm)	0.62
RTTOV ash mean volume radius r_V (μm)	1.93
Particle density ρ (kg m ⁻³)	2300
Particle refractive indices	Andesite indices [6]
Distribution type	Lognormal
Distribution spread s	1.85

Table 2: Fixed ash cloud properties.

tions, number density concentrations used by SRFM and RTTOV differ slightly, as shown in Table 3. This is likely due to a limited amount of significant figures used for the value of r_V when computing RTTOV number density.

2.2 Processing SRFM and RTTOV radiance simulations

While line-by-line models output radiances for each spectral wavenumber, band models produce single radiance values for discrete spectral bands, corresponding to wavenumber channels in which satellite instruments measure radiation. In order to have a valid comparison, the SRFM radiance spectra were treated in such a way as to give equivalent radiances for channels 7, 9, 10, 11 of the MSG-3 SEVIRI instrument in RTTOV, centred around the wavelengths shown in Table 4. Channels 7, 9, 10 are located within infrared atmospheric windows, in which the satellite measures thermal radiation emitted by the surface or clouds. Channel 11 lies on the edge of the CO_2 absorption band, and is mostly sensitive to radiation

Ch. 7	Ch. 9	Ch. 10	Ch. 11
8.7 μm	10.8 μm	12 μm	13.4 μm

Table 4: MSG-3 SEVIRI channels and their corresponding central wavelengths.

from 900 - 800 hPa [7]. SRFM spectra were convolved with MSG-3 SEVIRI instrument response function for the four channels, applying appropriate weights to each wavenumber to reproduce the signal that would be measured by the SEVIRI instrument. Weighted channel averaged radiances were computed for each channel by integrating over wavenumber interval dv : $\frac{\int B(v,T)Rdv}{\int Rdv}$, where $B(v,T)$ is radiance and R spectral response function coefficient. For illustration, Figure 1 displays a radiance spectrum with the convolved radiance spectrum, highlighting the four SEVIRI channels. The corresponding weighted channel averaged radiances are also displayed.

The RTTOV dataset was converted from brightness temperature to radiance applying Planck’s radiation law to band corrected

Column mass loading m (g m ⁻²)	0.5	7	20	50
Number density SRFM n (cm ⁻³)	127.1	1779.6	5084.7	12711.7
Number density RTTOV n (cm ⁻³)	126.8	1775.6	5073.1	12682.7

Table 3: SRFM vs RTTOV number density for each mass loading, at layer 70.

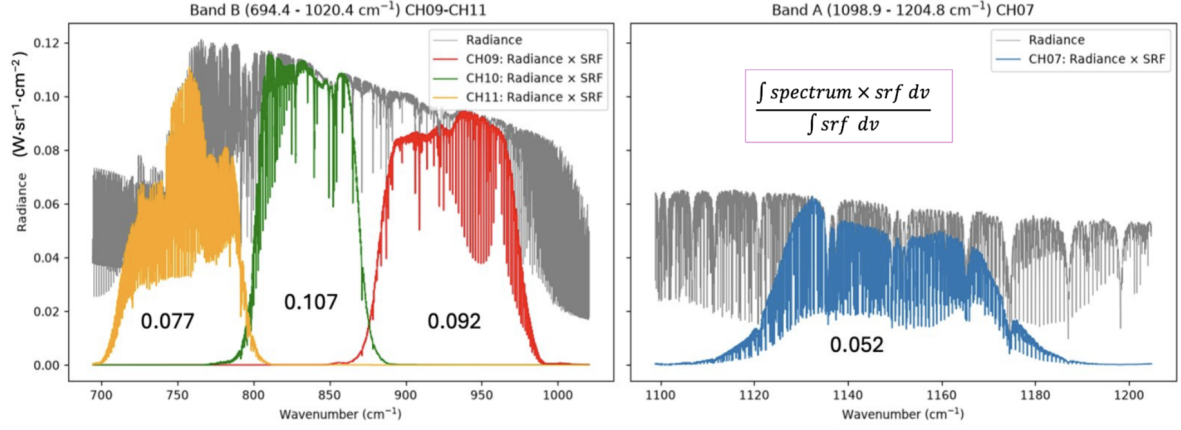


Figure 1: SRFM radiance spectrum in range $694.4\text{--}1204\text{ cm}^{-1}$ (grey) displayed along radiance spectrum convolved with MSG-3 SEVIRI instrument response functions for channels 7,9,10,11, with weighted channel averaged radiances $0.052, 0.092, 0.107, 0.077\text{ Wm}^{-2}\text{sr}^{-1}(\text{cm}^{-1})^{-1}$ respectively.

	Ch. 7	Ch. 9	Ch. 10	Ch. 11
central wavenumber ν	0.1147372612E+04	0.9270688810E+03	0.8368734588E+03	0.7481686747E+03
offset coeff. a	0.8439648226E-01	0.1448128235	0.3209138358E-01	-0.5612228281E-01
scale factor coeff. b	0.9995983065	0.9988828246	0.9994537860	0.9995570938

Table 5: MSG-3 SEVIRI RTTOV band correction coefficients.

brightness temperatures. Band correction is used when applying the Planck function for satellite channels with finite spectral bandwidth. The following band correction is applied to the RTTOV brightness temperatures, where a and b are offset and scale factor coefficients corresponding to each central wavenumber ν , as displayed in Table 5: $T_{corrected} = a + bT$. Radiances are then obtained applying Planck’s function to the band corrected brightness temperatures:

$$B(\nu, T_{corrected}) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(\frac{h\nu}{k_B T_{corrected}})}$$

3 Results

3.1 Clear Sky (ash-free) Datasets Comparison

In order to identify biases in the models due to the modelling of volcanic ash, it is necessary to take into account any discrepancies appearing without an ash layer. We can then differenti-

ate these from biases due to the ash modelling alone. For 10 atmospheric profiles, SRFM weighted channel averaged radiances were compared to RTTOV channel radiances, for MSG-3 SEVIRI channels 7, 9, 10, 11. Figures 2 and 3 compare absolute radiances and percentage differences between SRFM and RTTOV simulated radiances, with the datapoints being color-coded according to channel. Figures 4 and 5 show the same plots color-coded according to atmospheric profile instead. Table 6 presents the bias, standard deviation of difference σ and RMSE for each channel, averaged across the 10 profiles.

The RFM LBL model was used to simulate radiance datasets for profile 7 (polar region), offering an independent verification of the accuracy of the SRFM. The two models were first compared independently, as shown on Figure 6, to match the RFM to the SRFM as closely as possible. Table 8 displays weighted channel averaged differences between RFM and SRFM for channels 7, 9, 10, 11. Weighted channel

	Ch. 7	Ch. 9	Ch. 10	Ch. 11
Mean Bias	0.001106	-0.002581	-0.004392	0.005006
Mean % Bias	2.2615	-2.6091	-4.4361	6.8843
σ	0.000509	0.002231	0.002264	0.001624
RMSE	0.001218	0.003412	0.004941	0.005263

Table 6: Mean bias, standard deviation of difference and RMSE for the clear-sky comparison of top-of-atmosphere radiances simulated by SRFM and RTTOV.

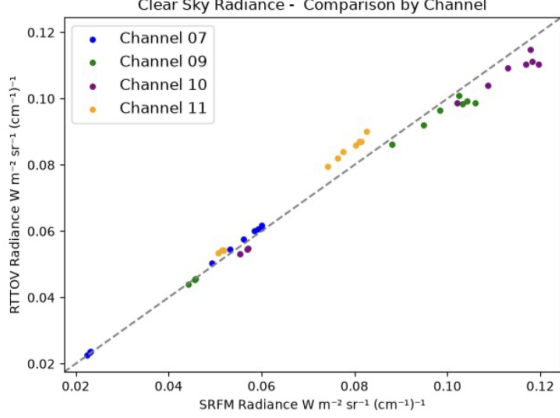


Figure 2: Comparison by channel of top-of-atmosphere radiances simulated by RTTOV and SRFM for a clear-sky scenario across 10 atmospheric profiles. Channels 7, 9, 10, and 11 are shown. The dashed $x = y$ line indicates where the SRFM and RTTOV radiances are equal.

averaged RFM radiances were then computed for each channel. These are displayed in Table 9. Table 10 compares weighted channel-averaged radiances for channel 7 across RFM, SRFM and RTTOV.

	Ch. 7	Ch. 9	Ch. 10	Ch. 11
Mean Bias	0.001294	-0.000158	-0.001845	0.002779
Mean % Bias	4.0054	-4.7763	-8.3124	4.3535
σ	0.005071	0.006821	0.008372	0.006216
RMSE	0.005234	0.006823	0.008573	0.006809

Table 7: Mean bias, standard deviation of difference and RMSE for the clear-sky comparison of top-of-atmosphere radiances simulated by SRFM and RTTOV.

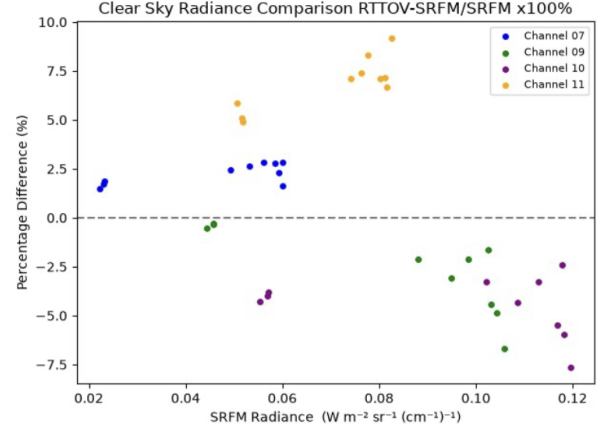


Figure 3: Percentage difference $RTTOV - SRFM/SRFM$ between SRFM and RTTOV, with $x = 0$ indicating where SRFM and RTTOV radiances are equal. Positive percentages values on the y-axis are where RTTOV predicts larger radiances than SRFM, and vice-versa for negative values.

Ch.7	Ch.9	Ch.10	Ch.11
0.00124	0.00057	0.00049	0.0070

Table 8: Weighted channel-averaged differences between RFM and SRFM radiances for channels 7, 9, 10, and 11.

3.2 Ash Layer Datasets Comparison

Figure 7 displays the radiances simulated by SRFM and RTTOV introducing an ash cloud in the atmosphere, across 10 profiles, four SEVIRI channels and 8 combinations of ash properties (mass loadings, cloud top altitudes and ash median radius listed in Tables 1 and 2). Figure 8 shows percentage difference $\frac{RTTOV-SRFM}{SRFM} \times 100\%$ as a function of SRFM radiance. Table 11 shows mean bias, mean

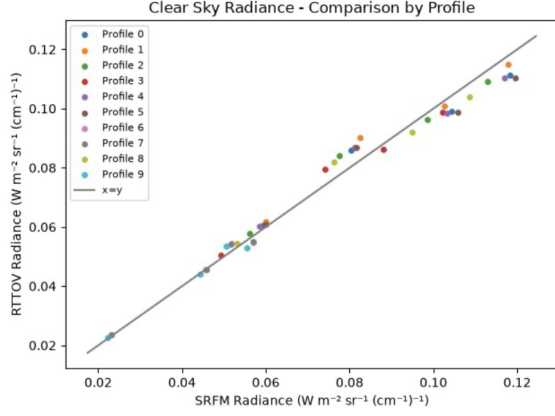


Figure 4: Comparison by profile of top-of-atmosphere radiances simulated by RTTOV and SRFM for a clear-sky scenario across 10 atmospheric profiles. Channels 7, 9, 10, and 11 are shown. The dashed $x = y$ line indicates where the SRFM and RTTOV radiances are equal.

Ch.7	Ch.9	Ch.10	Ch.11
0.02440	0.04635	0.05756	0.05855

Table 9: Weighted channel-averaged radiances for profile 7 for channels 7, 9, 10, 11.

% bias, standard deviation of difference and RMSE for the ash radiance comparison.

To investigate whether the systematic differences between the models could be attributed to a particular ash property, the percentage difference in the simulated radiances was plotted against mass loading, for a fixed altitude and channel. This is displayed in Figure 9, with panels (a) and (b) representing ash layers with cloud top altitudes 13.727 km and 16.999 km respectively. In these plots, profile 5 is omitted due to the extreme discrepancies it showed in Figure 8. (Figure 11 in 7 *Appendix* includes all

	SRFM	RFM	RTTOV
Ch.7	0.02315	0.02440	0.02359

Table 10: Weighted channel-averaged radiances for profile 7, channel 7, for the RFM, SRFM, RTTOV models.

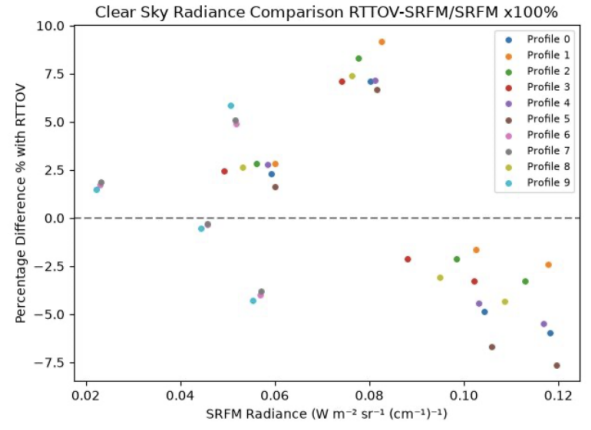


Figure 5: Percentage difference $RTTOV - SRFM/SRFM$ between SRFM and RTTOV, with $x = 0$ indicating where SRFM and RTTOV radiances are equal. Positive percentages values on the y-axis are where RTTOV predicts larger radiances than SRFM, and vice-versa for negative values.

	Ch. 7	Ch. 9	Ch. 10	Ch. 11
Mean Bias	0.001294	-0.000158	-0.001845	0.002779
Mean % Bias	4.0054	-4.7763	-8.3124	4.3535
σ	0.005071	0.006821	0.008372	0.006216
RMSE	0.005234	0.006823	0.008573	0.006809

Table 11: Mean bias, standard deviation of difference and RMSE for the clear-sky comparison of top-of-atmosphere radiances simulated by SRFM and RTTOV.

profiles.) Finally, Figure 10 shows percentage difference averaged across all profiles (excluding profile 5).

4 Discussion

4.1 Comparison of RTTOV and SRFM radiance simulations for a clear sky (ash-free) atmosphere

Comparing the clear sky SRFM and RTTOV datasets, Figure 2 shows a consistent linear relationship along the $x = y$ line across all profiles and channels. This indicates both models produce consistent radiances for the ash-free scenario, although minor discrepan-

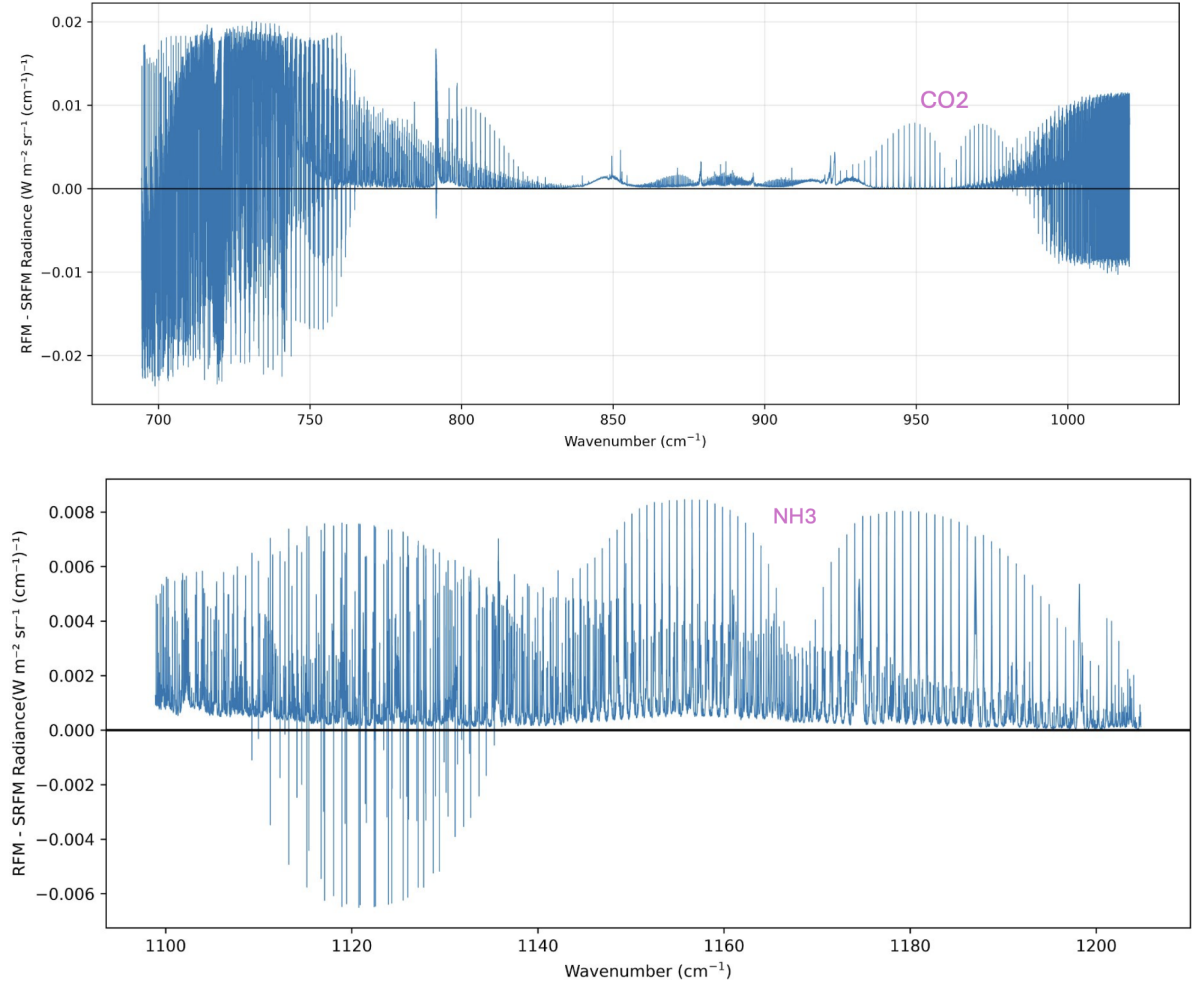


Figure 6: RFM–SRFM radiance difference in top-of-atmosphere radiance simulation for polar profile (7).

cies remain. The relative percentage difference between both models allows us to examine them. Considering Figure 5, no profile-dependent trends seem to appear. On the other hand, Figure 3 shows that discrepancies between the models are grouped by channels, with RTTOV overestimating radiances in channels 7 and 11, and underestimating radiance in channels 9 and 10, taking SRFM as the reference. Channel 7 shows least discrepancy, with an average positive bias of 0.001106 or 2.2615 % (as shown in Table 6). Channel 7 shows least spread across profiles, having a standard deviation of difference one order of magnitude smaller than Channels 9, 10, 11, and smallest RMSE value. This means

that for Channel 7, we can reasonably apply this bias as a correction in the comparison between ash datasets, allowing us to remove the effect of the clear sky bias in the comparison. Figure 3, along with Table 6, shows that mean percentage bias (absolute value) increases from Channel 7 to 11, with Channel 11 displaying the largest mean percentage bias of +6.8843%. Channels 9 and 10 show standard deviation values identical up to 4 significant figures, with Channel 9 showing less discrepancy having a mean percentage bias $\sim 2\%$ smaller. Figure 3 shows that their percentage differences across the 10 profiles form a similar pattern, with Channel 10 datapoints translated in the negative y-direction and positive

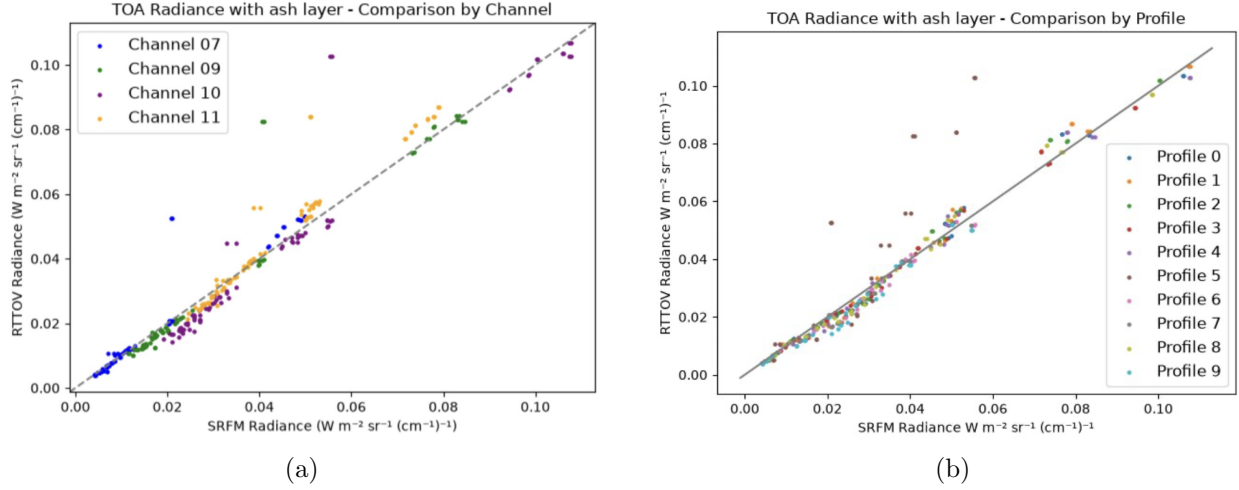


Figure 7: Comparison of top-of-atmosphere radiances simulated by RTTOV and SRFM for an atmosphere with an ash layer across 10 atmospheric profiles. Channels 7, 9, 10, and 11 are shown. The dashed $x = y$ line indicates where the SRFM and RTTOV radiances are equal. Panels (a) and (b) show data points colour-coded by channel and profile respectively.

x-direction relative to Channel 9 datapoints. This is likely due to both channels being located in the same infrared atmospheric window, which means there is less variability in the nature of their measurement. This reinforces the fact that discrepancy clearly depends on channel type, with channels that correspond to wavenumber bands close to each other showing similar behaviour in their discrepancy between RTTOV and SRFM. RMSE increases from channel 7 to 11. Taking the SRFM as the reference, this reflects that RTTOV likely produces most accurate clear sky simulations for radiance in the second infrared window (centred around $9\ \mu\text{m}$), with least accuracy for radiance in the CO_2 absorption band. Finally, clear sky discrepancies may also be attributed to a different treatment of the surface by each model. While the SRFM treats the surface as a Lambertian reflector, RTTOV treats the surface as a specular reflector. For further comparisons, it is therefore essential to have the same treatment of the surface in both models.

4.2 Comparing SRFM and RFM radiance simulation for a single clear sky profile

SRFM and RFM models were compared independently over wavenumber range $700\text{--}1200\ \text{cm}^{-1}$ to determine any spectroscopic differences and account for these in the comparison with RTTOV. The largest difference between the models appears in channel 11, with a weighted channel-averaged difference of 0.0070 , as shown in Table 7. Analysing gas signatures in Figure 6 RFM-SRFM spectrum, we can identify NH_3 signature in Channel 11 wavenumber band, with RFM seemingly neglecting NH_3 absorption. We can also identify a CO_2 signature in region $930\text{--}980\ \text{cm}^{-1}$ (corresponding to Channel 10). These differences between RFM and SRFM are likely due to the varying levels of complexity used to model these gases in these specific RFM/SRFM simulations. Table 9 shows that SRFM simulated radiance is closer to RTTOV (absolute difference = 0.00044) for profile 7, channel 7, than the RFM (absolute difference = 0.00081).

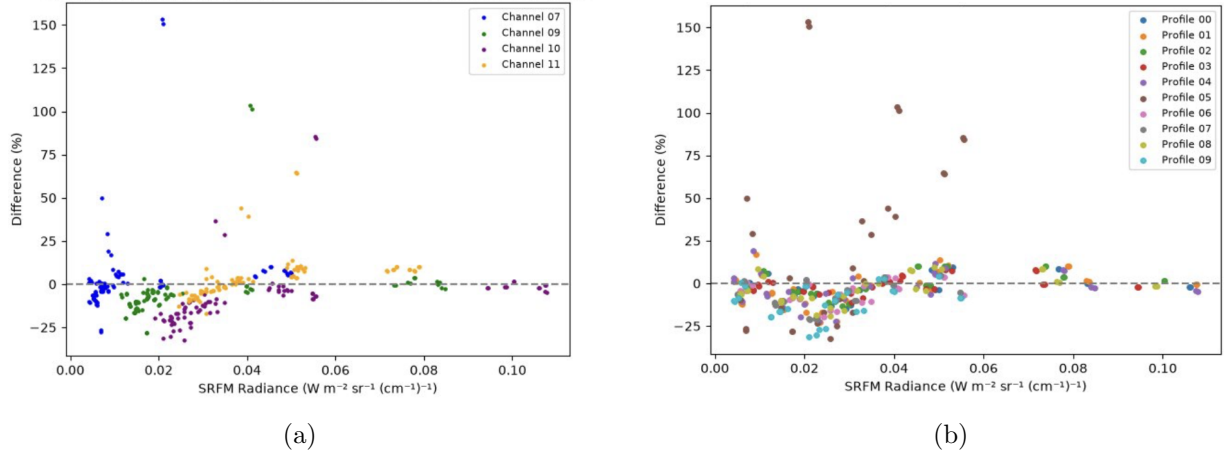


Figure 8: Percentage difference $RTTOV - SRFM / SRFM$ between SRFM and RTTOV for an atmosphere with an ash layer across 10 atmospheric profiles. Channels 7, 9, 10, and 11 are shown. The $x = 0$ indicates where SRFM and RTTOV radiances are equal. Pannels (a) and (b) show data points colour-coded by channel and profile respectively.

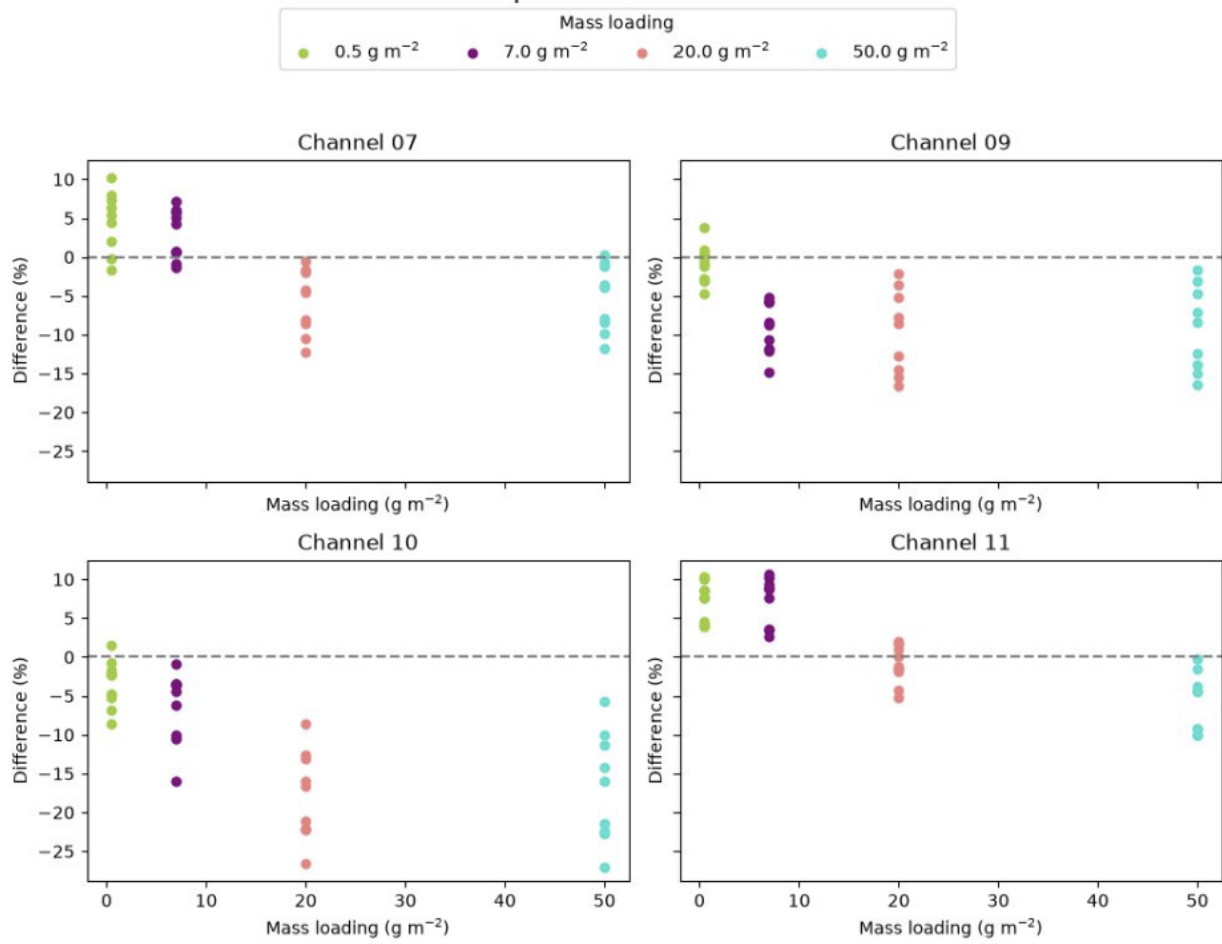
4.3 Comparison of RTTOV and SRFM radiance simulations for an atmosphere containing an ash layer

Figure 7 shows that RTTOV and SRFM produce consistent radiances over all channels, as most datapoints follow $x = y$. Figure 7(b) shows that all outliers correspond to profile 5, with Figure 8 (b) showing extreme discrepancies reaching 150% for this profile. In order to explain this discrepancy, the pressure/temperature/humidity specificities of the profile would need to be investigated. Ignoring profile 5, we observe on Figure 8 that SRFM generally produces larger radiances than RTTOV, across the other 9 profiles, 4 channels and all ash property combinations. We note that the mean % biases displayed in Table 11 are relatively consistent for Channels 7, 9 and 11 (their absolute value), while Channel 10 shows a mean % bias approximately twice as big as for the other channels.

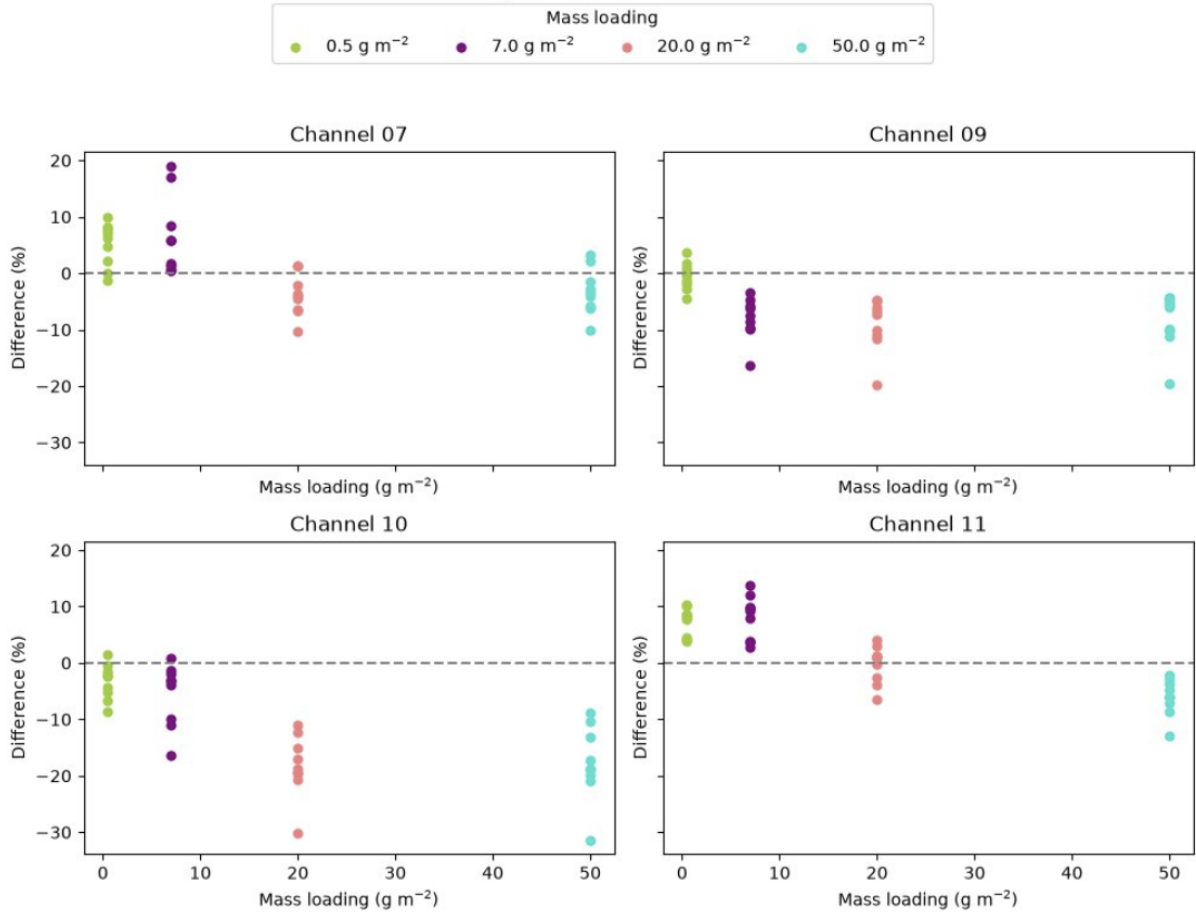
Figure 9 shows there are clear trends correlated to mass loading in the differences between SRFM and RTTOV radiance. We observe for both altitudes decaying trends with decreasing gradients as mass loading increases. We also observe larger discrepancies overall as

mass loading increases. Figure 10, which shows percentage difference averaged over all profiles, shows that for Channel 9, a plateau appears more quickly as mass loading increases compared to other channels. For Channel 9, mean percentage difference remains approximately constant from mass loading 7 gm^{-2} . Channels 7 and 10 seem to saturate from mass loading 20 gm^{-2} , while Channel 11 does not show a plateau over the mass loading values considered, while still showing a decreasing gradient. We can note that the shape of the trends for each channel remains consistent over both altitudes. This could indicate that there are no systematic differences related to cloud top altitude, although more altitudes would need to be considered to investigate.

In this project, limitations predominantly appeared in the compatibility of the datasets. In particular, the method used to convert RTTOV brightness temperature to radiance introduced an averaged bias of ~ 0.0136 in the RTTOV radiance ash dataset. Using different log-normal distributions for each simulation also introduced inconsistencies. While the number densities for both models were not exactly identical, we neglected this discrepancy in our analysis as we are interested in the general trends in the datasets. Furthermore, the clear sky

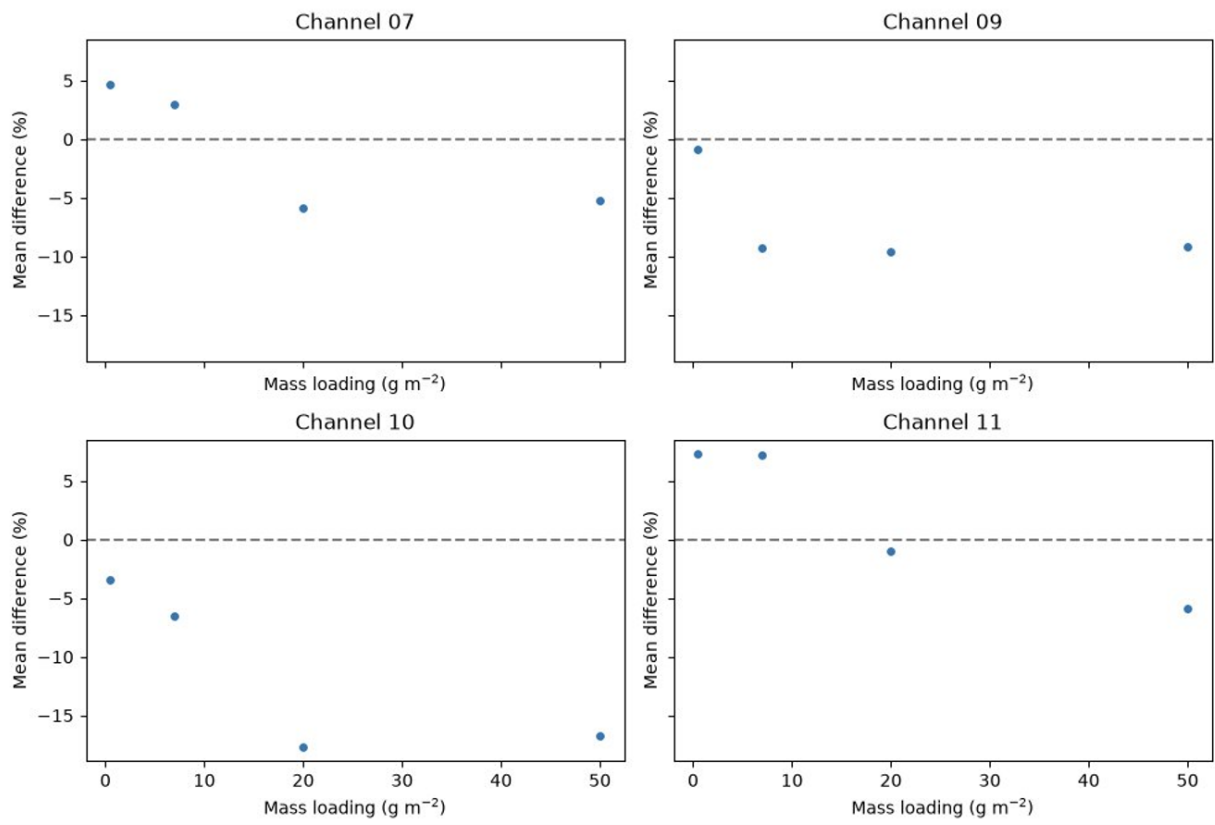


(a) Cloud top altitude 13.727 km.

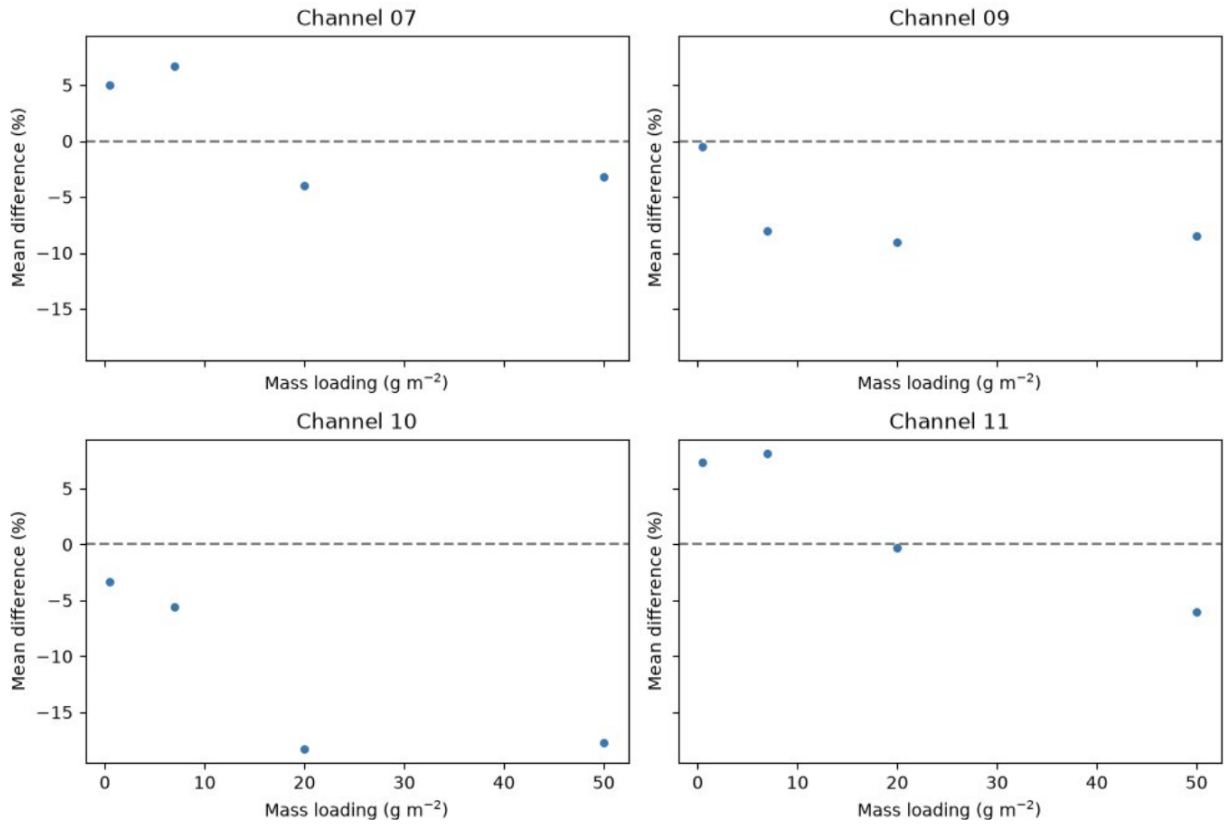


(b) Cloud top altitude 16.999 km.

Figure 9: Percentage difference $RTTOV - SRFM / SRFM$ between SRFM and RTTOV radiances as a function of mass loading, for cloud top altitudes 13.727 km and 16.999 km. The 9 datapoints displayed at each mass loading represent 9 atmospheric profiles (profile 5 was excluded). Each subpanel shows an individual SEVIRI channel.



(a) Cloud top altitude 13.727 km.



(b) Cloud top altitude 16.999 km.

Figure 10: Percentage difference $RTTOV - SRFM / SRFM$ in radiance averaged over 9 profiles as a function of mass loading.

discrepancies that were found affected the ash datasets comparison. To resolve this, clear sky corrections could be applied to the ash datasets using the clear sky biases corresponding to each channel.

For further development, one could investigate the origin of these trends and conduct a comprehensive analysis using a large set of ash properties. Specifically the effects of cloud top altitude and ash radius could be examined using an array of values for each. In addition, it would be valuable to carry out comparisons with SRFM using both RTTOV version 13 and version 14 to assess whether the results differ between the two versions.

5 Conclusions

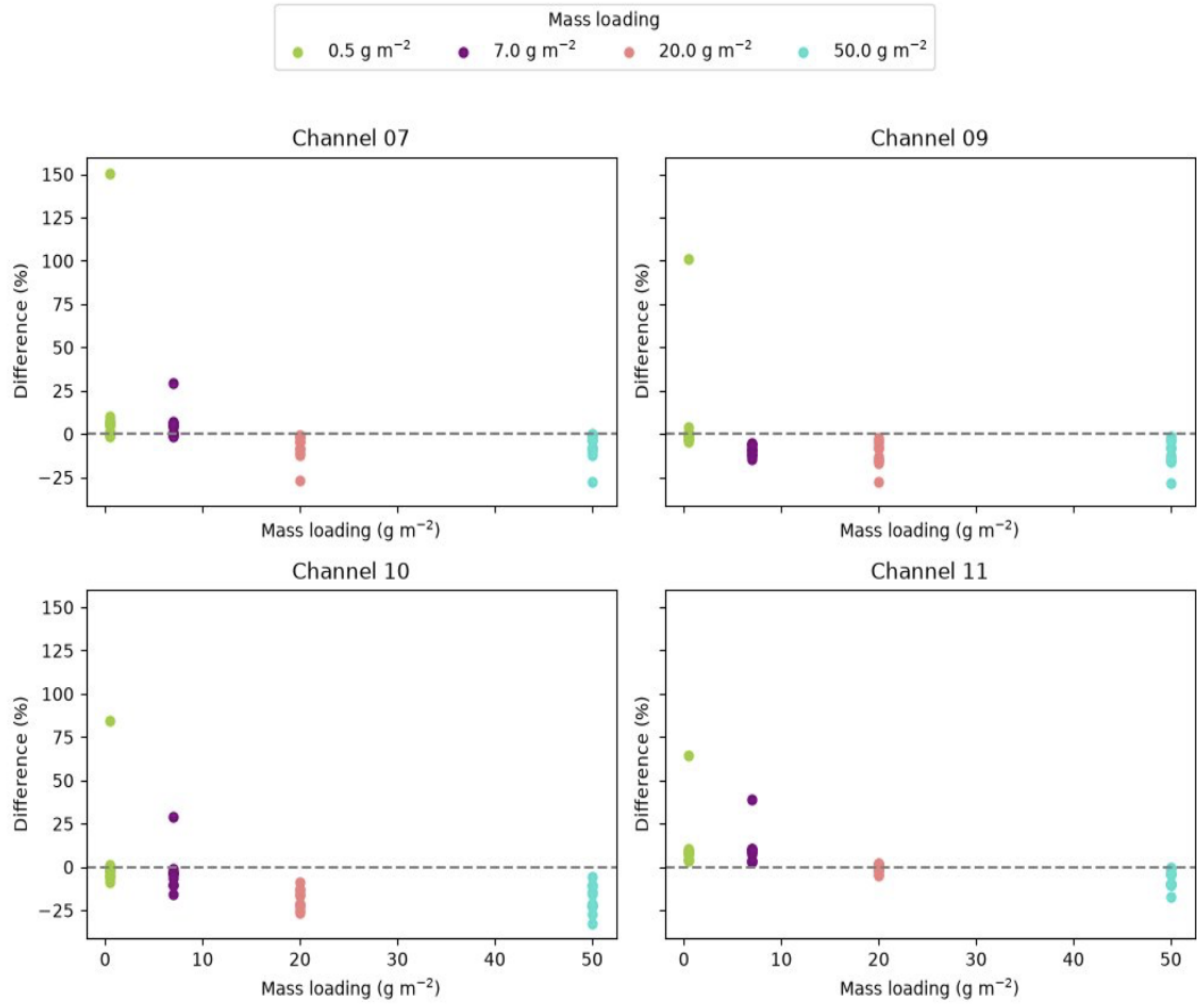
This study identified channel related discrepancies between radiance simulated by LBL model SRFM and parametrised model RTTOV for a clear sky (ash-free) scenario, considering MSG-3 SEVIRI channels 7,9,10,11 and 10 atmospheric profiles. Simulated radiance was found to be overestimated by RTTOV v.13 for channels 7 and 11, and underestimated for channels 9 and 10, taking SRFM as the reference. The models were once again compared introducing an ash layer in the atmosphere with varied mass loadings, cloud top altitudes and fixed ash radius. Clear trends in the difference between the models were identified and found to be correlated to mass loading. These trends were consistent across all channels and both cloud top altitudes, showing a decaying profile, with the gradient decreasing and the discrepancy increasing as mass loading increased. While these results indicate that there are biases correlated to mass loading in RTTOV’s modelling of volcanic ash, one would need to carry out a comprehensive analysis examining a larger set of ash properties to explore the characteristics of each trend and investigate their origin. In this way, RTTOV biases could be parametrised and corrections could be introduced into RTTOV for a more accurate modelling of volcanic ash.

6 References

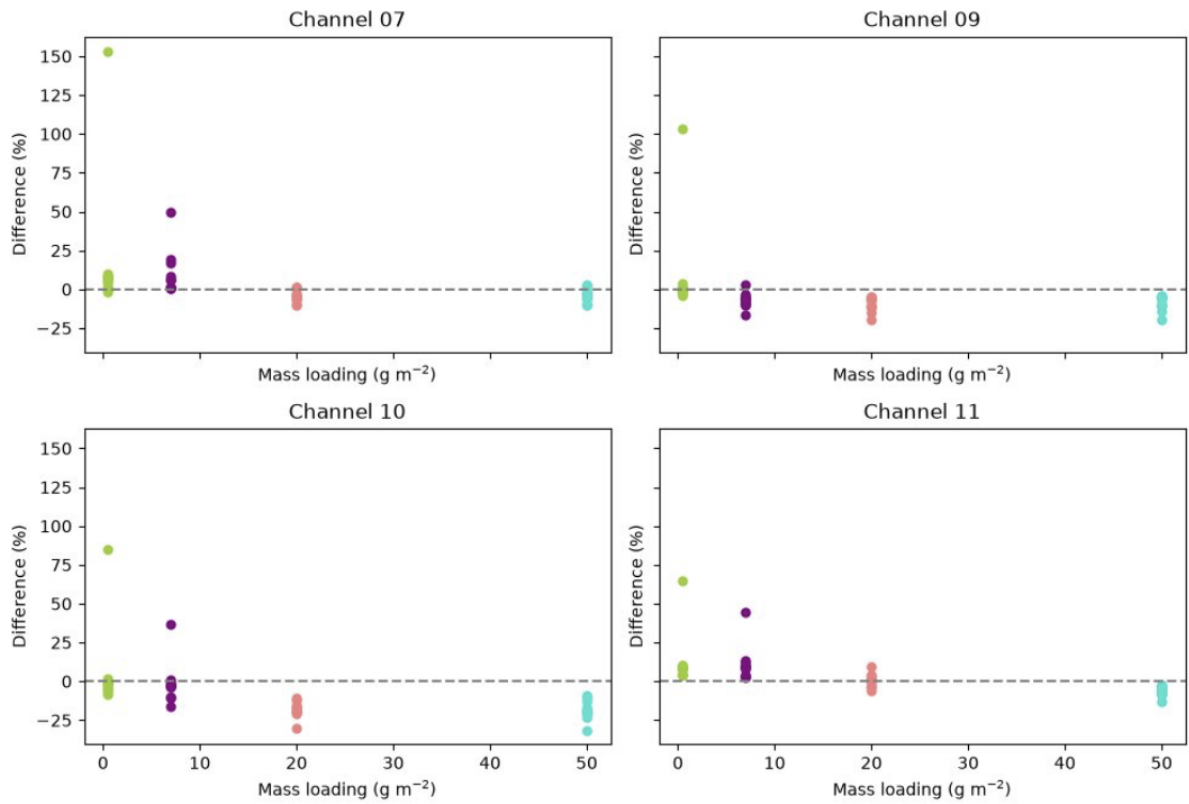
- [1] A. Brodtkorb et al. Estimating volcanic ash emissions using retrieved satellite ash columns and inverse ash transport modelling using volcanicash- inversion v1.2.1, within the operational eemep (emergency european monitoring and evaluation programme) volcanic plume forecasting system (version rv417). *Geoscientific Model Development* **17**, 1957–1974 (2024). <https://doi.org/10.5194/gmd-17-1957-2024>
- [2] Saunders, R. Sources of biases in infrared radiative transfer models. *ECMWF* (2006). https://www.ecmwf.int/sites/default/files/elibrary/2006/76302-sources-biases-infrared-radiative-transfer-models_0.pdf
- [3] Matricardi, M. Radiative Transfer for IASI. *ECMWF* (2009). <https://www.ecmwf.int/en/elibrary/75598-assessment-accuracy-rttov-fast-radiative-transfer-model-using-iasi-data>
- [4] Saint, C., Beckett, F. M., Dioguardi, F., Kristiansen, N., & Tubbs, R. N. Using simulated radiances to understand the limitations of satellite-retrieved volcanic ash data and the implications for volcanic ash cloud forecasting. *Journal of Geophysical Research: Atmospheres*, 129 (2024). <https://doi.org/10.1029/2024JD041112>
- [5] “The HITRAN database.” *HITRAN* (2024). <https://hitran.org>
- [6] Pollack, J. B. et al. (1973), Optical properties of some terrestrial rocks and glasses, *Icarus*, 19(3), 372–389, doi:10.1016/0019-1035(73)90115-2.
- [7] “Basic Channels.” *EUMeTrain* (2013).

7 Appendix

7.1 Results: Ash Layer Datasets Comparison



(a) Cloud Top Altitude 13.727 km.



(b) Cloud Top Altitude 16.999 km.

Figure 11: Percentage difference $RTTOV - SRFM / SRFM$ between SRFM and RTTOV radiance as a function of mass loading, for cloud top altitudes 13.727 km and 16.999 km. The 10 datapoints displayed at each mass loading represent 10 atmospheric profiles. Profile 5 is included and shows unreasonable discrepancy. Each subpanel shows an individual SEVIRI channel.