Response to Reviewers

Manuscript title: "Initial conditions control transport of volcanic volatiles, forcing and impacts"

Manuscript authors: Zhihong Zhuo, Herman F. Fuglestvedt, Matthew Toohey and Kirstin Krüger

We would like to thank the reviewers for their efforts and insightful comments, which have contributed to improving the clarity and quality of our manuscript. We have carefully revised the manuscript in accordance with the reviewers' feedback. Below, we provide the list of reviewers' questions and comments (in gray italics), along with our responses (in black). Texts in the revised manuscript are highlighted in red.

1. **Response to Reviewer #1**

https://egusphere.copernicus.org/preprints/egusphere-2023-2374#RC1

There's some interesting stuff in here, and I think with some revision this paper could be a useful contribution. I am recommending major revisions. I have a few big issues:

The first is that many of your descriptions are unclear, so you get conclusions that don't obviously make sense. I've pointed out some detailed examples below.

Thank you for your valuable and constructive feedback, which significantly contributed to enhancing the clarity and quality of our manuscript. We carefully reviewed and revised the manuscript in accordance with the comments provided, focusing on the clarity of the descriptions, the main purpose of the study and its flow. Please see also our responses to your detailed comments below.

The second is that your experiment is not well controlled. You don't provide simulations of sulfur injection without halogens. You also don't carefully control for different ENSO states. Perhaps this can be addressed through my first main point, in that it's not entirely clear what questions you're trying to answer.

We apologize for any lack of clarity regarding our experiment descriptions. As outlined in Table 1, we conducted sensitivity simulations involving sulfur injection without halogens. These simulations include one January and one July injection for both tropical and extratropical eruptions. The results of these sensitivity simulations are presented in Figure 6 and discussed in Sections 4.3 and 4.4.

Our primary objective is to study the impact of initial atmospheric conditions on the transport of volcanic volatiles, forcing and impacts, with particular emphasis on the combined sulfur and halogen injections into the stratosphere, which is mostly neglected in previous studies. Our secondary objective is to compare the difference between tropical and extratropical eruptions with sulfur and halogen injections.

Thus, we conducted ensemble simulations of sulfur injection with halogens with varied initial atmospheric conditions (starting from different ENSO, westerly QBO and polar vortex states) and studied how they influence subsequent volcanic forcing and impacts. For investigations on impacts of volcanic sulfur-only versus sulfur and halogen injections, atmosphere-only simulations, as conducted, f.e., in Staunton-Sykes et al. (2021), may be more suitable, and large model ensembles for the initial climate impact of ENSO as designed and discussed by the VolMIP paper in Zanchettin et al (2022).

To enhance the clarity regarding the goal of our study, we have revised lines 70-73 in the introduction to: "In this study, we address the following questions: How do initial atmospheric conditions influence transport of volcanic volatiles and volcanic forcing after tropical eruptions, particularly in light of the co-injection of sulfur and halogens into the stratosphere? What differences do tropical and NH extratropical eruptions have on volcanic forcing and subsequent climate and ozone impacts?". Please refer also to our answers to the related comments below for further clarification.

Third, which may also be related to the first point, is about statistical significance. You do a good job of showing when the ensemble members are different from the control run. You do not differentiate the ensemble members from each other, which I think is the more interesting question and better aligned with what I interpreted as the purpose of your manuscript. This also leads to figures that are hard to interpret, as they contain a huge amount of information that obfuscates the intra-ensemble differences.

The conclusions are drawn from all six ensemble members, as the difference remains consistent among them across variables. We aim to highlight the intra-ensemble differences by discussing the differences between H1/H2 and H6 in the manuscript. To enhance clarity regarding these differences, we have included quantifications of percentage changes between members H1 and H6. Next, we have also simplified Figures 1 and 2 according to yours and the second Reviewer's comments. For example, when describing the total sulfur burden changes in the revised Figure 2, we write now: "In contrast, the global total sulfur burden exhibits a 42% longer e-folding time in H1 compared to H6, with respective e-folding times of 27 months and 19 months (Fig. 2a)". Further elaborations are provided in the related detailed comments above and below.

Some more detailed comments:

I think some more careful description in the first few pages is warranted. There are several points where you say that the initial conditions of the eruption are important, which is also known from the El Chichón and Pinatubo eruptions (the wind direction dictated where the aerosols went). But then you also talk about the season of the eruption, which matters more from a large-scale circulation perspective. I'd like you to be specific about what you mean by initial conditions and clarify the relevant timescales/processes.

In our experiment design, we incorporated varying initial atmospheric conditions starting from different ENSO, QBO westerly and polar vortex states. These ambient atmospheric conditions contribute to different wind directions, which dictate the initial transport of volcanic volatiles and aerosols within the first month, subsequently impact volcanic forcing, and thus the climate and environmental responses. We agree that our formulation has led to confusion as different initial climatic states, such as ENSO, impact also the following volcanic climate response from months to years. To better elucidate this aspect, we have emphasized the role of initial atmospheric conditions as exemplarily shown here for the Title, Abstract, Introduction and in the Discussion as follows:

Title:

"Initial atmospheric conditions control transport of volcanic volatiles, forcing and impacts"

Abstract:

"Moreover, initial atmospheric conditions of the climate system play an important role in shaping the volcanic forcing and response… Here, we perform ensemble simulations of volcanic eruptions at 15° N and 64° N in January, injecting 17 Mt of SO_2 together with HCl and HBr at 24 km altitude. Our findings reveal that initial atmospheric conditions control the transport of volcanic volatiles…"

In the introduction from line 53:

"The evolution of stratospheric volcanic materials and associated radiative forcing has been suggested to depend on the state of the atmosphere at the time of the eruption. The initial spread of volcanic clouds depends on the wind direction at the time of eruption, as

evidenced by the different volcanic cloud distribution observed a few weeks after 1982 El Chichón and 1991 Pinatubo eruptions (Robock 2000). In the stratosphere, the Quasi–Biennial Oscillation (QBO) dominates the tropical circulation with alternating easterly and westerly winds (Baldwin et al., 2001). Stratospheric aerosols experience greater lofting and tropical confinement under easterly shear conditions in the QBO region, as opposed to when a westerly shear is present (Trepte and Hitchman, 1992). In the extratropical stratosphere, the initial stability of polar vortex largely modulates evolution and distribution of volcanic materials (Fuglestvedt et al., 2024), which also relates to the seasonal cycle of the Brewer Dobson Circulation (BDC, Butchart, 2014; Toohey et al., 2011) and seasonal variation of OH concentration at different latitudes (Fuglestvedt et al., 2024; Toohey et al., 2019). Most of these variabilities operate on scales ranging from hourly to interannually, collectively shaping the evolution and distribution of volcanic materials and subsequently determining volcanic forcing.

The volcanic forcing plays an important role in determining the post-eruption climate response. The initial climatic state such as the pre-eruption El Nino Southern Oscillation (ENSO) modulates the post–eruption ENSO responses and the surface winter warming pattern (Coupe and Robock, 2021; Khodri et al., 2017; Pausata et al., 2016, 2020). For addressing the role of the initial climate state, the use of large model ensembles and multi model comparison is suggested (Zanchettin et al, 2022)."

Results, Section 3.2.2: We have deleted the last sentence about the potential ENSO impact, and only discussed it at the Discussion Section.

Discussion, Section 4.1:

"Overall, we show that initial atmospheric conditions impact the distribution of volcanic materials already in the first month as well as the following evolution and distribution of volcanic aerosols, ultimately shaping the volcanic forcing. Our results reveal the potential for predicting the latitudinal distribution of volcanic volatiles and assessing the subsequent volcanic forcing and associated climate and environmental impacts already after the first month of tropical and NH extratropical eruptions. More models and large ensembles are needed to corroborate these findings, and to test how different initial climate states such as ENSO and the QBO could impact the distribution of volcanic materials, volcanic forcing and subsequent responses for tropical and extratropical eruptions. The future phase of the Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP) (Zanchettin et al., 2022) holds potential as a valuable resource for addressing these research needs."

This isn't as controlled of an experiment as it could be, as you don't provide simulations of sulfur injection without halogens. You mention that this could be important in lines 340-344. I realize doing new simulations could be a lot of work (although the simulations are short), so perhaps this could be solved by better caveating your study. And then your discussion of lines 346-347 (and perhaps all of Section 4.4) will need to be modified.

We apologize for any confusion caused by lines 340-344. To clarify, we considered the co-injection of sulfur and halogen in our baseline experiments. In addition, we tested the sensitivity of sulfur only injection simulations, and these findings are discussed in lines 326-339.

To enhance clarity, we have revised this paragraph as follows:

"In this study, we focused on the co-injection of sulfur and halogens in our baseline experiments and conducted sensitivity tests to examine the impact of sulfur-only injection. Volcanic ash and other volatiles, such as water vapor, can also be injected (LeGrande et al 2016, Millán et al 2022, Zhu et al 2020), which can alter the composition, distribution, and volcanic forcing…."

There isn't much discussion of the phase of the QBO and tropical confinement in the Easterly phase.

Good point. Our simulated eruptions occur in a westerly phase of the QBO but under an easterly vertical shear, which is linked to tropical confinement of aerosols (Trepte and Hitchman, 1992). Taking also the second reviewer's comment into account, we have added the following in Section 4.1:

"In this study, we conducted experiments with a QBO westerly phase at 30 hPa, accompanied with an easterly phase above (Fig. S7). The differences among the ensemble members, particularly regarding the asymmetry of volcanic forcing, might be amplified if varying initial QBO states are considered, such as including a westerly shear."

Line 140: I suppose it depends on what you mean by "climate impact". If one cares about tropical precipitation shifts or northern hemisphere winter warming, high latitude eruptions are known to have a greater impact than tropical eruptions.

Here, we considered the radiative and temperature impact. We revised it to "Tropical eruptions have usually been thought to induce stronger surface cooling than extratropical eruptions, as SO_2 and volcanic aerosols are transported to both the Northern and Southern Hemispheres."

Lines 146-148: So is the difference between the ensemble members due to wave breaking? It's not obvious from reading this _how_ the ensemble members differ. I don't see analysis supporting your statements.

Thanks for the comments. To clarify the differences between the ensemble members better, we revised Figure 1 and the corresponding text accordingly, see our detailed response to reviewer 2 below.

With regard to the wave breaking, which is associated with SO_2 filaments pulled out of the subtropics in H6 in contrast to H1, we have added the new Figure S1 (shown below). Figure S1 indicates that tropical air masses are pulled out due to planetary wave activity in the extratropics, which is associated with wave breaking and mixing of air masses in the surf zone (Krüger et al., 2005, McIntyre et al., 1983). However, it is more about discussion instead of result description, thus, we changed the text to: "During this boreal winter, filaments of high SO_2 concentration are pulled towards NH mid-latitudes, particularly evident in H5 and H6 (Figs. 1a and S1)."

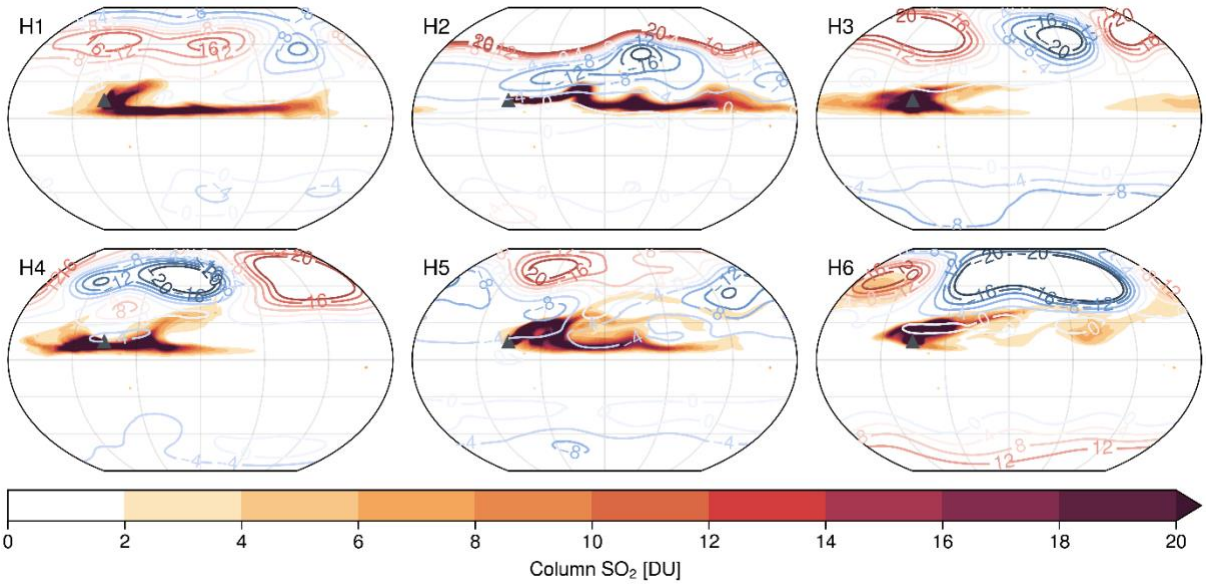


Figure S1. The first month longitudinal and latitudinal distribution of SO_2 column burden (filled contours) and geopotential height anomaly in units of geopotential decameters

(contours) at 30 hPa after tropical eruptions in January for the six members of the baseline experiment. The gray triangle denotes the eruption latitude and longitude at 15° N and 91° W.

Figure 2 is extraordinarily complicated, and it's not obvious what the take-home message is just by looking at it. I wonder if this figure could go into supplemental material, and then another, simpler figure that highlights the main points can be in the main text.

Following your suggestion, we have simplified Figure 2 and relocated subfigures 2a-2f and corresponding text to the supplement (new Figure S3 and Section S1).

In the revised figure 2, displayed below, we show now the total sulfur burden alongside SAOD.

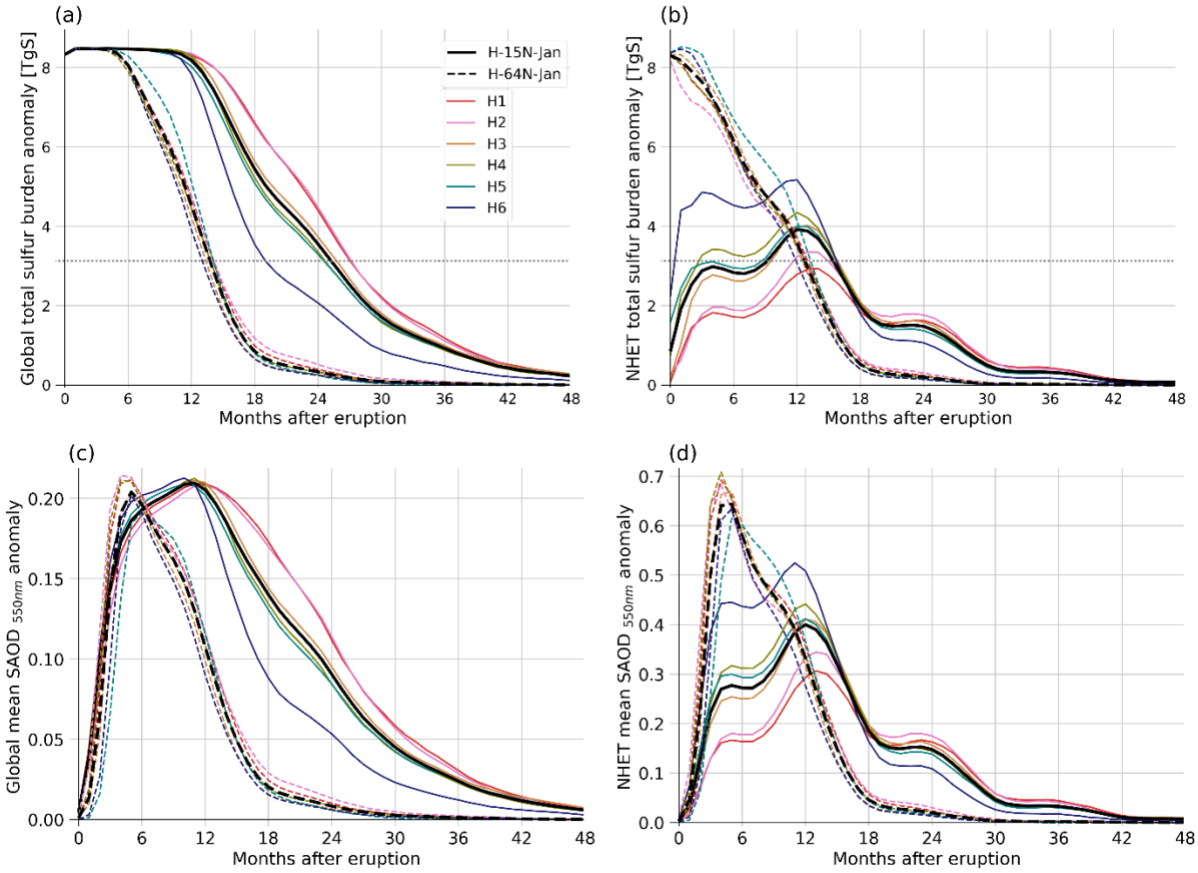


Figure 2. Global (left panel) and Northern Hemisphere extratropics (NHET [30 °N – 90 °N], right panel) total sulfur burden (a, b), and stratospheric aerosol optical depth (SAOD, c, d) anomaly. Solid lines and dashed lines are for tropical and NH extratropical eruptions, respectively. Different colors represent different ensemble member realizations. The black lines represent the ensemble means of the baseline experiments. The gray dotted horizontal line in (a) represents the e–folding of total sulfur. Note the different axes in (c) and (d).

The text in Section 3.2.1 is accordingly revised as follows:

"3.2.1 Sulfur burden and aerosol evolution determines volcanic forcing

Figure 2 shows time series of global and NHET total sulfur burden and stratospheric aerosol optical depth (SAOD). The global total sulfur burden initially displays a plateau for both tropical (H–15N–Jan, solid lines) and extratropical eruptions (H–64N–Jan, dashed lines), followed by declines beginning approximately 9 and 5 months after tropical eruptions and NH extratropical eruptions, respectively (Fig. 2a). The difference in timing of the start of the decay in sulfur burden between tropical and extratropical eruptions suggests differences in transport processes. Specifically, the NHET total sulfur burden from tropical eruptions exhibits a sharp increase within the initial 4 to 5 months, followed by a decelerated increase, ultimately peaking at 12 to 14 months (solid lines, Fig. 2b). Conversely, a continuous decline is visible in the NHET following NH extratropical eruptions (dashed lines, Fig. 2b).

As shown in Figure 1, the initial atmospheric conditions control the transport of volcanic materials. As a result, the progression of total sulfur burden exhibits a large spread among the six ensemble members of tropical eruptions (Fig. 2). Four months after the eruption, the NHET total sulfur burden peaks at 1.8 Tg and 4.8 Tg in H1 and H6, respectively. Consequently, 8-10 months later, the peak NHET total sulfur burden is 79 % higher in H6 (5.2 Tg) than in H1 (2.9 Tg) (Fig. 2b). At the same time, the global total sulfur burden exhibits a 42% longer e-folding time in H1 compared to H6, with respective e-folding times of 27 and 19 months (Fig. 2a).

SO_2, SO_4, SO_4-mass-weighted mean effective radius (Reff) and SAOD evolution are tightly connected and modulated by initial conditions (Figs. 2 and S3; see Section S1). The volcanic forcing is closely related to the sulfur burden, as shown by a similar evolution of the SAOD (Fig. 2c and 2d) and SO_4 (Fig. S3), although fluctuations occur due to variations in effective radius (Fig. S3), resulting in varying scattering efficiency (Lacis, 2015). The maximum global–mean SAOD shows a similar magnitude (~0.2) after tropical and NH extratropical eruptions, but it takes longer to reach the maximum and the forcing lasts longer after tropical eruptions compared to NH extratropical eruptions (Fig. 2c). Due to the wider spread of aerosols, tropical eruptions result in a smaller and delayed peak of NHET–mean SAOD, but a longer–lasting forcing compared to NH extratropical eruptions, after which aerosols are confined in the NHET region (Fig. 2d)."

Lines 172-174: Can you provide a brief summary of the findings of Fuglestvedt et al. (2023) for readers who haven't studied that paper in detail?

As suggested, we have added a brief summary of the findings from our related paper published in npj *Climate and Atmospheric Science* in January 2024. The revised text now reads: "For NH extratropical eruptions at 64° N in January, as shown in our related paper by Fuglestvedt et al. (2024), the initial stability of the polar vortex strongly influences the lifetime of SO_2 and effective radius of SO_4 by controlling the dispersion of injected volcanic gases."

Lines 204-205: Are these differences statistically significant?

The difference range of 0.05 is approximately 15 times larger than the 2σ-variability of the control run without volcanic injection, considering monthly variations. From this perspective, the differences are significant. In response to the comment regarding Figure 2, we have relocated the subfigures on effective radius and corresponding text to the supplement and added following text to clarify the difference: "After tropical eruptions, the NHET–mean Reff is larger in maximum, i.e., 0.43 μm in H6 compared to 0.38 and 0.39 μm in H1 and H2, this difference range of 0.05 is approximately 15 times of the 2σ-variability of the control run without volcanic injections."

Line 211: Well, sort of. The figures in Lacis stop at 1 micron. Above that you start to get pretty strong warming by the aerosols, which has an important effect on forcing. And the figures by Lacis refer to aerosol size, which is very different from effective radius.

Upon reviewing the Lacis (2015) paper, it's evident from Figure 1 of Lacis (2015) (attached below) that the aerosol size distribution is presented in effective radius. While the figures do indeed stop at 1 micron, panel (B) illustrates that at an effective radius of 0.25 μm the largest shortwave and net shortwave radiation response is reached, as indicated by the blue and red points, respectively. The maximum global mean effective radius modeled in our study falls between 0.3 to 0.4 μm (Figure 2e), which still remains considerably below the boundary of 1 μm, beyond where a strong aerosol warming effect is observed.

However, considering this comment, we revised the text to "The volcanic forcing is closely related to the sulfur burden, as shown by a similar evolution of the SAOD (Fig. 2c and 2d) and SO_4 (Fig. S3), although fluctuations occur due to variations in effective radius (Fig. S3) with varying scattering efficiency (Lacis, 2015)."

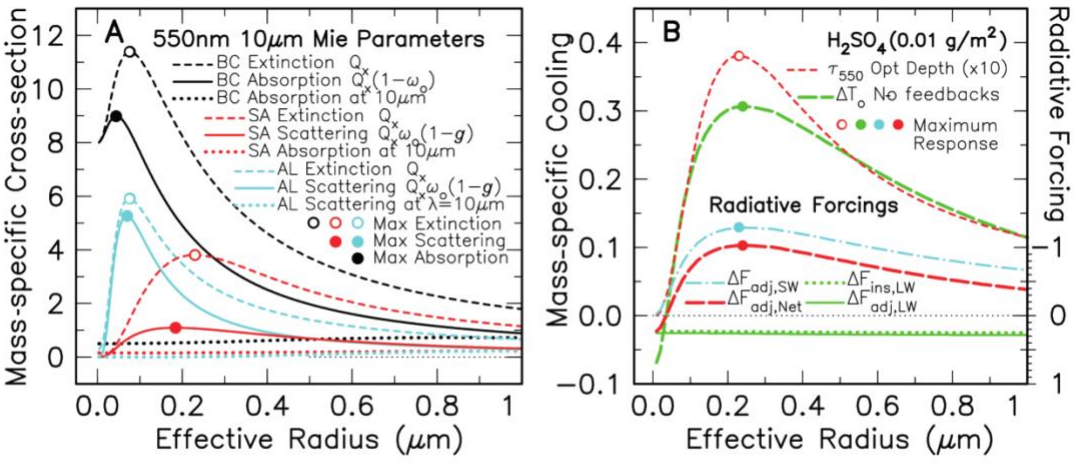


Figure 1: (A) Mass-specific cross-sections ($m^2 g^{-1}$) at 550 nm and 10 μm for black carbon (BC), sulfuric acid (SA), aluminum (AL) aerosols as functions of aerosol size. Dashed lines are Mie extinction efficiency factors Q_x. BC absorption cross-section is solid black. Solid red and blue lines depict effective scattering cross-sections of SA and AL aerosols. Black and red dotted lines are BC and SA absorption cross-sections at 10 μm. Blue dotted line is AL scattering at 10 μm. **(B)** Mass-specific cooling for SA aerosol for mass density 0.01 gm^{-2} as functions of aerosol size. Dashed red line is SA optical depth (x10). Long-dash green line depicts no-feedback surface temperature (cooling) change. Radiative forcings use right-hand scale. The long-dash red line depicts adjusted forcing with solar only (SW) component given by the dot-dash cyan line. The green lines are LW instantaneous and adjusted forcings.

Line 222: Citation to Kravitz and Robock (2011) seems appropriate here.

We agree and have added Kravitz and Robock (2011) in the introduction of the revised manuscript, and revised the text here to "The eruption season plays an important role in the temperature variation. When our simulated volcanoes erupt in January, both global–mean and NHET–mean SAOD peak around 12 months after tropical eruptions…".

Lines 235-237: I find this part a bit unsatisfying, in that it does not represent a controlled experiment. Only H1 and H2 have strong positive ENSO states. Is that coincidence, or is there a reason that a strong positive ENSO would not lead to more poleward transport of sulfur? (Edit: you do address this somewhat in Section 4, but I think it's still a bit lacking. Only two instances of positive ENSO states can't cover the spread of initial conditions.)

We agree that drawing definitive conclusions from just two instances is inadequate. Therefore, we deleted this sentence.

Lines 249-250: Is this surprising? It seems as though mechanisms that transport one thing would transport other things.

It is not surprising given the existence of the mechanism. If the transport of SO_2 and sulfate aerosol is purely random, then the transport of halogens could vary significantly. The representation of SO_2, aerosol, and halogen transport mutually validate the influence of initial conditions on transport of volcanic volatiles.

Lines 262-264: This needs more clarification. Halogens from CFCs (what we typically think of when discussing stratospheric ozone) have a very long lifetime, so there shouldn't be a lower burden due to removal. So what exactly are you injecting, and what are the removal processes and lifetimes? This will also aid Figure 4, in that you may not need to extend the panels out to 60 months to highlight differences between the ensemble members.

Indeed, halogens from CFCs have an exceptionally long lifetime; however, it's important to note that our simulations do not include this aspect. Instead, as emphasized in the "Experimental design" Section, we utilized the 1850 pre-industrial configuration.

We injected volcanic HCl and HBr into the stratosphere, which do not directly react with ozone. As mentioned in lines 239-240 "Injected HCl and HBr in the stratosphere reacts with OH to produce chlorine and bromine radicals, reacting with ozone in a catalytic destruction cycle (Solomon, 1999)." Thus, we displayed total inorganic chlorine (Cly) and bromine (Bry), which undergo chemical reactions with O3. To provide clarity regarding the injection, we have added now the time series of global and NHET mean HCl and HBr burden anomalies in the supplement (as shown below).

We have added the following in the section 3.2.3:

"Figure 4 shows the evolution of total inorganic halogen burden and the ozone response. Injected HCl and HBr (timeseries in Fig. S5) in the stratosphere reacts with OH to produce chlorine and bromine radicals, reacting with ozone in a catalytic destruction cycle (Solomon, 1999)."

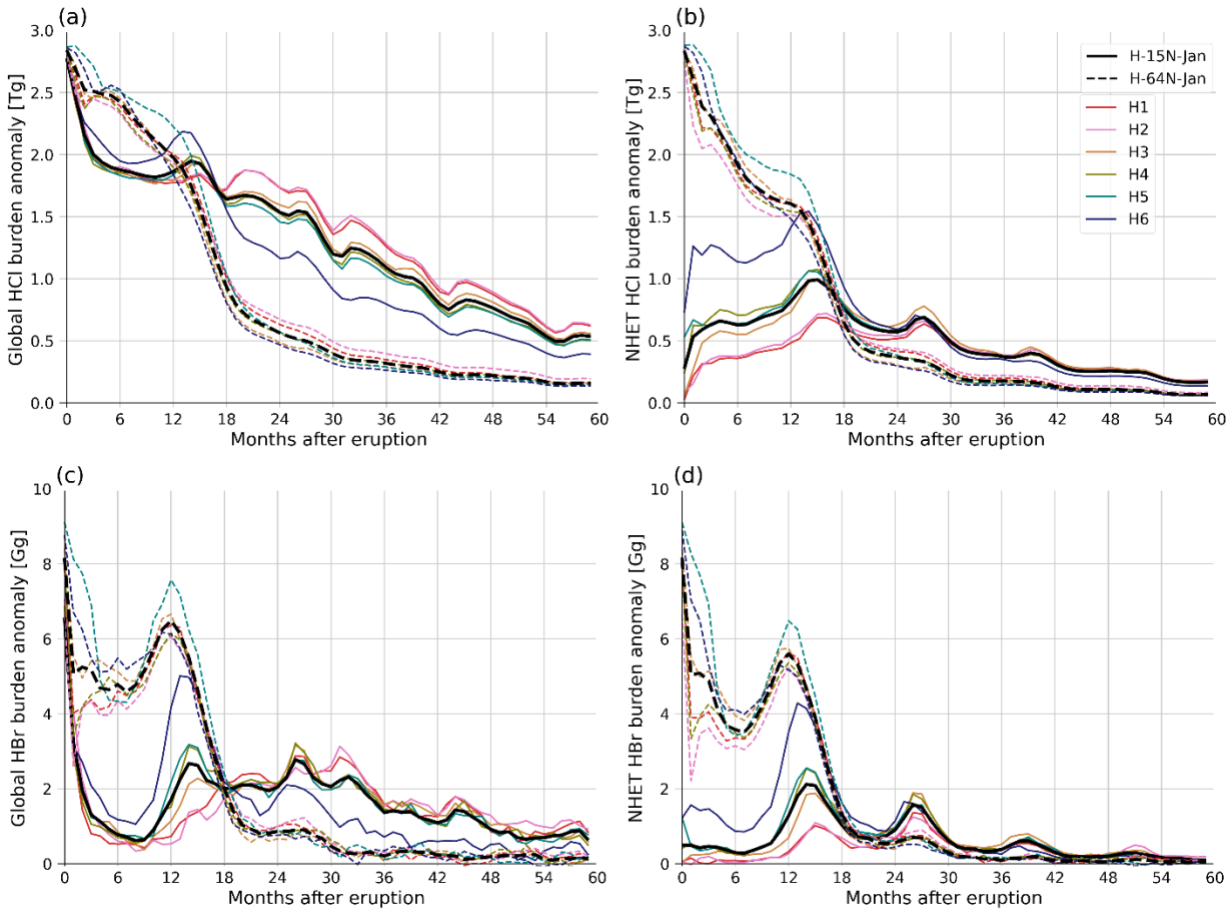


Figure S5. Global (left panel) and Northern Hemisphere extratropics (NHET [30 °N – 90 °N], right panel) HCl (a, b) and HBr (c, d) burden anomaly. Solid lines are variations after tropical eruptions, while dashed lines are variations after NH extratropical eruptions. Different colors represent different ensemble member realizations. The black lines represent the ensemble means of the baseline experiments.

Figure 3: Are the ensemble members statistically significantly different from each other? It's not obvious from this figure that the initial conditions of the eruption lead to climatically important differences.

The NHET mean surface temperature (Figure 3b) shows that the order of the members aligns with the NHET total sulfur burden anomaly (Fig. 2). Particularly noteworthy is the substantial difference between H1 and H6, especially in the 4 to 12 months following the eruption. During this period, the anomaly in H1 falls within the 2σ-variability range of the control run, whereas the anomaly in H6 exceeds this range by more than two-fold. This pronounced surface cooling in H6 has the potential to exert significant impacts on ecology

and society, unlike the case in H1. From this perspective, the initial conditions of the eruption can result in climatically important differences. However, it is important to emphasize that we have refrained from drawing conclusions that the atmospheric initial conditions lead to statistically significantly different surface temperature responses among the members. Instead, we have added more quantified descriptions, as shown in the response to a related comment from the second reviewer below.

Lines 283-287: Your results don't make sense in the context of these lines. H6 involves the strongest polar vortex, which should serve as a transport barrier. The opposite is true for H1. Perhaps I'm unclear as to what you mean by poleward transport and how/where you're measuring it?

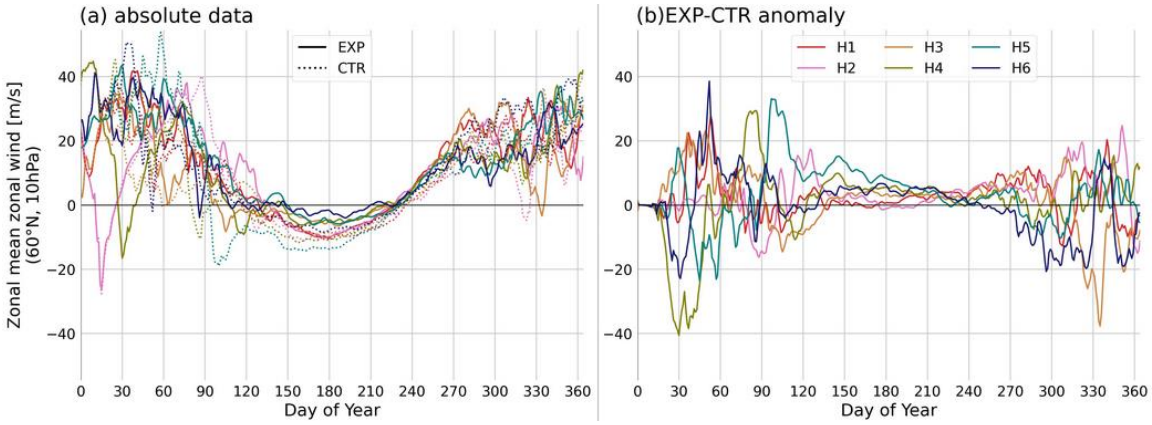
Here, we have discussed the connection between ENSO and the polar vortex at the pre-eruption initial state, aiming to elucidate why the four former members and the two latter members exhibit differentiation, both in this study and in Fuglestvedt et al. (2024), despite the differing criteria used to order the members between the two studies.

We acknowledge that a generally strong polar vortex is expected to act as a transport barrier. However, it's important to note that the polar vortex state undergoes significant variability after the initial state, as depicted in the figure below. For instance, in H6, the wind strength decreased considerably within one month and exhibited considerable variability thereafter, ultimately resulting in a significant weakening of the polar vortex 3 to 4 months after the eruption. Nevertheless, we refrain from drawing definitive conclusions that a single factor determines transport, as dynamics are inherently interconnected and influenced by multiple factors.

To enhance clarity and emphasize the need for further studies, we have revised the text accordingly:

"H1 and H2 correspond to initial El Niño states, while H3 and H4 correspond to neutral ENSO states. The latter two members, H5 and H6, correspond to La Niña states (Table 1). The labelling of the ensemble members, based on the first month's SO_2 transport, may correlate with the ENSO state and would also provide insights into the influence of ENSO on the polar vortex. As highlighted in van Loon and Labitzke (1987), El Niño events are typically linked to a warming and weakening of the polar vortex, along with a cooling in the tropical lower stratosphere. Nevertheless, a simultaneous injection of volcanic gases and aerosols can counteract this ENSO-related cooling, resulting in

unusual tropical stratospheric warming. In contrast, La Niña events are often connected with a strengthening of the polar vortex. Future studies with large ensemble simulations should be conducted to investigate the ENSO-polar vortex-volcanic eruption connection."



From Figure S2, it looks like all of your simulations begin at approximately the same QBO state. So how exactly are you testing the influence of the QBO phase on your results?

As stated in lines 65-66, our aim is to test the volcanic eruption impact under QBO westerly state, defined by the monthly equatorial mean zonal wind at 30 hPa between 2° N-2° S. However, the six ensemble members reveal variability with regard to their QBO strength and profile, with an accompanying easterly phase above. To better clarify this point, we have revised Figure S2 to Figure S7 and added the initial QBO profile of the six ensemble members (see also our responses to second Reviewer's comment).

The revised Figure 1 includes now diagnostics for the ensemble spread of the upward motion and tropical confinement of SO_2 in the first month, which is modulated by our experimental set up (varying westerly QBO state) next to wave breaking in the extratropics. A detailed study on how different QBO phases affect the forcing and impact of volcanic eruptions would be interesting but is beyond the scope of this study. We have acknowledged the necessity for future research dedicated to exploring this as well, which could be facilitated through forthcoming VolMIP studies (see Discussion). Please see also our response to your third detailed comment above.

2. Response to Reviewer #2

This study uses CESM2 to look at the dependence of the evolution of volcanic aerosols, forcing, and impacts on surface temperature and ozone on the eruption latitude, season, atmospheric initial conditions, and presence of halogens.

This is an interesting study and could be a valuable addition to the literature, but I am suggesting major revisions as some of the statements (detailed below) are not well supported by the data. The authors need to be more quantitative when describing the difference between simulations.

Also, the figures contain a lot of information and I found it hard to follow at times. It might be clearer to reduce the amount of information to what is strictly necessary, but I recognise this is difficult.

Thank you very much for your positive evaluation of our study and for providing constructive comments. In response, we have incorporated quantitative details when describing our results. Additionally, we have revised the subfigures in Figures 1 and 2 to enhance clarity and adjusted the accompanying descriptions accordingly. For detailed explanations of the changes and revisions made, please refer to the major comments provided below.

Major comments:

Fig 1 : Too many lines and difficult to read. Is it possible to choose certain ensemble members?

Can you specify exactly what measure you used to classify from H1 to H6?

We recognize the challenge in interpreting Figure 1 and have revised it and corresponding text based on both your and the first reviewer's comments.

Our study relies on analyzing all six ensemble members. The ensemble members are ordered using the ratio of meridional (poleward) versus vertical (upward) transport. This order remains consistent in the asymmetric NH/SH ratio of the 60 months cumulative SAOD, as shown by the inset axes of the revised Figure 1c. These collectively demonstrate that initial conditions play a significant role in controlling the transport of SO_2 from the first month and subsequently modulate the latitudinal distribution of SO_4 and SAOD.

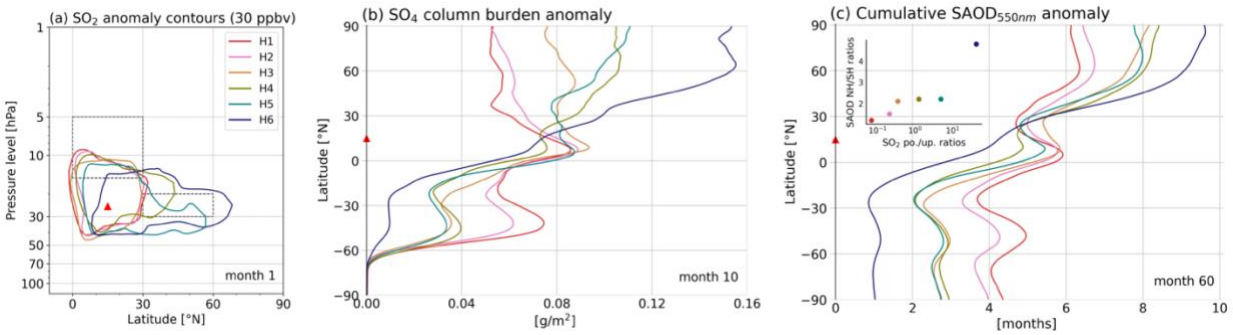


Figure 1. First month latitudinal and vertical distribution of SO_2 concentration anomaly at 30 ppbv (contour, a), the 10th month SO_4 column burden anomaly (b) and 60 months cumulative SAOD anomaly at 550 nm (c) for six members of the baseline experiment. The red triangle denotes the eruption latitude at 15° N in panels (a-c), and the injection altitude at 24 km in panel (a). The inset axis in (c) indicates the relationship between the poleward/upward ratio of the first month SO_2 concentration anomaly and the NH/SH ratio of the 60 months cumulative SAOD anomaly.

The text in Section 3.1 has been revised to as follows:

3.1 Initial atmospheric conditions control aerosol transport and volcanic forcing after tropical eruptions

Tropical eruptions have usually been thought to have a larger climate impact than extratropical eruptions, as SO_2 and formed aerosols are transported to both the Northern and Southern Hemispheres. Here, we examine how initial atmospheric conditions affect the transport and evolution of volcanic volatiles and subsequent volcanic forcing after tropical eruptions.

Figure 1a shows the first month latitudinal and vertical distribution of SO_2 concentration at 30 ppbv after the 15° N tropical eruptions in January. The contours reveal a range of dispersion of SO_2 across the six baseline ensemble members. In some simulations, SO_2 is strongly contained in the tropical pipe, with stronger vertical ascent, while in others, SO_2 is strongly mixed into the NH mid-latitudes. Accordingly, we labeled the ensemble members H1 to H6 based on the ratio of poleward versus upward transport, calculated by dividing the latitude- and altitude-weighted means of the first month SO_2 concentration over the regions poleward (20-30 hPa, 30-60° N) and upward (5-15 hPa, 0-30° N) relative to the injection point (dash outlined in a). Note that this labeling differs from Fuglestvedt et al. (2024), who labeled their ensemble members based on the ascending SO_2 e-folding time, which also correlated with an increasing stability of the polar vortex. During the first month, filaments of high SO_2 concentration are pulled towards the NH high latitudes, particularly

evident in H5 and H6 (Figs. 1a and S1). In contrast, the ensemble members with stronger upwelling exhibits stronger tropical confinement, and lesser distribution towards the NH, as exemplified especially in H1 (Fig. 1a and S2).

The latitudinal distribution of SO_2 in the first month modulates the subsequent latitudinal dispersion of SO_4. Figure 1b shows the latitudinal distribution of the 10th month SO_4 column burden for the six ensemble members. H6 exhibits a greater transport of SO_4 to the NH high latitudes between 30° N and 90° N, compared to the other members, particularly when contrasted with H1 and H2. Differences in the transport of SO_2 and SO_4 result in differences in cumulative volcanic forcing in the NH and SH high latitudes among the ensemble members (Fig. 1c). H6 shows a pronounced asymmetric volcanic forcing with large meridional forcing differences, e.g., 60 months cumulative SAOD reaching up to 8.4 months between the NH and the SH. In contrast, H1 exhibits a relatively symmetric volcanic forcing between the hemispheres. Here, even with identical eruption source parameters, tropical volcanic eruptions give rise to differing degrees of hemispheric asymmetry of volcanic forcing solely due to variations in initial conditions. The inset scatter plot clearly illustrates a correlation between the poleward/upward ratio of the first month SO_2 and the hemispheric asymmetry of cumulative SAOD over 60 months. ..."

L.161/2 : "there is comparatively lower upward transport of SO_2 compared to the other members" How do you deduce that? They look similar to me.

As explained and illustrated above, we utilized a revised Figure 1 to enhance clarity in the comparison and employed poleward/upward ratios to directly quantify the inter-member differences.

L.166-8 : Again, that does not seem terribly obvious to me.

We have moved subfigure 1d to the supplement, and we have revised Figure 1a, including 30 ppbv SO_2 contours for the six members within the same figure for clarity. This reveals a more pronounced upward transport in the tropics for H1 and H2 in contrast to H5 and H6. This pattern is not limited to an SO_2 concentration of 30 ppbv; similar evolutions are discernible when plotted with various contour levels (not shown here).

Fig 2 : What latitudes is NHET defined over?

NHET is defined over 30 to 90°N. To make this clear, we have revised the figure caption to "Northern Hemisphere extratropics (NHET [30 °N – 90 °N], right panel)".

L.179 : Is the difference in e-folding times significantly different?

Since it's only 0.4 months of e-folding time difference, we did not conclude that it's significantly different. Considering this comment and in response to a comment from reviewer 1, we decided to simplify figure 2 by moving subfigures 2a-2f to supplement and replaced SO_2, SO_4 with combined total sulfur burden anomaly figure. See also our reply to reviewer 1 above for details.

L.197-8: "the global–mean SO_4–mass–weighted mean effective radius (Reff , Fig. 2e) increases faster after tropical eruptions compared to NH extratropical eruptions for the first 6 months." Again, I don't really see a significant difference between the 2 ensembles in the first 6 months, so this claim is not supported by the data.

As mentioned above, we have relocated subfigures 2a-2f and corresponding text to the supplement.

L.218-220 : "Both global–mean (Fig. 3a and 3c) and NHET–mean surface temperature (Fig. 3b and 3d) show a weaker but longer–lasting surface cooling after tropical eruptions (Fig. 3a and 3b) compared to NH extratropical eruptions (Fig. 3c and 3d)." Again, I am a little concerned about whether the data supports that statement.

We added the following detailed description about our quantification to support this statement.

"Global-mean surface temperature shows a maximum cooling of 0.7 K within 23 months, returning to the control run's 2σ-variability range 42 months after tropical eruptions (solid black line in Fig. 3a). Conversely, a maximum cooling of 0.8 K occurs 9 months after extratropical eruptions (dashed black line in Fig. 3c), with temperatures returning to the 2σ-variability range within 24 months. NHET-mean surface temperature displays a maximum cooling of 2.0 K within 22 months, returning to the 2σ-variability range 37 months after tropical eruptions (solid black line in Fig. 3b). In contrast, a maximum cooling of 2.6 K occurs within 9 months and recovers within 25 months after extratropical

eruptions (dashed black line in Fig. 3d). Extratropical eruptions lead to only slightly stronger global-mean cooling, but much more pronounced NHET-mean surface cooling than tropical eruptions. However, both the global-mean and NHET-mean surface temperatures show a longer-lasting cooling after tropical eruptions compared to extratropical eruptions."

L.268-9 : Again you might want to be more quantitative here, because the blobs in figure 1 all look similar to me.

To enhance the visibility of intra-member comparisons, we have revised figure 1 and utilized the ratio of poleward versus upward transport for quantification. Accordingly, the text has been revised to: "Figure 1 illustrates that H1 and H2 exhibit enhanced upward transport of SO_2, as indicated by a small ratio of poleward/upward transport in contrast to H5 and H6 with a larger poleward transport (large poleward/upward ratio)."

L.316 be more quantitative, the differences are really quite small.

We used percentage change to quantify the changes and revised the text to:

"The simulated maximum global–mean SAOD is 5% higher in H–15N–Jan than in S–15N–Jan, and 10% higher in H–15N–Jul than in S–15N–Jul (Fig. 6a). The percentage change in July eruptions closely aligns with the findings of Staunton-Sykes et al. (2021) for a 10 Tg SO_2 injection in July, revealing a 11% higher peak global-mean SAOD when sulfur and halogens were co-injected compared to sulfur-only injection."

Minor comments:

L.48 : replace "next to" with "as well as"

Revised as suggested.

L.72/76 : replace "co-injecting" with "which inject"?

Considering this and one comment from the first Reviewer, we revised this sentence to "How do initial atmospheric conditions influence transport of volcanic

volatiles and volcanic forcing after tropical eruptions, particularly in light of the co-injection of sulfur and halogens into the stratosphere?"

L.121 : lasts -> lasting

Revised as suggested.

L.224 The use of "interrupt" here is weird.

We revised it to "When our simulated volcanoes erupt in January, both global–mean and NHET–mean SAOD peak around 12 months after tropical eruptions (Fig. 2c and 2d). During boreal winter, less incoming solar radiation reaches the NH, suspending the reduction of net radiation at the top of the atmosphere…"

L.250 representative -> present

Revised as suggested.

Fig S2 : make the vertical lines thicker. Also the difference between the initial states might be clearer if you did a line plot with the winds along the transects?

As suggested, we made the vertical lines thicker. To show the difference between the initial states, we added a subplot to the right showing the wind profile of each initial state. Below is the revised Fig. S2:

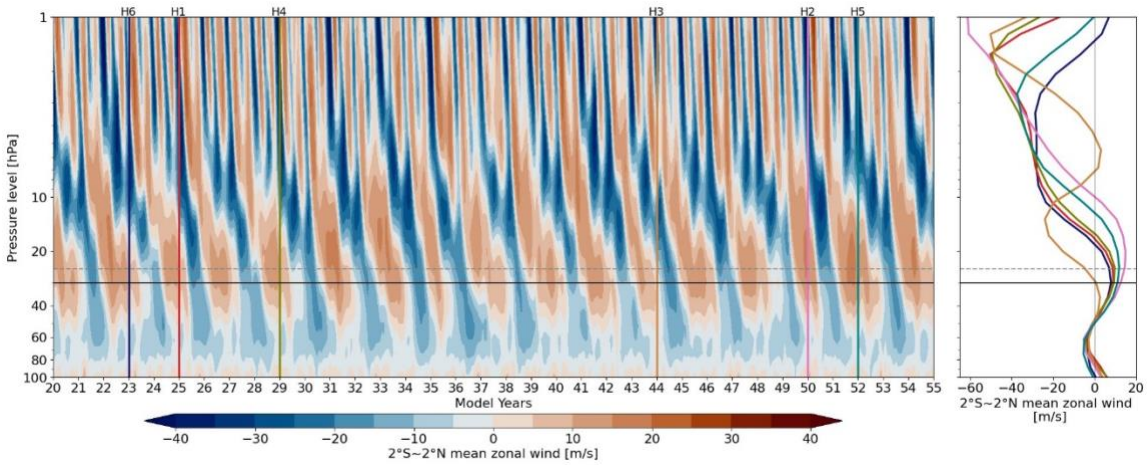


Figure S7. Initial Quasi-Biennial Oscillation (QBO) state indicated by the equatorial (2º S to 2º N) mean zonal wind at 30 hPa (black horizontal line). The grey horizontal line indicates the volcanic volatile injection altitude at 25 hPa. Vertical lines denote the selected initial QBO state in January for six members of the baseline experiment, whose wind profiles are displayed in the right panel, with colors corresponding to those shown in Figures 1 to 4.

L.300-311 : Nice paragraph!

Thank you.

Fig 5 : Need to clarify that the first bar is Cly and the second bar is Bry, that confused me a bit.

As suggested, and considering that the first and second bars might be misleading, we used high and low bars instead. We have added the following description in the figure caption "In the top right panel, the high and low bars are Cly and Bry, respectively."

Fig 6 : are panels e-h the same as figure 3 with added lines for S injections?

The ensemble mean (thick lines) in panels e-f are the same as in figure 3. However, the shades show two-standard deviations of the six members baseline experiment, thus it is different from figure 3. The added thin lines are for sensitivity tests with sulfur-only injections in Jan and sulfur-only and sulfur and halogen injections in July.

To make this clearer, we revised the figure caption to: “The thick lines and the shades are for the ensemble mean and two-standard deviation of the six members-baseline experiment. The thin lines are for sensitivity tests. Red and blue colors represent variations after tropical and NH extratropical eruptions, respectively. "

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