Response to Reviewers' Comments

Injection Near the Stratopause Minimizes the Stratospheric Side Effects of Sulfur-Based Climate Intervention

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We thank very much the reviewers for their helpful comments. The response to each reviewer's comment is marked in blue.

RC1

The authors present an analysis of the effects of stratospheric aerosol injections in the upper stratosphere, in comparison to more typical lower stratospheric injections, as simulated in the WACCM-MAM3 climate-chemistry-aerosol model. While the results are generally presented in a clear way and could be interesting I think that the analysis lacks depth in several respects. My major concerns are listed below.

The comparison of emissions at 50 km is only done with respect to equatorial emissions at lower altitudes. However, there are earlier studies comparing different lower tropospheric emission strategies and also reporting some benefits in comparison to equatorial emissions. I think the authors need to put the potential benefits of their strategy into the perspective of these other emission strategies.

We assume the reviewer meant to ask the difference among various lower stratospheric (not "tropospheric") injection strategies.

We added discussions about high-latitude injection strategy in Lines 56-62:

"Tropical injection leverages the ascending branch of the BDC to efficiently transport aerosols into the global stratosphere, producing cooling across hemispheres and more effective surface cooling, while equatorial injection leads to substantial overcooling in the tropics and residual surface warming in the high latitudes (Kravitz et al., 2019; Tilmes et al., 2018b). High-latitude injections reduce the stratospheric warming, enhance polar cooling and sea ice preservation compared with tropical injection strategies (Lee et al., 2021; 2023b). However, it requires larger injection amounts to achieve the same global cooling as tropical injections due to the shorter aerosol lifetime (Henry et al., 2024; Zhang et al., 2024; Duffey et al., 2025)."

I think that the model validation in 3.1 is too superficial concerning the upper mesosphere. I agree that it is useful to show an AOD comparison for the Hunga Tonga eruption where the sulfate also reached the upper troposphere. However, a distinct difference between emissions at 50 km and lower altitude emissions is the reported meridional distribution. This will depend on the representation of the overturning circulation in the upper stratosphere which for which an important feature is the semiannual oscillation near the stratopause. How well is that represented in the model. I don't think it is sufficient to say "temperature at 100 hPa, QBO strength, and polar vortex strength" show reasonable agreement with reanalysis data, because these are all features evaluated in the lower to middle stratosphere. Of course, evaluations of near-stratopause circulation are more difficult due to the lack of observations, but I think this needs to be discussed.

We agree that model evaluations near the stratopause are not easy due to a lack of observations. We compare the simulated Semiannual Oscillation (SAO) with reanalysis data in Figure S1c to evaluate model performance near the stratopause. The model can reproduce the 1 mb winds from MERRA2. We discuss SAO validation in Lines 124:

"Comparison with MERRA2 reanalysis data (2000-2020) shows reasonable agreement in key stratospheric metrics including temperature at 100 hPa, Quasi-biennial Oscillation (QBO) strength, Semiannual Oscillation (SAO) strength (1 mb tropical zonal winds) and polar vortex strength (Fig. S1), …."

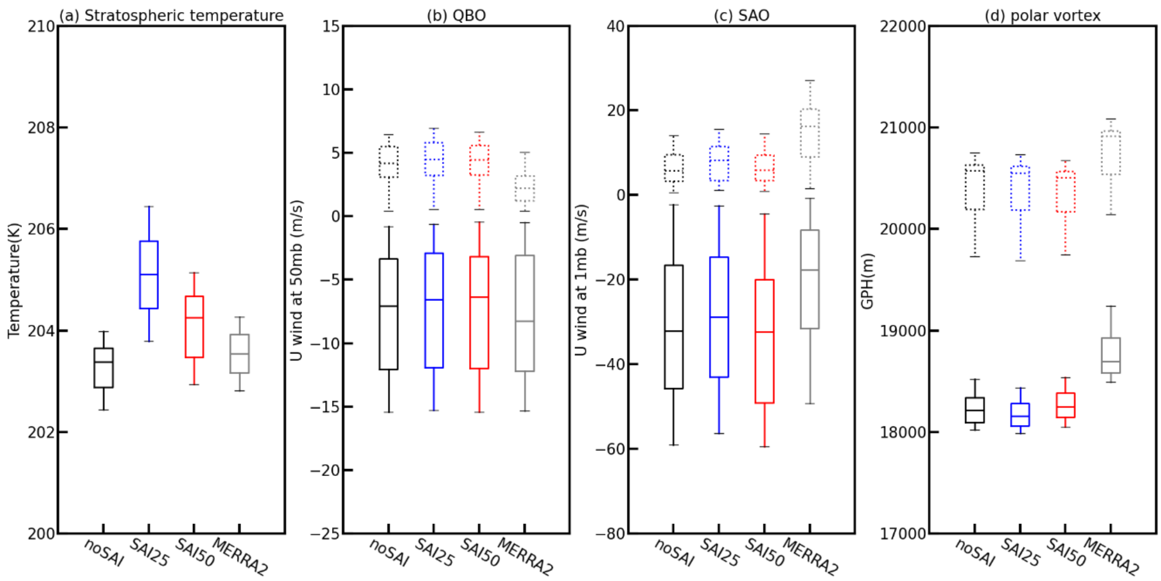

Figure S1: Box plots comparing stratospheric variability between model simulations and MERRA2 reanalysis (2000-2020). (a) near-global (60°S-60°N) temperatures at 100 mb; (b) Quasi-biennial Oscillation (QBO) strength (tropical zonal mean zonal wind at 50 mb) with east phase (dashed) and west phase (solid); (c) Semiannual Oscillation (SAO) strength (tropical zonal mean zonal wind at 1 mb) with east phase (dashed) and west phase (solid); (d) Antarctic (solid) and Arctic (dashed) polar vortex strength (denoted by the geopotential height averaged over 65°S-90°S at 50 mb) in the model and MERRA2 reanalysis dataset between year 2000 and 2020. Box plots show the median (horizontal line), 25th-75th percentiles (box), and 5th-95th percentiles (whiskers).

I disagree with the title. The study doesn't provide evidence that SAI emissions near the stratopause "minimize" side effects. There could be other strategies reducing the side effects further that haven't been tested. Who knows what effects would be caused by an emission in the upper mesosphere?

Revised to be: "Injection Near the Stratopause Mitigates the Stratospheric Side Effects of Sulfur-Based Climate Intervention"

At the end of Section 3.2 the authors write "The distinct latitudinal and vertical distributions of aerosols in SAI50 enhance climate cooling benefits while minimizing negative impacts of climate intervention." Besides the issue with the word "minimizing" mentioned in connection with the title, I also think this statement is not sufficiently backed up, at least not at this point of the manuscript. Possibly the sentence is meant as an announcement for the following two subsections, but it sounds like a summary.

We revised the sentence in Line 156: "The distinct latitudinal and vertical distributions of aerosols in SAI_{50} are expected to influence the climate cooling benefits and mitigate the associated stratospheric impacts, as detailed in the following subsections."

More in general the manuscript suffers from the lack of the definition of a goal for the SAI. Without such a goal, without defining a metric it is impossible to compare which strategy performs best. The goal could (but doesn't have to) be to produce a climate as similar as possible to an unengineered climate of the same global temperature at lower greenhouse gas levels. In this sense, it is not clear if the stronger Arctic amplification simulated for SAI_{50} than for SAI_{25} is actually a desired effect. How strong is the Arctic amplification in greenhouse gas caused warming in WACCM? Which injection strategy is counteracting the amplification more exactly?

Thanks for the comment.

We acknowledge the importance of defining clear metrics for evaluating SAI strategies. Our study uses a fixed injection rate of 10 Tg per year as an idealized experimental design to compare the fundamental differences in climate response between SAI_{25} and SAI_{50}. This simplified approach allows us to isolate and understand the physical mechanisms controlling aerosol transport and distribution at different injection heights.

In more practical scenarios (e.g. GLENS, ARISE, GeoMIP), injection amounts would need to vary over time to counteract increasing greenhouse gas forcing (Henry et al., 2024; Macmartin et al., 2022; Tilmes et al., 2018b). Regarding Arctic amplification, previous studies have shown that it cannot be fully offset under tropical SAI scenarios at ~25 km (Figure R1, Henry et al., 2024). While SAI_{25} effectively offsets greenhouse gas–induced warming in the tropics and mid-latitudes, the Arctic still experiences significant residual warming. The enhanced high-latitude cooling in SAI_{50} could potentially provide better compensation for Arctic amplification.

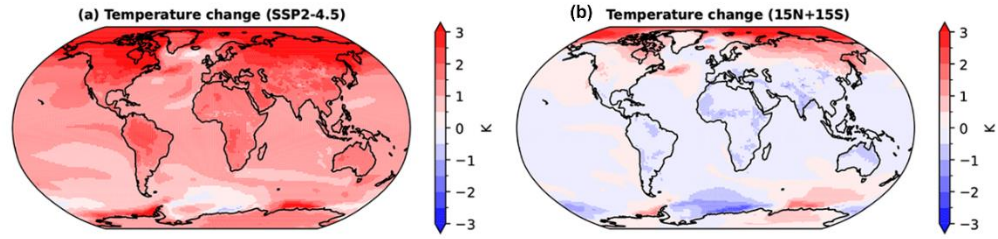

Figure R1. The ensemble-mean temperature change in 2050-2069 relative to the target period (2014–2033) in SSP2-4.5. (Figure A6 in Henry et al., 2024). (a) The surface temperature anomalies for SSP2-4.5; (b) The surface temperature anomalies for tropical SAI strategy (15S/15N).

We add the discussions in the manuscript in Line230-235:
"Additionally, while this study uses idealized fixed-rate injections to compare fundamental differences between injection heights, more practical implementation would require varying injection rates to meet specific climate objectives (Henry et al., 2024; Macmartin et al., 2022; Tilmes et al., 2018b). The enhanced high-latitude cooling observed in SAI_{50} suggests potential advantages for offsetting Arctic amplification, though determining optimal injection strategies would depend on defined climate goals and metrics."

Concerning Arctic amplification, the authors write: "In SAI50, the simulated 22% greater global mean surface cooling compared to the 10% increase in global mean AOD (Fig. 1a), is primarily attributed to Arctic amplification effects (Barnes and Polvani, 2015), with a minor contribution from the reduced stratospheric water vapor enrichment (Fig. 2c-d)." I don't understand this statement. Arctic amplification, depending on the mechanism which causes it in WACCM, should be part of the temperature response in both strategies. Shouldn't part of the difference between SAI50 and SAI25 be due to the different aerosol distributions. Is the idea that polar aerosols create a larger forcing than low-latitude aerosols? Would that be related to the surface-temperature dependence of stratospheric aerosol forcing as discussed by Hegde et al. (2025). Or to aerosol forcing being more efficient at high than low latitudes? Anyhow, I think it is necessary to physically explain the relatively strong additional global cooling for a relatively weak AOD increase.

Sorry for the confusion. The reviewer is correct that Arctic amplification occurs in both SAI_{50} and SAI_{25} scenarios. The stronger cooling response in SAI_{50} (22% greater global mean surface cooling) relative to its AOD increase (10%) can be attributed to two factors:

- The spatial distribution of aerosols: SAI_{50} has a higher proportion of aerosols at high latitudes compared to SAI_{25}.
- Enhanced efficiency of aerosol forcing at high latitudes: Due to Arctic amplification mechanisms (such as ice-albedo feedback and stable atmospheric conditions), aerosol forcing in the Arctic region produces a stronger cooling effect per unit AOD than at lower latitudes.

This explains why a relatively modest 10% increase in global mean AOD results in a disproportionate 22% enhancement in global mean surface cooling in SAI_{50}.

We clarified in the manuscript in Lines 193-197:

"In SAI_{50}, the simulated 22% greater global mean surface cooling compared to the 10% increase in global mean AOD (Fig. 1a) primarily reflects the higher proportion of aerosols distributed at high latitudes, where Arctic amplification mechanisms enhance the cooling efficiency of aerosol forcing. Arctic amplification processes, including ice-albedo feedback and stable atmospheric conditions (Barnes and Polvani, 2015), contribute to this enhanced regional cooling response. A minor contribution also comes from the reduced stratospheric water vapor enrichment (Fig. 2c-d)."

Figures 3c and 3d show simulated annual cycles of the high-latitude cooling signals. In the Arctic there is a pronounced seasonal cycle, while it is negligible in the Antarctic. This behaviour is just stated but not explained. To develop trust in such signals it is important to explain the physical mechanism causing this difference. Moreover, with respect of the "cooling benefits" discussion it would be important to discuss if these different annual cycles just offset different annual cycles of high-latitude greenhouse gas warming or if seasonal cycles are strongly modified.

The pronounced seasonal cycle of Arctic cooling compared to Antarctic cooling under SAI scenarios reflects fundamental differences in surface characteristics between these regions. The Arctic Ocean's seasonal sea ice plays a crucial role, while Antarctica's permanent ice sheet leads to more stable conditions year-round.

Arctic amplification - the enhanced temperature response in the Arctic region - occurs primarily from October to April and is strongly tied to sea ice loss (Dai et al., 2019). During summer, incoming solar energy is consumed by sea ice melt. In fall-winter, areas where sea ice has retreated expose open water, leading to increased outgoing longwave radiation and heat fluxes that drive stronger temperature changes. This mechanism explains why both Arctic warming under greenhouse gas forcing and Arctic cooling under SAI scenarios show maximum intensity during October-April.

We have explained this mechanism in the manuscript (Lines 206-209):

"The Arctic cooling exhibits pronounced seasonality, with maximum effects during fall-winter seasons (Fig. 3c). This seasonal pattern aligns with the mechanism of Arctic amplification, which is driven by increased outgoing longwave radiation and heat fluxes from areas of seasonal sea ice loss during October-April (Dai et al., 2019). In contrast, Antarctica's year-round ice cover results in more uniform cooling throughout the year (Fig. 3d)."

SAI effectively offsets the seasonal peak of polar warming, while the simulated seasonal cycles of surface temperature over both poles remain largely unchanged, as shown in Fig. R2.

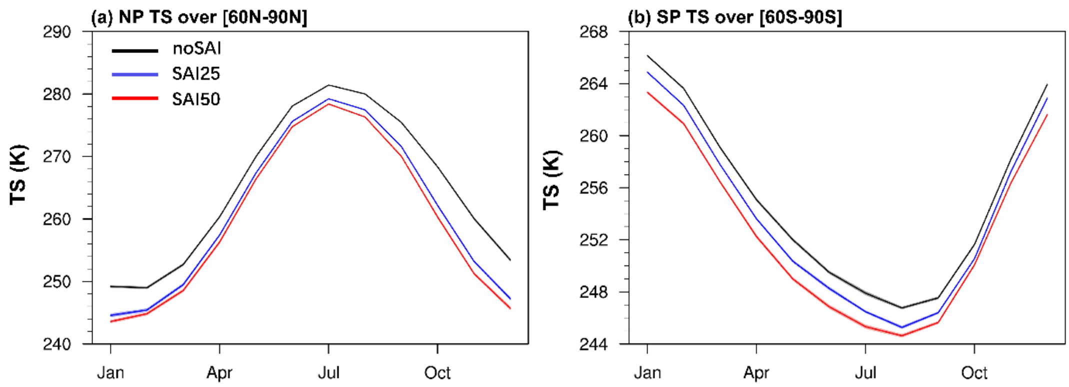

Figure R2: (a) The averaged surface temperature over Arctic (60N-90N). The black line denotes the global warming scenario in 2040. The blue and red lines denote the SAI25 and SAI50 scenarios, respectively; (b) Same as (a) but for Antarctic over 60S-90S.

Finally I see a major issue with the lack of discussion of the additional costs of emitting near the stratopause compared to the lower troposphere. The authors are briefly mentioning the option of using rockets and conclude that the "results clearly indicate that a detailed engineering design study […] is warranted." I think at least a brief estimation of costs based on existing rockets would be necessary. One could argue that scientifically it is interesting to see the dependence of SAI effects on the injection height. But if feasibility plays no role, why not emit at 70 or 100 km? As the authors claim to "propose a novel SAI approach" I think a minimum effort on estimating feasibility is necessary.

We appreciate the reviewer's comment regarding implementation costs. While cost considerations are indeed important for real-world deployment of any SAI approach, our study represents a theoretical exploration using idealized numerical experiments and focuses specifically on understanding the physical mechanisms and climate response to stratospheric aerosol injection at different altitudes. This theoretical exploration is essential for advancing our fundamental understanding of stratospheric dynamics and aerosol-climate interactions.

While we acknowledge that implementation feasibility is an important consideration for any proposed climate intervention strategy, a detailed engineering and economic analysis would require expertise beyond atmospheric sciences and would constitute a separate study entirely. Our results provide the physical basis necessary for future interdisciplinary assessments that could then evaluate technical feasibility and economic viability in detail.