Answers to comments of reviewer 2:

We thank Prof. Stenchikov for the valuable and constructive comments on our paper that helped us improve the quality of the presentation. The reviewer's comments are written in black. Our answers to the comments are given in blue. Modifications in the manuscript are additionally written in italic letters.

This paper uses the novel ICON-ART modeling system to examine the initial one-week evolution of water vapor (WV), SO_2, SO_4, and ash plumes following the 2022 Hunga eruption. The authors implement volcanic plume initiation through the 1-D plume rise model, FPlume, which is tuned to match observed injection altitudes. This approach introduces an innovative method for representing volcanic injections in the model. Additionally, the study includes ash emissions, investigates ash-sulfate interactions, and compares results with CALIOP, OMPS, and IMS/IASI observations.

The simulations suggest that a 1.2 Tg SO_2 emission aligns more closely with observed plume characteristics than the 0.4 Tg estimate based on OMI/OMPS data. The findings also indicate that ash influences the plume's descent trajectory and that WV is critical in accelerating SO_2-to-SO_4 conversion. While some of these conclusions have been reported in previous studies, using a newly developed modeling system provides a fresh perspective. However, the presentation could be more focused.

Using a 1-D plume model for injecting volcanic materials is interesting but requires better documentation. At a minimum, the vertical distribution of injected materials should be discussed. Most WV is likely released in the form of solid hydrometeors (ice, snow, and graupel), but this is not explicitly stated. The energy required for melting or sublimation could influence atmospheric cooling, distinguishing this study from others—an aspect worth highlighting.

We extended the description of the coupling of ICON-ART and FPlume in general in l. 148-151:

"The parametrization by Gouhier et al. (2019) calculates the fraction of very fine ash (particles <30 µm), which is relevant for atmospheric transport, from the given height and the calculated MER. The MER of SO_2 is prescribed based on observations and emitted in the same emission phases as for ash. The vertical distribution of all emitted masses (here ash, H_2O and SO_2) is calculated according to the Suzuki profiles (Suzuki,1983)."

Additionally, we rephrased and extended the description on the WV emission in l. 159-161:

"This derived water vapor MER is added to ICON's water vapor mixing ratio. The phase partitioning between vapor, liquid and solid hydrometeors is calculated in ICON's microphysics scheme (Sect. 2.2.1)."

With the setup used in this work, we cannot provide precise numbers on the energy required for melting and sublimation, because the plume rise dynamics are not explicitly simulated in ICON-ART. However, explicit simulation of this eruption with ICON-ART in large eddy mode configuration is the topic of ongoing work.

The simulation duration is notably short. Is there a specific reason for this limitation? Extending the simulations to at least a couple of months would enable a more robust comparison with observations. Furthermore, the initial ash amount and size distribution appear arbitrary, and the study does not clearly demonstrate ash's significance in improving observational agreement.

The goal of our study is to investigate the early-phase processes within the volcanic plume, particularly the interaction between the emissions and the surrounding atmospheric conditions during the first week following the eruption. To best resolve these short-term dynamical and microphysical processes, we use the ICON model in its numerical weather prediction (NWP) configuration, which is specifically designed for high-resolution short-range simulations.

The chosen horizontal resolution of 40 km allows for a detailed representation of the evolving tracer distributions and their dependence on emission strength, injection height, and environmental conditions. Extending the simulation period to several months would have required a different model configuration (e.g., climate mode with coarser resolution and different parameterizations), which is not suited to the specific objectives of this study.

We therefore intentionally limited the simulation period to seven days in order to ensure a realistic meteorology (synoptic scales) and process-resolving representation of the plume evolution.

We discussed the ash distribution in the comment ‘Specific concerns’ in L. 171. One aim of this study was to understand the quick loss of ash after the eruption. Our results show that aerosol dynamical processes do not explain this quick loss, however, we discussed that some ash might be hidden from the observations as it is heavily coated. Understanding the role of different ash removal processes in the Hunga plume is the topic of our ongoing work and will be submitted soon (Chopra et al., in prep.).

The description of the radiative transfer model is missing. Including stratospheric aerosol optical depth (SAOD) would be beneficial, as it is one of the best-constrained observational metrics. Addressing these concerns will strengthen the study and improve its readiness for publication.

We added a paragraph on the aerosol-radiation interaction (ARI) in ICON-ART (l. 140-143):

“The ecRad model by Hogan and Bozzo (2018) calculates the radiative fluxes in ICON. It requires the mass extinction coefficient, the single scattering albedo, and the asymmetry parameter to account for the radiative effects of aerosols. For all modes, these properties were derived offline and individually based on Mie calculations and stored in look-up tables for online calculations of ARI (Muser et al., 2020).”

Furthermore, we extended the description on the calculation of the model sulfate aerosol optical depth (and moved it from section 2.3.3 to 2.4; l. 255-259) :

"For the comparison with the IMS/IASI SOAD, the ICON-ART SAOD was calculated offline from the mass concentration m_l in kg/m3 of the two soluble modes l and their respective mass extinction coefficients $k_{i,\,1130\,cm-1}$ derived from Mie calculations for 1130 cm−1:

$$\tau_{1130\,cm-1} = \sum_{i=1}^{z} \sum_{l=1}^{2} m_l * k_{i,\,1130\,cm-1} * \Delta z_i$$

with z the model level."

Specific concerns:

L23: "dynamical" > "microphysical"

We deliberately use the term "aerosol dynamical processes" rather than "aerosol microphysical processes" to clearly distinguish them from cloud microphysical processes, which are treated separately within the weather forecast model. This distinction is particularly important given that our study focuses on weather-scale processes rather than climate-scale effects. Using this terminology helps to avoid confusion between the two process categories and ensures clarity in the context of our modeling framework.

L80: Are these two emissions on January 15?

Done.

L136: uptake by sulfate or by ash?

Water uptake is activated for all aerosol particles in our simulation, i.e. insoluble (ash), mixed (ash coated by soluble components) and soluble (mainly sulfate) particles. Therefore, we do not make a distinction here.

L152: Is it a restriction?

The FPlume model considers the atmospheric state in the calculation of the plume dynamics. For other eruptions such as the 2019 Raikoke (Bruckert et al, 2022) and 2021 La Soufriere eruption (Bruckert et al., 2023), we used atmospheric profiles from ICON as input to FPlume at every model time step. The advantage is that changing atmospheric conditions, especially during long-lasting eruptions, are considered in the plume dynamics. As the two phases of the Hunga eruption are short and close together, we consider the effect of changing atmospheric conditions during the eruptions to be small. Reading the atmospheric profiles from external files in case of the Hunga eruption is mainly a technical necessity. The emitted water vapor from the eruption is added to the specific humidity, a variable needed as input for the FPlume model.

L161-165: When did you start the run from initial conditions?

We added (l. 175-178):

"For each experiment, we simulated seven days initialized on 15 January 2022 at 00:00 UTC with analysis data provided by the German Weather Service (DWD). The analysis data contained variables describing the atmospheric state, variables needed by the land component, and sea surface temperatures. Due to the short time span of the simulation, sea surface temperatures are temporally fixed throughout the simulation."

L171: Is it evenly distributed in number-density or volume? I doubt ash is evenly distributed.

We evenly distributed mass of very fine ash by mass, i.e. also by volume as we consider equal density for the three ash modes. This distribution has been used for the 2019 Raikoke eruption and was validated against observations with respect to the ash mass loading in Muser et al. (2020). We used this distribution due to the lack of direct observations from the Hunga eruption. Nevertheless, we agree that the composition and physical processes in the plume in case of the Hunga eruption were clearly different from those of the Raikoke eruption. Investigating the role of wet aggregation, its effects on the ash mass distribution as well as on atmospheric lifetime is part of our ongoing work.

L191-195: OMPS does not see the initial stage well because of insufficient sampling.

Thanks for pointing this out. We included when interpreting the results (l. 385-386):

"Furthermore, OMPS might not have detected the SO_2 plume well in the first days because of insufficient sampling."

L276-279: What was the vertical distribution of volcanic debris soon after the injection?

We added a plot on the vertical distribution of volcanic debris soon after the injection to the appendix (Figure A1). We do not place it in the main text, because it is rather a technical detail than an actual result. Nevertheless, we agree that it could be helpful for a reader to understand the concept of our emission.

Figure 4: No-ash experiment produces the most realistic results.

We included (l. 365):

"The descent rate of water vapor in the experiment noAsh is closest to the observed descent rate of the water vapor plume by Khaykin et al. (2022)."

L341: Do you mean sulfate particles? 70% of sulfate absorption is coming from LW. WV cooling is the most important.

We rephrase this sentence to clarify our message as (l. 357-359):

"For particles of the same composition but different size, the smaller particles interact stronger with radiation in the visible range. This increases the warming and lofting of the plume in the noCoag case, which also affects the mass-averaged height of the water vapor plume."

Subsection 4 should be first in the results section.

We chose it this way, because we first want to discuss the contribution of the different processes to the plume development. As some processes such as ARI or coagulation have negligible impacts on the SO_2 and ash mass loading as well as aerosol aging and sulfate formation, in subsection 4, we only validated the experiments which show distinct differences among each other.

Figure 5: Explain how the amplitude, structure, and location factors are computed.

A general description of the SAL method and its components is already given in section 2.4. This method is a quite common method to validate simulated objects such as precipitation or aerosol plumes on NWP scales and we do not want to repeat the equations and details of the work by Werli et al. (2008) here.

L403: Or you injected too much ash.

We agree with this concern. However, it is indirectly addressed by the “effect of a missing process”. The reason why we might have injected too much ash could be because we neglected the process of wet aggregation during the plume rise. Wet aggregation in the Hunga plume could have been stronger than in “typical” volcanic plumes leading to larger particles and a faster sedimentation. Therefore, we might have assumed a too high fine ash fraction in addition to the uncertain distribution into the three ash modes discussed above.

Section 5: Do you have background aerosols before the eruption?

We have not initialized background aerosols before the eruption. However, our background aerosols are small but different from zero in order to avoid division by zero in some subroutines.

L413: Use radius; do not switch to diameter in some places.

Done.

L415-420: Please be specific. Is it an effective radius or median radius makes a difference? I do not believe in these very big radii. It is not consistent radiatively. The mass of aerosol will be exaggerated. The lifetime will be shorter than it is observed. For example, Boichu et al. (2023) measured Hunga's size distribution through AERONET through the entire depth of the atmosphere. They could detect large cloud particles.

We agree that comparing effective radii to median radii or peak radii is not straight forward and we mixed things up in this paragraph. We removed or rephrased sentences to avoid a comparison of different quantities. Instead we focused on trends now.

Figure 8 is difficult to read. What are the isolines for?

We revised the description of isolines in Figures 3, 4 and 8, and included labels in the plot.

L435: How much sulfate is on the ash?

The coating of soluble compounds on ash (for volcanic aerosols mainly sulfate and water) is shown in Figure 3. Large differences in coating between experiments mainly arise when

considering or neglecting the water vapor effect on chemistry. Therefore, we argue that about 40-50% of the particles' volume consists of soluble components in the region of the main plume mass for all experiments including the effect of water vapor on chemistry. Figure 1c shows that the soluble shell on ash consists of approximately 40% water and 60 % sulfate by mass.