

Review of Yang et al., Transport of volcanic aerosol from the Raikoke eruption in 2019 through the Northern Hemisphere

Original referee comments are in blue.

Our responses are in black with regular bold format. Text from the updated manuscript:

*Appears in italic and with 0.5 cm indentation and with **the modified parts in red.***

General comments

The submitted manuscript uses aerosol profiles measurements made by COBALD sondes at Lhasa and POPS at Boulder to study the distribution of aerosol from the Raikoke volcanic eruption in June 2019, particularly within the Asian Summer Monsoon Anticyclone but also including transport to Boulder.

Firstly, back trajectories are used to study the transport pathways to Lhasa, and then in the second part, the CLaMS model is used to try to simulate the profiles after injection of an SO₂ tracer. (Not including the upper peak seen in the COBALD and POPS profiles around 470-480 K).

The model shows a reasonable ability to reproduce the observed results and some interesting sensitivity studies are also performed to try to obtain the best possible agreement and assess model settings.

Overall this is an interesting and worthwhile study about an important topic and well within the scope of ACP, and I would be happy to recommend publication after some minor improvements.

The presentation is generally very clear and well-written with a small number of exceptions listed below.

To me, the agreement of the model and observations seems only modestly good so I would suggest a small amount of additional text in the discussion section or conclusions to put these results into context and how happy you were with them.

I also note that the CLaMS simulations did not attempt to model the upper peak seen in Figure 2 and Figure 8 which seems disappointing, so some comment about that would also be welcome.

We thank the reviewer for the encouraging assessment and the detailed, constructive comments, which helped us improve the manuscript.

Regarding the upper peak (Lhasa on 3 August; Boulder on 27 August), we agree that the current CLaMS set-up does not reproduce this feature by the SO₂-based tracer fraction profile like shown in the Fig. 9 and Fig. 11 in the revised manuscript. Indeed, on 12 July 2019 a condensed VVP structure can be identified in TROPOMI observations (as shown in Fig. 1 of this reply). We performed an additional CLaMS three-dimensional SO₂-based tracer sensitivity simulation by injecting tracer at 00:00 UTC on 12 July in the 440–460 K layer and analyzing the subsequent tracer fraction distribution (as shown in Figs. 1 and 2 of this reply). Although this run does not create a distinct additional peak in the simulated SO₂-based tracer fraction profiles, it yields enhanced tracer fractions near the observation times/locations

(Lhasa on 3 August; Boulder on 27 August). We therefore infer that the filament transport is broadly consistent with the observations. However, due to the fact that the filament is highly localized and small-scale, the current CLaMS simulation is not able to fully capture the feature with the given model resolution

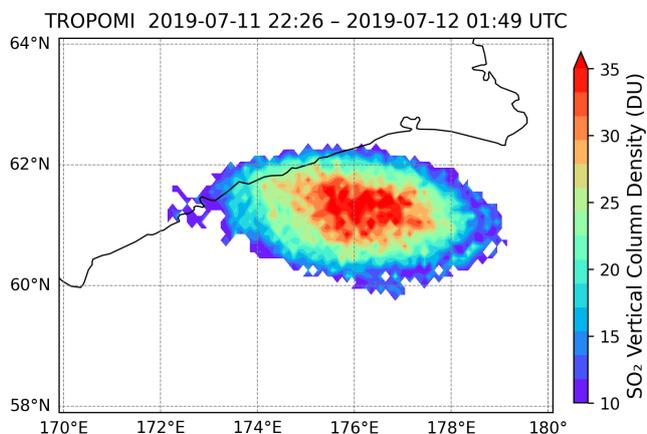


Figure 1. TROPOMI SO₂ total vertical column showing the condensed vorticed volcanic plume (VVP) from the 2019 Raikoke eruption during 11 July 2019 22:26 to 12 July 2019 01:49 UTC.

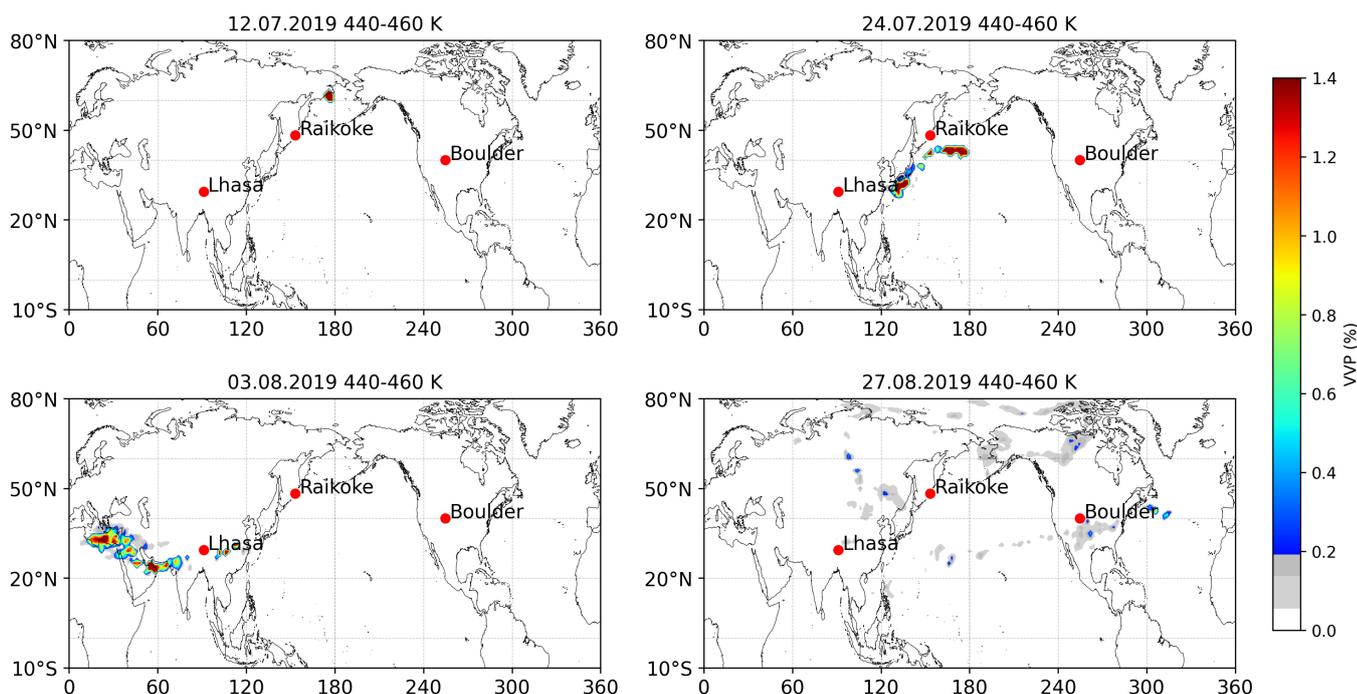


Figure 2. Four maps of CLaMS SO₂-based tracer fraction (%) averaged over 440 to 460 K at 00:00 UTC on 12 July, 24 July, 3 August, and 27 August 2019, using the injection SO₂ mask from Fig. 1. Red markers indicate the location of Raikoke, Lhasa, and Boulder.

Specific comments

Lines 19, 34 – this is a very minor comment, but I am not aware of much discussion of volcanic injection of water vapor prior to Hunga.

We agree and revised the text to avoid implying that substantial water-vapour injection into the UTLS/stratosphere is common for large eruptions. The discussion now emphasizes SO₂

and ash as the primary injected species, and mentions stratospheric water vapour impacts only as an exceptional case (e.g. the 2022 Hunga Tonga eruption).

Large eruptions can inject significant amounts of ash, water vapor, and sulfur dioxide (SO₂) into the upper troposphere–lower stratosphere (UTLS).

~~The Volcanic Explosivity Index (VEI) serves as a proxy for eruption intensity (Newhall and Self, 1982), and events with VEI ≥ 4 can inject vast quantities of SO₂, water vapor, and ash, causing marked climate perturbations. Eruption magnitude can be characterized by the amount of SO₂ and ash released, which largely controls aerosol formation potential and radiative forcing. Notably, substantial perturbations of stratospheric water vapour and aerosol microphysics have also been reported for the 2022 Hunga Tonga eruption despite modest SO₂ injection (Carn et al., 2022; Zhu et al., 2022).~~

Lines 39-41 The wording implies there are other examples of this in the record apart from Hunga?

We agree that the previous wording could be interpreted as implying multiple examples. We have revised the text to clearly refer to the 2022 Hunga Tonga eruption as the illustrative case for pronounced stratospheric water vapour perturbations

Lines 44-46 These sentences need some minor re-wording for clarity. It is hard for the reader to understand "... the circulation acts as a ... barrier, trapping those air masses ... Simultaneously, the barrier is permeable ... This dual role ...". This reads like a superposition of contradictory states.

We agree that the text might be somewhat confusing and rewrote the respective paragraph to enhance clarity as follows:

Among the various transport mechanisms influencing volcanic aerosol fate, the ASMA plays a particularly important role during the boreal summer. Deep convection injects pollutants into the UTLS, where the ASMA's strong anticyclonic circulation acts as a dynamical transport barrier, trapping those air masses in its circulation. Simultaneously, the barrier is permeable, and the horizontal outflow of the ASMA can transport monsoon air masses to the extratropical UTLS (Vogel et al., 2016; Yu et al., 2017). This dual role makes the ASMA a key element in understanding aerosol dispersion in the Northern Hemisphere following volcanic eruptions. In the Northern Hemisphere summer, the ASMA is the dominant circulation system in the UTLS. Deep convection injects pollutants into the UTLS, where the ASMA's strong anticyclonic circulation acts as a dynamical transport barrier that confines these air masses over Asia during their ascent into the stratosphere (e.g., Park et al., 2007; Randel et al., 2010; Fadnavis et al., 2014; Santee et al., 2017; Vogel et al., 2019). However, the ASMA boundary is not a strict barrier, and air masses can be exported from the monsoon circulation into the extratropical UTLS (Vogel et al., 2016; Yu et al., 2017). This combination of confinement and export is important for interpreting aerosol dispersion during boreal summer, including the dispersion of volcanic aerosol. Previous work on the 2011 Nabro eruption debated whether its plume reached the stratosphere directly or was lofted by monsoon ascent. Bourassa et al. (2012) proposed that the plume remained in the upper troposphere and was subsequently transported into the stratosphere by large-scale ascent in the monsoon, whereas later studies showed evidence of direct stratospheric injection, independent of monsoon-driven lifting (e.g., Fromm et al., 2013; Vernier et al., 2013).

Lines 96 You should add a sentence to explain how β_{air} is distinguished from $\beta_{\text{particles}}$.

We thank for the Reviewer for this comment and clarify that the COBALD measurement does not directly separate molecular and particle backscatter; it measures their sum. The molecular contribution (β_{air}) is obtained in post-processing by computing the Rayleigh backscatter from the collocated pressure and temperature profiles, and the particle contribution ($\beta_{\text{particles}}$) is then derived as the residual after subtracting β_{air} from the measured total backscatter. We have added this clarification in the revised manuscript.

The instrument measures only the total backscatter ($\beta_{\text{total}} = \beta_{\text{air}} + \beta_{\text{particles}}$); β_{air} is calculated in post-processing from Rayleigh scattering using the measured pressure and temperature profiles, and $\beta_{\text{particles}}$ is obtained as $\beta_{\text{total}} - \beta_{\text{air}}$.

Line 165 Please re-word "are empirically highlighted" – I think the criterion is really just that BSR is high without high RH.

Thank you for the suggestion. We agree that “empirically highlighted” was misleading. In the revised manuscript, the highlighted regions are identified using objective threshold criteria rather than subjective highlighting. Specifically, we exclude cirrus using $\text{BSR}_{455} > 1.2$, $\text{RH}_{\text{ice}} > 70\%$, and $\text{CI} > 7$, then define aerosol layers by $\text{BSR}_{455} > 1.1$, and finally classify them using $\text{CI} = 6$ (Raikoke plume: $\text{CI} > 6$; ATAL: $\text{CI} < 6$). The text has been revised accordingly.

Line 172 "Typical ATAL profiles ..." – do you mean typical enhancements in the profiles?

We reworded “Typical ATAL profiles” to “ATAL-related enhancements in COBALD BSR profiles” to clarify that we refer to the altitude/ θ range of ATAL enhancements rather than the full profile.

In general, ATAL-related enhancements in COBALD BSR_{455} profiles are largely confined to 360 to 400 K, with a core near 370 to 390 K. Occasional extensions up to 420 to 440 K occur depending on region and year (Vernier et al., 2015, 2018; Appel et al., 2022). The 2013 ATAL profile shown in Fig. 3a is taken from the COBALD measurements over Lhasa reported by Vernier et al. (2015). The 2019 median peak occurs near 417 K, about 33 K above the 2013 ATAL peak at 384 K, corresponding to roughly 1.7 km in altitude in the UTLS based on the 30 July 2019 background sounding. Because the vertical extent of ATAL enhancements varies across regions and years, we emphasize peak magnitude as the more robust difference. The 2019 Raikoke-related median BSR_{455} reaches about 1.25, exceeding the 2013 ATAL peak of about 1.10 (Fig. 3a).

Lines 172-175 It seems to me that the distinguishing feature of the 2019 profiles is the magnitude of the peak rather than the height. You say the ATAL profile can reach 420-440 K at times.

We agree and revised the text to emphasize peak magnitude as the primary difference (2019 median $\text{BSR}_{455} \approx 1.25$ vs 2013 ≈ 1.10), while treating the higher peak altitude (417 K vs 384 K; ~ 1.7 km) as supporting information given the variability in the ATAL vertical extent.

Figure 3 the thin gray lines are very hard to see – I couldn't see them at all on my screen until I zoomed to at least 300%.

Thank you for pointing this out. We have revised Fig. 3 of our manuscript (Figure 3 in this reply) and increased the visibility of these lines by using a darker gray color and a larger line width.

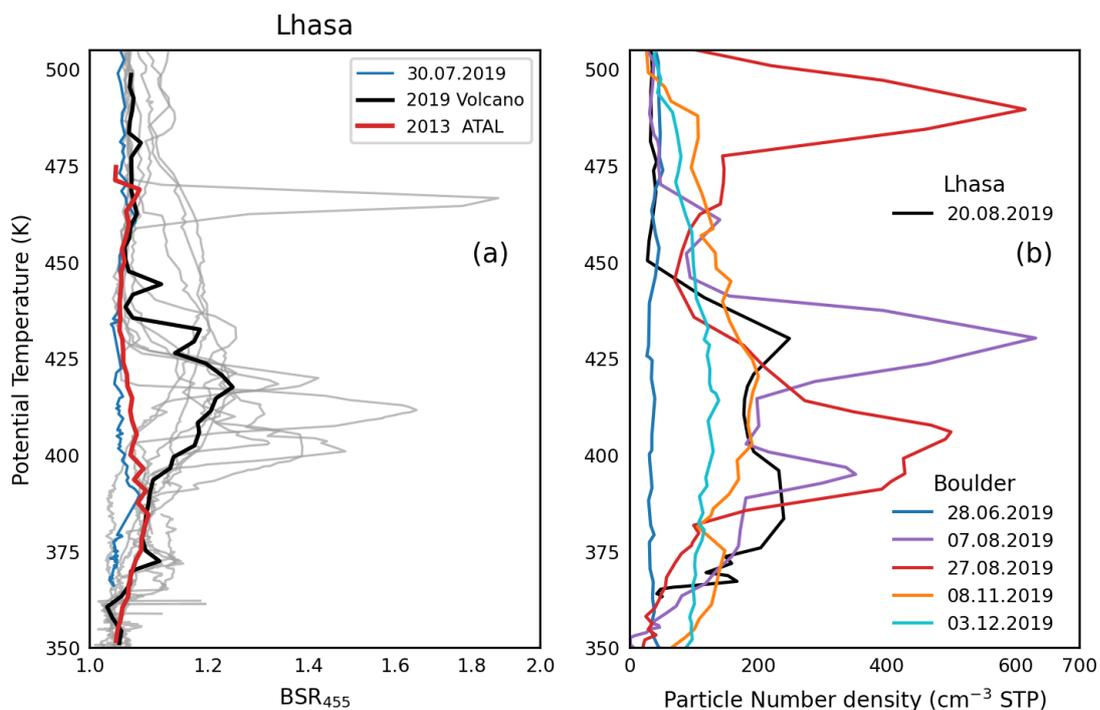


Figure 3 (also Figure 3 in the revised manuscript). (a) COBALD measurements in Lhasa. The black line represents the median BSR₄₅₅ for the 2019 profiles influenced by the volcanic event, and the gray lines show the corresponding individual profiles. The red line shows the median BSR₄₅₅ during the ATAL in 2013. The blue line corresponds to the BSR₄₅₅ on 30 July 2019, which was not affected by the Raikoke eruption. (b) POPS measurements in Boulder and Lhasa.

Lines 184-185 Please re-word "we performed backward-trajectory analyses based on in-situ balloon-borne measurements ..." This reads to me that the back trajectories are using data from the balloon measurements.

We rephrased this sentence to clarify that the trajectories are calculated from ERA5 wind fields. The balloon observations are used only to define the trajectory initialization times and potential temperature ranges of the observed plume layer, with parcels released along the balloon flight track.

To verify that the enhanced aerosol layer observed over Lhasa originated from the Raikoke eruption, we performed backward-trajectory analyses based on in-situ balloon-borne measurements over Lhasa, driven by high-resolution ERA5 data (Fig. 4). To verify that the enhanced aerosol layers observed over Lhasa are linked to the Raikoke eruption, we calculated ERA5-driven diabatic backward trajectories with CLaMS (Fig. 4). Trajectories were released every second along each balloon ascent within the selected plume-layer potential-temperature intervals indicated by the orange shading in Fig. 2, using iMet-derived time and location (longitude, latitude, pressure, and temperature) as initial conditions. All trajectories were calculated backward to a single common reference time, 21 June 2019 at 18:00 UTC, which serves as the common trajectory endpoint for all cases.

Lines 184-221 The back trajectories are run for periods from 1.5 to 5 months. Do you have any confidence that the results are meaningful over such a long period of time?

We agree that confidence in backward-trajectory reconstructions decreases as the period becomes longer, even when using high-resolution ERA5-driven CLaMS trajectories. For this reason, we do not include backward trajectories for the September–November flights in the manuscript, since they require tracing air parcels much further back in time. We focus the trajectory analysis on the July–August period, when plume structures remain more coherent and the trajectories provide clearer transport pathway information.

Figure 4 Are the labels on the x-axes date and month? (dd.mm ?)

Yes, these are dates in dd.mm format. We updated the x-axis title to “Date (dd.mm.yy)” in **Figure 4** of the revised manuscript (**Figure 4** of this reply)

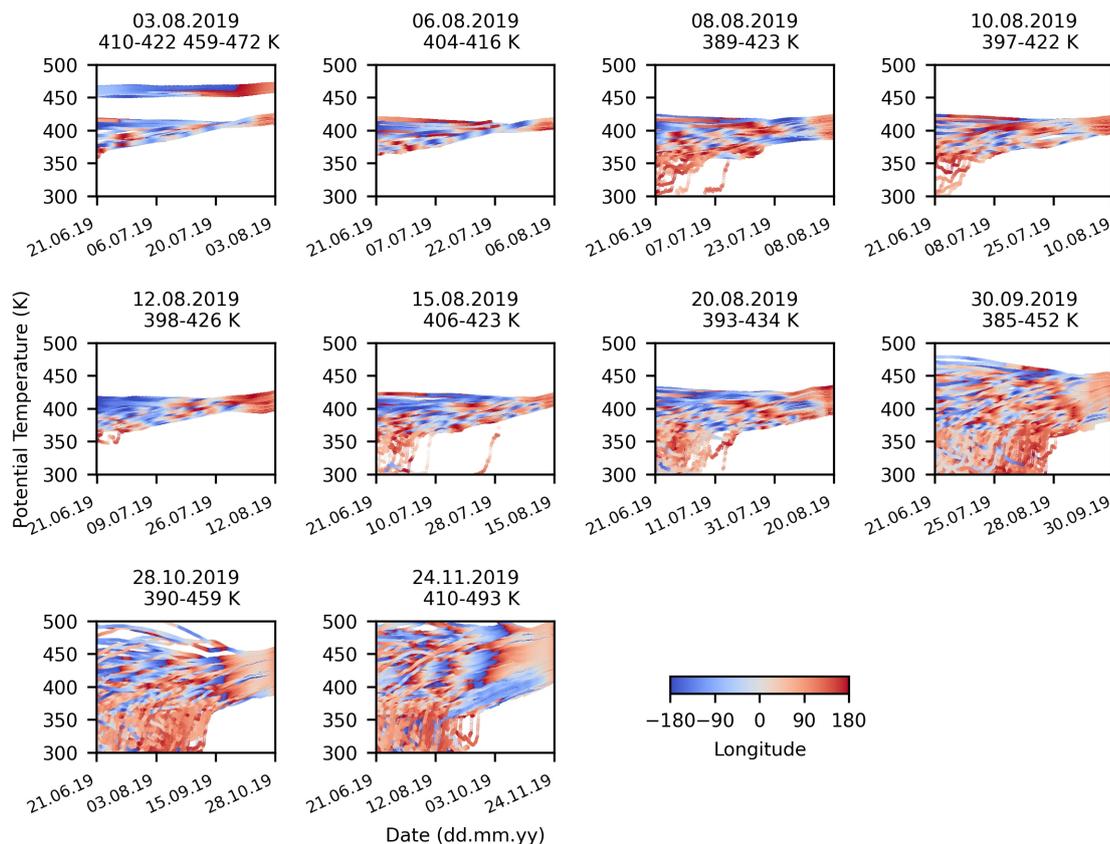


Figure 4 (also Figure 4 in the revised manuscript). Backward trajectories initialized from the Lhasa balloon observations and traced back to the Raikoke eruption reference time (21 June 2019, 18:00 UTC). Only trajectories initialized within the enhanced BSR₄₅₅ potential-temperature range (orange shading in Fig. 2) are shown. Colors indicate trajectory longitude. The x-axis shows date (dd.mm.yy) along the backward integration (right: balloon initialization time; left: eruption reference time).

Figure 4 It would be very helpful to mark the height of the tropopause on these plots.

Thank you for the suggestion. We agree that indicating the tropopause can help interpretation. However, the trajectories in Fig. 4 span a wide range of latitudes across the Northern Hemisphere, and the tropopause potential temperature varies strongly with latitude. Therefore, plotting a single “tropopause line” on each panel would not be representative.

Lines 203-206 I don't quite understand this – what is the denominator of the fraction exactly? You need to give more detail on how you initialized the starting positions and times of the backward trajectories., and how many you ran for each date.

Thank you for pointing this out. In Fig. 5, the fraction is defined as (number of trajectories that meet the eruption-region criterion) / (total number of backward trajectories initialized for the corresponding flight date and θ -layer shown in Fig. 4). A trajectory is counted as meeting the criterion if it passes through the eruption-region filter, defined by the TROPOMI-observed SO₂ plume area during the satellite overpass window (24 Jun 2019 22:46–25 Jun 2019 03:50 UTC), at least once.

Backward trajectories are initialized from the selected plume layer(s) for each flight day, using the corresponding starting positions and times measured by the balloon-borne measurement. The denominator is therefore the number of trajectories whose starting θ lies within the selected θ interval(s). For the six cases shown in Fig. 5, the total numbers are 79 and 50 (03 Aug, two θ -layers), 72 (06 Aug), 190 (08 Aug), 165 (10 Aug), and 105 (12 Aug). The corresponding fractions are 5.06%, 6.0%, 9.72%, 3.16%, 6.67%, and 5.71%, respectively. We have added this definition and the per-case trajectory counts to the revised manuscript.

In Fig. 5, the reported fraction is the percentage of the total backward trajectories in Fig. 4 that pass through the eruption-region mask during that window. Because this filtering criterion is highly selective, only a small fraction of trajectories remain, and the fractions can be regarded as conservative estimates. defined as (number of trajectories that meet the eruption-region criterion) / (total number of backward trajectories initialized for the corresponding flight date and θ -layer shown in Fig. 4). For the six cases shown in Fig. 5, the total numbers of initialized trajectories are 79 and 50 (03 Aug, two θ -layers), 72 (06 Aug), 190 (08 Aug), 165 (10 Aug), and 105 (12 Aug). Because this filtering criterion is highly selective, only a small fraction of trajectories remains, and the resulting fractions can be regarded as conservative estimates.

Lines 209-211 Looking at the top right panel of Figure 5 it looks like the air parcel travels directly from the area of Raikoke westwards to Lhasa. However the text says it circles the globe three times, while the red and blue colors of figure 4 (second panel) make it look to me as if the plume circled the globe once.

Could you clarify this point please?

Thank you for pointing this out. The phrase “encircled the globe three times” referred to the satellite-tracked evolution of the VVP core reported by Gorkavyi et al. (2021) and Khaykin et al. (2022), and was not meant to imply that three full revolutions are visible from our single map panel. To avoid confusion, we have removed this wording from the revised manuscript. Figure 5 shows backward trajectories that are consistent with the early stage of the VVP pathway around late July. We have clarified this wording in the revised manuscript.

Satellite observations from TROPOMI on Sentinel-5P indicate that the VVP core was entrained into the summertime easterlies around 20–25 July (Gorkavyi et al., 2021; Khaykin et al., 2022). The backward trajectories initialized in the 3 August 2019 plume layer (459–472 K) shown in Fig. 5 are consistent with the late-July stage of this satellite-tracked pathway. The potential temperature of the VVP during its transit through the ASMA, inferred from satellite detections, also closely matches the altitudes of enhanced BSR₄₅₅ (Gorkavyi et al., 2021; Khaykin et al., 2022).

Lines 219-221 The 'clockwise advection' within AMSA isn't very noticeable to me on the back trajectory plots in Figure 5.

Thank you for the comment. We agree that a clear clockwise rotation is not identifiable from the trajectories as plotted in Fig. 5. We therefore revised the text and removed the wording “clockwise advection”, replacing it with a more neutral statement that the trajectories enter and remain within the ASMA region, which is consistent with subsequent transport shaped by the ASMA circulation.

From 6 to 20 August 2019, the overall transport pattern remained similar to that on 6 August—corresponding to the main volcanic aerosol plume primarily driven by the subtropical westerly jet. However, after entering the ASMA, some air parcels took different paths: they were advected clockwise within the ASMA’s anticyclonic circulation. This clockwise advection diluted the aerosol concentration, contributing to the observed decrease in BSR₄₅₅. After entering the ASMA, some air parcels deviate from the jet pathway and circulate within the anticyclonic region. This increased spreading of trajectories suggests dispersion and lateral mixing with surrounding air, which may contribute to the observed decrease in BSR₄₅₅.

Lines 262-265 It was disappointing to me to read that the upper peaks from 1 August and 3 August were not going to be simulated. Could you perhaps add another sentence to explain why these weren't included too.

Thank you for the comment. The reason why the upper peaks (1 and 3 August) are not simulated is discussed in detail in our response to the major comment (see above). We have added a short reference sentence in the manuscript.

In Fig. 7, the SO₂-based tracers are also released at 400–420 K. This setup primarily samples the diluted main plume rather than the higher-altitude trailing filament of the vorticed volcanic plume (VVP). Accordingly, the higher-altitude peak on 3 August 2019 likely originates from the VVP filament near 460–490 K and is not resolved by the 400–420 K release. A sensitivity simulation targeting the upper-level VVP filament shows enhanced tracer fractions near the observation region (not shown here); however, with the currently used CLaMS resolution, this thin and sharp aerosol peak at a single profile location is difficult to reproduce.

Figure 7 The correlation coefficient seems a limited metric because in some cases the peak is dispersed over a wide altitude range (in other words, you're correlating one gentle curve with another gentle curve, in which situation correlation is not very helpful). Is the relation between tracer fraction and BSR linear across all the different profiles? It looks like it is. Would it be more meaningful to calculate the fit across all the different profiles?

We thank the referee for the insightful comment. The suggested single overall linear fit across all profiles would mainly address amplitude scaling, whereas Fig. 7 is intended to evaluate the vertical structure (shape and peak height) for each individual profile. Because BSR amplitude is not expected to follow one universal linear scaling with a transport tracer across different days, we keep r (after normalization) together with $|\Delta\theta|$ and clarified this point in the manuscript.

Line 323 I think this is the first time you have discussed horizontal entrainment, the previous discussion was about upwelling air diluting the aerosol concentration.

Thank you for this comment. By “horizontal entrainment” we refer to the situation after the trajectories enter the ASMA (from 6 August onward in Fig. 5), where some air parcels circulate within the anticyclonic region and the trajectories spread out. This increased spreading suggests enhanced dispersion and lateral mixing with surrounding air, which may contribute to the observed decrease in BSR₄₅₅. We have clarified this interpretation in the corresponding discussion paragraph and revised the conclusion accordingly, using the same wording (“dispersion and lateral mixing with surrounding air”) rather than introducing “horizontal entrainment” as a new mechanism there.

After entering the ASMA, both upwelling from lower potential temperature levels and horizontal entrainment of surrounding air contribute to this dilution. dilution may be driven by upwelling from lower potential temperature levels and by dispersion and lateral mixing with surrounding air.

Lines 335-337 How have you shown that?

We agree that the original wording was too strong. Our results do not demonstrate global dispersal by the ASMA. Instead, they show that only a small fraction of the Raikoke plume is entrained into the ASMA. Within the ASMA, confinement and summertime diabatic uplift can promote redistribution and dilution in the UTLS and can potentially transport this fraction to higher altitudes, consistent with established ASMA dynamics (e.g., Vogel et al., 2019). We revised the text accordingly.

In particular, our findings show that the ASMA may play an important role in dispersing aerosols from mid-latitude volcanic injections throughout the global stratosphere. Our results suggest that a small fraction of the Raikoke plume becomes entrained into the ASMA. Within the ASMA, confinement and summertime diabatic uplift can potentially transport these plume fractions to higher altitudes(e.g., Vogel et al., 2019).