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:

This study presents comprehensive analyses of transport pathways of a rare volcanic eruption event and its impact on the stratospheric circulation by combining in-situ and satellite observations and global modeling. The results were reasonably structured throughout and well explained. However, most information in the main text seems to be focused rather on description of the results and lacks its significance or context. I think the authors should also emphasize the novelty of this work more clearly. A statement emphasizing how valuable in-situ measurements used in this study are and what can be achieved by using both the trajectory and global models can be included. I would also like to know if any studies that are similar to this work have ever done before. There are many places where the writings are vague. I would recommend improving clarity of writings to strengthen the paper's scientific quality.

We thank the reviewer for the constructive general and specific comments. In the revised manuscript, we strengthened the motivation and novelty statements, and expanded the discussion and conclusions to better highlight the broader implications for UTLS transport and ASMA circulation. We also clarified the value of the in-situ balloon-borne measurement and what can be achieved by combining trajectory analyses with global there dimensional tracer simulations, and added brief context on related studies. Finally, we revised the manuscript throughout to reduce vague wording and improve clarity. Specific changes are addressed point-by-point in our responses to the reviewer's specific comments below.

Specific Comments:

P1, L4: SO_2 -> sulfur dioxide (SO_2)

Done. We now write sulfur dioxide (SO_2) at first mention.

P1, L14: What does 'out-of-region' validation mean?

We clarified that "out-of-region validation" refers to evaluating the model with independent observations outside the ASMA region (here: Boulder, USA).

~~Independent Portable Optical Particle Spectrometer (POPS) profiles over Boulder (USA) confirm the plume's timing and altitude, providing out-of-region validation.~~ Portable Optical Particle Spectrometer (POPS) profiles over Boulder (USA) confirm the plume's timing and altitude, providing an independent evaluation of its transport outside the ASMA region.

P1, L15: 'Sensitivity…lofting' – The meaning of this sentence is unclear. Does this mean 'Sensitivity test using the CLaMS model indicates that the aerosols can be lifted additional ~4-5 km depending on the injection height due to aerosol-radiative lofting?

We agree that the original sentence was unclear. We have rephrased it to state that our CLaMS sensitivity tests show the best agreement with the observed profiles for tracer release

levels around 400–420 K (~15–16.5 km), which is about 4–5 km higher than the peak injection altitude (~11 km) reported by Cai et al. (2022). We now present aerosol radiative self-heating lofting as a possible explanation for this vertical offset, and we acknowledge that it may also reflect uncertainties in injection-height estimates and discrepancies between the model and the observational techniques. Accordingly, we removed wording that suggested radiative lofting as a conclusion of the paper.

P2, L18: It would be nice to add more recent work here, if there is any.

The impact of volcanic eruptions on climate has been a subject of widespread concern (McCormick et al., 1995; Thompson and Solomon, 2009; Solomon et al., 2011; Bourassa et al., 2012; Masson-Delmotte et al., 2021; Schmidt and Black, 2022).

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., eds.: Climate Change 2021: The Physical Science Basis, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896, 2021.

Schmidt, A. and Black, B. A.: Reckoning with the rocky relationship between eruption size and climate response: toward a volcano-climate index, Annual Review of Earth and Planetary Sciences, 50, 627–661, 2022.

P2, L26: negative -> negative radiative

Done.

P2, L31: from an eruption -> from an eruption are

Done.

P2, L35: There should be something at the end of this sentence. 'far longer than xxx'.

Done. We completed the sentence by specifying the comparison (longer than tropospheric plumes).

Eruption products injected directly into the stratosphere—or volcanic plumes in the upper troposphere that self-loft via radiative heating into the lower stratosphere—can persist far longer than plumes confined to the troposphere.

P2, L36: It needs a reference for the Brewer-Dobson circulation here.

Done. We added a reference for the Brewer–Dobson circulation.

Aerosols from tropical eruptions are transported most efficiently via the Brewer–Dobson circulation (Brewer, 1949; Dobson, 1956; Butchart, 2014), whereas mid-latitude eruption aerosols can still reach the tropics through Rossby-wave breaking or transport by the Asian Summer Monsoon Anticyclone (ASMA) (Konopka et al., 2009; Kloss et al., 2021; Wu et al., 2023).

Brewer, A. W.: Evidence for a world circulation provided by the measurements of helium and water vapour distribution in the stratosphere, Q. J. R. Meteorol. Soc., 75, 351–363, https://doi.org/10.1002/qj.49707532603, 1949.

Dobson, G. M. B.: Origin and distribution of polyatomic molecules in the atmosphere, Proc R Soc London A, 236, 187–193, 1956.

Butchart, N.: The Brewer-Dobson circulation, Rev. Geophys., 52, 157–184, https://doi.org/10.1002/2013RG000448, 2014.

P2, L42-44: Among…summer. Deep…circulation -> These need to be supported by references.

We agree. We have removed the original phrasing and reorganized the text to more clearly emphasize the ASMA's role in boreal-summer UTLS transport, supported by appropriate references.

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, confining these air masses over Asia during 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, as the ASMA boundary is not a strict transport barrier, 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.

P3, L52: How was June 21-22 period determined to be during the anticyclone's mature phase?

Thank you for the comment. We clarified that "mature phase" refers to August 2019, when the Raikoke plume is transported into and through the ASMA (the period relevant to our balloon observations), rather than to the eruption dates (21–22 June 2019).

~~The mid-latitude Raikoke volcano (48° N, 153°E) erupted on 21–22 June 2019 (VEI 4), and its aerosol plume was advected through the ASMA during the anticyclone's mature phase, providing an ideal case to examine how the ASMA modulates volcanic plume transport.~~ The mid-latitude Raikoke volcano erupted on 21–22 June 2019. …. In August 2019, part of the aerosol plume was transported into and through the ASMA during the mature stage of the boreal-summer anticyclone, providing an ideal case to examine how the ASMA modulates volcanic plume transport.

P3, L56-58: The…plumes. -> Are these also in Khaykin et al. (2022)?

Yes. We added the appropriate reference (Khaykin et al., 2022).

Three days after the eruption, compact anticyclonic "vorticized volcanic plumes" (VVPs) detached from the main volcanic cloud, trapping more than half of the SO_2 mass (Khaykin et al., 2022). The primary VVP then rose to ∼27 km, spanning ∼400 km in width but only ∼1.5 km in depth. Meanwhile, the residual main plume was diluted at lower altitudes, resulting in two distinct Raikoke plumes (Khaykin et al., 2022).

P3, L59: when the site…levels. -> This sentence needs to be more specific. Was this based on the measurements of a specific variable, such as, geopotential height?

Yes, we now specify that the ASMA position is indicated using ERA5 geopotential height at 150 hPa and we added the corresponding contour in Figure 1 (Figure 1a of the manuscript). The text and caption have been revised accordingly.

Beginning in August 2019, frequent balloon-borne measurements were conducted over Lhasa (29.66◦N, 91.14◦ E), ~~when the site lay inside the ASMA at UTLS levels.~~ which was located within the ASMA at UTLS levels, as indicated by the ERA5 150 hPa geopotential height field (Fig. 1a).
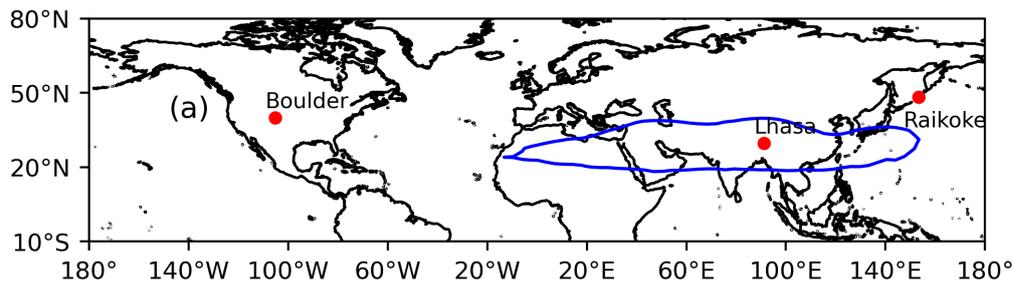

Figure 1 (Figure 1a of the revised manuscript). Map showing the locations of the balloon measurement sites over Lhasa (29.7°N, 91.1°E) and Boulder (39.9°N, 105.2°W), and the Raikoke volcano (48.3°N, 153.3°E). The blue contour shows the ERA5 geopotential height at 150 hPa averaged over August 2019 at 00 UTC. The 14.32 km contour is used here as an indicator of the ASMA at UTLS levels.

P3, L64: from the TROPOsperic Monitoring Instrument (TROPOMI)

Done.

from the Tropospheric Monitoring Instrument (TROPOMI) aboard Sentinel-5P (Theys et al., 2024).

P3, L65: from Lhasa and Boulder -> Are those measurement locations? Why was Boulder selected here?

Yes, Lhasa and Boulder are the measurement locations. Boulder was included as an independent site outside the ASMA region to assess the plume evolution and its transport within the Northern Hemisphere, and to provide an external evaluation of the CLaMS simulations.

~~We also incorporate Portable Optical Particle Spectrometer (POPS) measurements from Lhasa (Tibet) and Boulder (USA).~~ We further use POPS profiles from Lhasa and Boulder to evaluate the simulated plume evolution over the Northern Hemisphere. In particular, Boulder serves as an independent site outside the ASMA region to evaluate plume transport.

P3, L67: I think the authors should state that why their work is new and how it is different from the previous studies. I think scarcity of in-situ measurements for the Raikoke or any volcanic eruption should be mentioned here.

We agree and have added a brief statement on the novelty and the limited availability of in situ UTLS measurements for the 2019 Raikoke eruption. We highlight that our study combines rare balloon-borne measurements with high-resolution ERA5-driven CLaMS trajectories and global SO_2-based tracer simulations, which together provide observational constraints on transport pathways, timing, and plume dilution in the ASMA.

~~This study investigates how the ASMA modulates UTLS volcanic plume transport following the Raikoke eruption.~~ In situ UTLS observations of volcanic aerosol are rare, particularly for the 2019 Raikoke eruption. Here we combine balloon-borne COBALD and POPS profiles with high-

resolution ERA5-driven CLaMS backward trajectories and global three-dimensional SO$_2$-based tracer simulations to identify transport of the Raikoke plume through the Northern Hemisphere and into the ASMA, with particular attention to transport pathways and time scales.

P3, L75: Please include exact days of the SWOP campaign. Also, why were the ECC measurements not analyzed?

We have added the exact balloon launch dates (Table 1 in the revised manuscript) for the SWOP measurements used in this study. ECC ozone data are not analyzed because this paper focuses on aerosol plume identification and transport using COBALD and POPS; ozone analysis is beyond the scope of the present work.

Site	Flight ID	Date	Mid-ascent time (UTC)	Key instruments	Observed plume layer: θ (K)	Observed plume layer: p (hPa)
	F01	30.07.19	17:58	COBALD CFH	–	–
	F02	01.08.19	15:45	COBALD CFH	–	–
	F03	03.08.19	15:23	COBALD CFH	410–422; 459–472	78–71; 59–56
	F04	06.08.19	15:26	COBALD CFH	404–416	82–75
	F05	08.08.19	15:10	COBALD CFH	389–423	98–73
	F06	10.08.19	16:05	COBALD CFH	397–422	84–70
Lhasa	F07	12.08.19	15:49	COBALD CFH	398–426	84–71
	F08	15.08.19	17:24	COBALD CFH	406–423	79–71
	F09	20.08.19	17:14	COBALD CFH POPS	393–434	89–68
	F10	30.09.19	15:34	COBALD CFH	385–452	96–64
	F11	28.10.19	15:24	COBALD CFH	390–459	100–60
	F12	24.11.19	15:09	COBALD CFH	410–482	79–55
	F13	04.01.20	15:29	COBALD CFH	393–399; 415–432	118–115; 99–91
	F14	28.06.19	17:05	POPS	–	–
	F15	07.08.19	17:08	POPS	373–442	122–73
Boulder	F16	27.08.19	16:38	POPS	385–429; 480–505	117–80; 59–52
	F17	08.11.19	17:58	POPS	389–435	107–76
	F18	03.12.19	18:05	POPS	–	–

Table 1 (revised manuscript). Summary of analyzed balloon flights at Lhasa and Boulder, including sequential flight ID, date, mid-ascent time (UTC), key instruments used in this study, and the potential temperature (θ) and pressure (p) ranges of the observed volcanic plume layer. The plume layer was identified from COBALD measurements where BSR$_{455}$ > 1.1 and CI > 6, and from POPS measurements where the particle number concentration exceeded 150 cm^{-3}. Mid-ascent time denotes the midpoint of the ascent period from launch to balloon burst. The "Key instruments" column lists only the instruments analyzed in this work; additional payload components were flown but are not listed here. A dash (-) denotes that no volcanic plume layer was identified for that flight.

P3, L81: Please add information about location of the ASMA relative to Lhasa during July-August 2019. As an option, a contour of a geopotential height can be added in Fig. 1a.

Please see our response to P3, L59. We added the ERA5 150 hPa geopotential height contour in Fig. 1a to show the ASMA location relative to Lhasa and updated the figure caption accordingly.

P5, L103: A citation is needed for the iMet radiosonde.

Done. We now specify the radiosonde as an International Met Systems (InterMet) iMet-1-RSB and added a reference to the manufacturer documentation at first mention.

Balloons were equipped with an electrochemical concentration cell (ECC) ozonesonde, a cryogenic frostpoint hygrometer (CFH), a compact optical backscatter aerosol detector (COBALD), and an International Met Systems (InterMet) iMet-1-RSB radiosonde (GRUAN Lead Centre, 2025). *ECC measurements are not analyzed in this study.*

GRUAN Lead Centre: InterMet iMet-1 (iMet-1-RSB) — GRUAN instrument information (radiosonde models), https://www.gruan.org/instruments/radiosondes/sonde-models/intermet-imet-1, accessed 13 Jan 2026, 2025.

P5, L110: Is 'sizing' referring to aerosol particles sizing?

Yes. Here, "sizing" refers to particle sizing (the conversion from scattering signal to particle diameter). We clarified this in the text.

Measurement uncertainties are dominated by particle *sizing (including sensitivity to the assumed refractive index) and flow-rate calibration (Gao et al., 2016).*

P5, L121: …limit are excluded following Theys et al. (2024).

We clarified that values below 0.3 DU are excluded following Theys et al. (2024).

…values below the instrument's 0.3 DU detection limit are excluded, following Theys et al. (2024).

P6, L127: 'applied' can be substituted with 'used'.

Done. We replaced "applied" with "used".

CLaMS is ~~applied~~ used *here to investigate the transport of the volcanic plume following the Raikoke eruption.*

P6, L129: hybrid coordinate   -> hybrid coordinate

We revised this sentence for clarity.

The CLaMS ~~vertical coordinate—the hybrid coordinate ζ—~~ hybrid vertical coordinate (ζ) *follows orography near the surface and transitions smoothly into θ once σ = p / psurf reaches 0.3 (usually about 300 hPa) (Pommrich et al., 2014).*

P6, L132: main runs -> control runs

We replaced "main runs" with "standard runs" to clarify that the native hourly 0.3° × 0.3° ERA5 forcing is our standard configuration.

…the ~~main~~ standard *runs use the native hourly fields on the 0.3° × 0.3° grid with 137 vertical levels up to 80 km (Hersbach et al., 2020), whereas …*

P6, L132: 0.3° x 0.3° (latitude x longitude)

Done. We clarified that the 0.3° × 0.3° grid refers to latitude × longitude.

…on the 0.3° × 0.3° (latitude × longitude) grid…

P6, L134 (and elsewhere): 6 h -> 6 hours
Done. We replaced "6 h" with "6 hours" throughout.

L6, L147: what does 'tracer injection mask' mean? Is this term used in CLaMS modeling in general?

By "tracer injection mask" we mean the 0/1 geographic source region used to initialize the tracer (value 1 inside the selected SO_2 plume area and 0 outside) at the injection time. We clarified this definition in the text and use "source-region mask" in the revision for clarity.

…~~as the tracer injection mask; only the spatial extent, not the column amplitude, was used.~~as a 0/1 source-region mask for tracer initialization (1 inside the selected SO_2 plume area, 0 outside); only the spatial extent, not the column amplitude, was used.

P7, L158: Briefly explain why this method is practical.

We added a brief explanation that the method is practical because it combines collocated backscatter (COBALD) and humidity (CFH), allowing a straightforward distinction between ice clouds and aerosol layers in situ.

The COBALD–CFH tandem provides a practical method for identifying cirrus clouds and aerosol layers because collocated backscatter and frost-point humidity measurements allow a straightforward separation of ice-cloud signatures from aerosol enhancements (Brabec et al., 2012; Cirisan et al., 2014; Reinares Martínez et al., 2021; Yang et al., 2023).

P7, L165: What does 'empirically highlighted' mean?

Thank you for the comment. We agree that the phrase "empirically highlighted" was unclear. We have replaced it with a description of the objective selection criteria: cirrus is excluded using $BSR_{455} > 1.2$, $RH_{ice} > 70\%$, and CI > 7; aerosol layers are then defined by $BSR_{455} > 1.1$ and classified using CI = 6 (Raikoke plume: CI > 6; ATAL/background: CI < 6).

P7, L174: …differs markedly… -> Could this be 'is significantly higher'?
The phrase "differs markedly" was not intended to emphasize the peak position, but rather the peak magnitude. We have revised the text to clarify that the more robust difference is the higher median BSR455 peak in 2019 (about 1.25) compared with the 2013 ATAL peak (about 1.10), while the higher potential temperature of the 2019 peak is retained as supporting information.

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

P7, L178: Why was the particle number density over Boulder so high in August? I think the impact of large-scale global circulation transporting aerosols between Lhasa and Boulder should be explained.

Thank you for the comment. Our global three-dimensional CLaMS tracer simulations (Sect. 4.2) show that the main Raikoke plume is transported predominantly along the subtropical westerly jet in the mid-latitude UTLS. Boulder lies closer to this main transport corridor, whereas Lhasa is located within the ASMA, where the anticyclonic circulation acts as a partial horizontal transport barrier. As a result, the plume fraction reaching Lhasa represents a more limited filament of the plume, which helps explain why POPS number densities at Boulder can be higher than at Lhasa in August. We added a short clarification in the text.

> *The particle number density at Lhasa on 20 August was lower than that at Boulder on 7 August and 27 August. This is consistent with the global CLaMS tracer simulations (Sect. 4.2; cf. Figs. 7 and 8), which show that the main Raikoke plume is transported along the subtropical westerly jet in the mid-latitude UTLS, while transport into the ASMA interior is more limited due to the anticyclone acting as a partial horizontal barrier. Section 4 presents backward-trajectory calculations and three-dimensional tracer simulations with CLaMS to verify the origin and transport pathways of the plume observed over Lhasa and Boulder.*

P9, L187: Is the 'eruption period' same as 21-22 June 2019?
We use a single reference time as the endpoint for the backward trajectories, 21 June 2019 at 18:00 UTC, rather than the full 21–22 June eruption period. We clarified this in the text.

> ~~*Backward trajectories were launched every second along the balloon's vertical ascent in the potential temperature range where an enhanced BSR455 was observed in Fig. 2, and traced back to the eruption period.*~~ *All trajectories were calculated backward to a single common reference time (21 June 2019, 18:00 UTC), which serves as the trajectory endpoint for all cases.*

P10, Fig. 4: It is hard to understand the direction of transport in this figure. Is the air moving mostly to the East from the eruption location? Also, what is the unit of x-axis? It looks like x-axis has irregular intervals, which makes it hard to understand.

Thank you for the comment. We have revised the figures as follows. Figure 2 (Figure 4 of the revised manuscript) shows backward trajectories; we clarified the time axis by labeling it as Date (dd.mm.yy) and by updating the caption to state that the x-axis represents the backward integration from the balloon initialization time back to the eruption reference time.
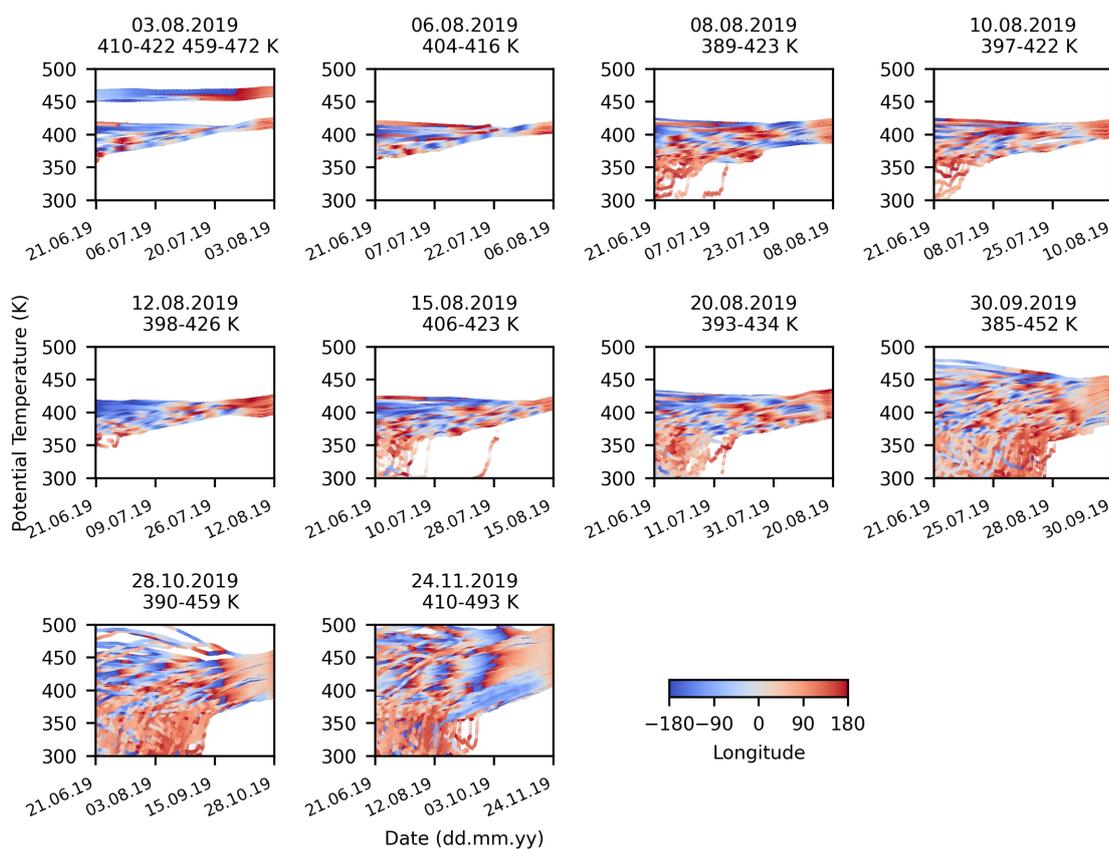
Figure 2 (Figure 4 of the revised manuscript). Backward trajectories initialized from the Lhasa balloon observations and traced back to the Raikoke eruption reference time (21 June 2019, 18:00 UTC). Only trajectories initialized within the enhanced BSR455 potential-temperature range (orange shading in 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).

P11, L211: Which satellites were used in these studies?

We clarified this in the text. The satellite observations in Gorkavyi et al. (2021) and Khaykin et al. (2022) are primarily based on TROPOMI on Sentinel-5P.

~~*Furthermore, the potential temperature measured by the satellite during its ASMA transit also closely matched the altitudes of enhanced BSR455 (Gorkavyi et al., 2021; Khaykin et al., 2022).*~~ *The potential temperature inferred from TROPOMI (Sentinel-5P) plume detections during the ASMA transit also closely matched the altitudes of enhanced BSR_{455} (Gorkavyi et al., 2021; Khaykin et al., 2022).*

P11, L215-217: This is somewhat vague. I would suggest revising it with more specific information for clarity.

We agree and revised this sentence to specify the two branches and their controlling circulation regimes.

~~*Although both sets of air parcels correspond to the same balloon-borne observation profile, they represent entirely different transport pathways—originating from two distinct regions of the Raikoke plume at different altitudes and driven by different processes.*~~ *Although both sets of air parcels belong to the same balloon profile, they trace back to two distinct plume components:*

the l lower-θ main plume in the subtropical westerly jet (~410–422 K) and the higher- θ VVP filament in the summertime easterlies (~459–472 K). This indicates different source altitudes within the Raikoke plume and distinct dynamical transport pathways.

P11, L223 (and elsewhere): What do 'SO$_2$-based tracers' mean?

By "SO$_2$-based tracers" we mean passive tracers initialized from the observed SO$_2$ plume mask (1 inside, 0 outside) at the injection time and then transported and mixed in CLaMS. We clarified this in the text.

In the global three-dimensional CLaMS simulations, ~~SO$_2$-based tracers were released within the defined region (Fig. 1b) at potential-temperature levels of 400–420 K at 00:00 UTC on 25 June 2019 to simulate the dispersal of the volcanic plume.~~ we use passive tracers initialized from the observed SO$_2$ plume mask (Fig.~1b). We refer to these as SO$_2$-based tracers. At 00:00 UTC on 25 June 2019, the tracer is set to 1 inside the mask (0 outside) within three potential-temperature ranges (380–400 K, 400–420 K, and 420–440 K) and then advected and mixed throughout the global atmosphere in CLaMS.

P11, L225: global maps with -> global maps of?

Done.

Figure 7 shows global maps of fractions of the SO$_2$-based tracers falling within the 400–420 K layer for each measurement day from 30 July to 20 August 2019, using the modified simulation.

P12, L231: the dynamical situation…-> the isentropic transport, showing outflow of the ASMA and in-mixing…

Done. We revised the wording to refer to isentropic transport and to describe ASMA outflow and in-mixing more directly.

The 11 PVU potential vorticity contour (layer mean over 400–420 K) ~~indicates the dynamical situation, showing in addition outflow of the ASMA (filaments) and in-mixing of PV-rich air from high latitudes.~~ illustrates the isentropic transport, including ASMA outflow (filaments) and in-mixing of PV-rich air from high latitudes.

P12, L234: Which 'observations' specifically?

We clarified that this refers to the Lhasa balloon observations (COBALD profiles) used in this study.

The results shown in Fig. 6 illustrate the overall intrusion of air masses into the ASMA and agree well with the Lhasa COBALD BSR$_{455}$ observations.

P12, L244: How does 'Lyapunov exponent' work in CLaMS?

We added a short explanation in the revised manuscript (Sect. 2.3). In CLaMS, parameterized mixing is triggered when the integral deformation between neighboring air parcels exceeds the critical value γc=λc Δt, where λc is the critical Lyapunov exponent and Δt is the mixing interval. Thus, for a given Δt, a larger λc (larger γc) implies less frequent parameterized mixing (and vice versa).

In the CLaMS mixing scheme, parameterized mixing is triggered when the integral deformation between neighboring air parcels exceeds an empirical critical deformation $\gamma c = \Delta t \, \Delta t$, where λc is the critical Lyapunov exponent and Δt is the advective time step (mixing interval). For a given Δt, a larger Δt (thus a larger γc) requires stronger deformation to trigger mixing and therefore corresponds to less frequent parameterized mixing (and vice versa) (Konopka et al., 2004, 2007). In our setup, the modified simulation corresponds to enhanced parameterized mixing compared to the control simulation. Throughout most of the paper we show results from the modified simulation, as these agree better with the observations. Sensitivity to parameterized mixing intensity and comparisons with the control simulation are discussed in Sect. 5.1. The mixing configurations and the additional sensitivity runs (rectangular mask and coarser ERA5 input) are summarized in Table 2.

P12, L252: driving data -> either change to 'input' or remove it

Done. We revised this sentence.

~~Note that, for the control simulation, changing the resolution of the ERA5 driving data has only a minor effect and does not affect our conclusions; compare Fig. A1 (0.3∘ × 0.3∘ resolution, 1 hours) with Fig. A2 (1∘ × 1∘ resolution, 6 hours).~~ However, changing the ERA5 resolution has only a minor effect and does not affect our conclusions. This is evident from the comparison of Fig. A1 (0.3∘ × 0.3∘ resolution, 1 hours) and Fig. A2 (1∘ × 1∘ resolution, 6 hours).

P14, L279-284: What is the significance of this result in terms of large-scale circulation?

These Boulder comparisons provide an independent evaluation outside the ASMA, showing that the modified simulation represents the timing and altitude of the Raikoke plume in the mid-latitude UTLS more reliably. This supports our interpretation that transport and dispersion along the large-scale mid-latitude circulation (including the subtropical jet and subsequent mixing) are sensitive to the representation of mixing, and that the modified configuration yields the most consistent large-scale evolution.

Over Boulder, we likewise compare the tracer-fraction profiles on the measurement dates with the POPS aerosol number concentration profiles at STP (Fig. 10). For the computation of r, we evaluate within 375–450 K for 7 August and 27 August 2019, and within 375–475 K for 8 November 2019. Overall, the SO_2-based tracers in the modified simulation (blue) reproduce the observed peak structure more closely, with higher r and smaller $|\Delta\theta|$ than the control and rectangle-based simulations. This indicates that the plume evolution along the mid-latitude UTLS circulation is sensitive to the representation of mixing, and that the modified configuration better captures the large-scale transport and dispersion.

P15, L286: How long did the initial injection last?

We added the duration of the main injection: 21 June 2019 18:00 to 22 June 2019 03:00 UTC (about 9 hours), noting that some reconstructions extend SO_2 release to ~06:00 UTC.

The Raikoke plume was injected primarily within 8–16 km (Kloss et al., 2021; Cai et al., 2022; Vernier et al., 2024). The main injection occurred between 18:00 UTC on 21 June and 03:00 UTC on 22 June 2019 (with SO_2 release possibly extending to ~06:00 UTC) (Cai et al., 2022; Vernier et al., 2024).

P15 (Figs. 7-10): The locations and dates are not easy to see on these figures. I recommend either using larger size fonts or placing them on them the title.

Done.

P16, L307-309: The relevance of these two sentences to this study is unclear.

We have revised the paragraph to state that the ~4–5 km vertical offset is only a possible interpretation (e.g., radiative self-heating lofting), and that it may also arise from uncertainties in injection-height estimates and model/technique differences. The text has been rephrased accordingly.

> ~~Based on the Lagrangian reconstruction by Cai et al. (2022), approximately 1.5 Tg of SO2 was initially injected between about 5 and 15 km, with a peak at around 11 km. If we use this central injection altitude to estimate plume self-heating effects, the cloud may then be lofted by an additional ~ 4–5 km. Therefore, the height at which our SO2-based tracers best match observations will exceed the true injection center altitude. However, different observational techniques often report varying estimates of the injection center altitude (e.g., Kloss et al., 2021; Cai et al., 2022; Vernier et al., 2024). This also leads to uncertainty in our assessment of radiative lofting heights in this study.~~ *Cai et al. (2022) estimate a peak injection altitude near 11 km, whereas the tracer level that best matches the observed profiles corresponds to ~15–16.5 km (400–420 K). This ~4–5 km offset could be consistent with radiative self-heating lofting of the SO_2-rich cloud, but it may also reflect uncertainties in injection-height estimates across techniques and model-related discrepancies (e.g., Kloss et al., 2021; Cai et al., 2022; Vernier et al., 2024).*

P17, L311: A motivation for this study can be stated here as well.

Done. We added a brief motivation sentence at the beginning of the Conclusions.

> *Motivated by the limited availability of in-situ UTLS measurements of volcanic plume transport and the need to better quantify ASMA-related pathways, we combined in-situ balloon observations over Lhasa and Boulder with Lagrangian transport simulations using the CLaMS model, driven by high-resolution ERA5 data, to investigate the transport pathways and mixing processes of the Raikoke plume in the UTLS during the mature phase of the ASMA. Our main conclusions are:*

P17, L337: What is the significance of the results in understanding role of volcanic eruption in our climate?

We added a brief statement in the Conclusions on climate relevance.

> *In summary, by combining observations and modelling, we provide further insights into how the mid-latitude Raikoke plume is transported through the Northern Hemisphere UTLS over long distances. We show evidence that the Asian summer monsoon plays a key role in this transport. In particular, parts of the plume are entrained into the monsoon anticyclone and are subsequently diluted by horizontal transport and vertical upwelling within the anticyclone. Our findings improve the understanding of how aerosols from a mid-latitude volcanic injection are transported and dispersed in the lower stratosphere, including in the vicinity of the Asian summer monsoon. This improved understanding of plume transport and dilution is relevant for*

estimating regional radiative forcing and assessing potential impacts on stratospheric ozone chemistry.

~~We identified two distinct isentropic transport pathways and quantified the dilution mechanism via mixing from air masses outside the plume. Our simulations show that small-scale atmospheric mixing processes are critical for dispersing the volcanic plume along its pathway through the stratosphere, and that representing these (often subgrid-scale) processes in models is essential for reliable simulations of volcanic plume transport. In this sense, changes in model resolution require adjustment of mixing parameterizations. 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.~~ We identified two distinct isentropic transport pathways and assessed plume dilution via mixing with air masses outside the plume. Our simulations show that atmospheric mixing processes, as parameterized in CLaMS in relation to flow deformation, are critical for dispersing the volcanic plume during stratospheric transport. Accordingly, changes in model resolution require adjustment of the mixing parameterization. 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).