Author Responses to Reviewer #1's Comments

Original referee comments are in italics in black

Author responses are in blue

1. *"The study is not comprehensive".*

We agree that the word "comprehensive" is not quite the right choice of word, and may not accurately describe the novelty of this manuscript. We have replaced that with the word "novel". We have changed the title to "Novel Hemispherically-Symmetric Strategies for Stratospheric Aerosol Injection".

This study systematically explores how the choice of SAI strategy affects climate responses, which is a key dimension of the range of possible climate responses to SAI. This study describes four hemispherically-symmetric injection strategies, including three strategies that are introduced for the first time and one equatorial injection strategy. Previous studies only look at up to two strategies at the same time. Zhang et al. (2022) have estimated that there are 6-8 injection strategies that produce detectably different surface climate responses, when providing 1C global cooling. The selection of these four injection strategies is based on the conclusion in Zhang et al. (2022), and is explained in Line 33-66, and Line 76-111. We have modified the paragraphs in Line 76-111 to better justify the selection of these strategies.

2. *"The abstract is poorly written. It does not explain what global warming scenario is used. It does not mention what climate models are used."*

We describe the global warming scenario and climate model in Section 2 and 3. The global warming scenario is SSP2-4.5, and cooling scenario is one that starts in 2035 and ramps down to a target of 1.0C above preindustrial; these are described in Section 3 – Simulations; we do not think it is appropriate to go into this level of detail in the abstract as it is not directly relevant to the conclusions. The climate model used is CESM2(WACCM6), which is described in Section 2 – Climate Model; we have added this information to the abstract.

3. *"It jumps right into SAI while ignoring the fact that it does not exist, and is only a proposed scheme."*

In the first paragraph in the introduction section, we make it very clear that stratospheric aerosol injection (SAI) could be an option in the future. We never said that it has been implemented.

4. *"It ignores the need to assess a wide range of potential benefits and risks before it is ever implemented."*

There are many possible design strategies for SAI. The purpose of this paper is to analyze how the surface climates respond to different strategies differently by simulating multiple new strategies that have not been looked at in existing studies. Knowing the surface

climate responses to different strategies is one component, and we agree only one among multiple, that helps evaluate the benefits and risks of injection aerosol in the stratosphere, and the fundamental limits of this approach.

In line 33-40, we wrote, “To inform future decisions on SAI deployment, it is important to have a sufficient understanding of the range of possible climate responses under SAI; these would depend on both the scenario and strategy… Collectively, these two studies capture two key dimensions of the range of possible climate responses to SAI”. In Section 6, we add “Climate response is only one factor to evaluate in supporting future climate decisions; other factors are also needed to be considered in evaluating benefits and risks of SAI ” to explicitly note that there are many factors that need to be considered in evaluating benefits and risks of SAI. We have also modified the abstract and explicitly note this in Line 3 (also see our response to the first point in #10).

5. *“It does not say what is being injected. In fact the experiments are injecting gas and not aerosol.”*

The term “Stratospheric Aerosol Injection” is a term used by the NASEM 2021 report, “Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance”, and we prefer to adhere to that nomenclature. In the abstract, we mentioned that in our simulations, SO2 is being injected in the stratosphere. In Line 30-32, we mentioned “such an approach would consist of injecting aerosols, or their precursors, in the lower stratosphere to reflect a small fraction of the incoming solar radiation back to space, as a result, lowering the global mean temperature”. In Line 32, we have added “In this paper, we focus on SO2 injection”.

6. *“The scientific questions being addressed by this paper are obscure. The paper says it wants to examine the response to certain sulfur dioxide emissions with respect to one global warming scenario using one climate model and specified injection altitudes and temperature reduction goal. It is by no means comprehensive. But why are they doing it?”*

We believe that it is important to explicitly show that injection strategy plays an important role when assessing the stratospheric aerosol injection approach, and to understand how different the climate responses would be under different injection strategies. This is relevant not just for understanding how the climate responds, but for ultimately being able to understand trade-offs and fundamental limitations, which is clearly more than any single paper can ever do.

We disagree with the reviewer that these ‘*scientific questions being addressed by this paper are obscure*’. In fact the crucial role of injection strategy in determining the simulated climate response to SAI has been recognized by many published studies in existing literature; those studies used either fixed-amount single-latitude injection simulations (Richter et al., 2017; Tilmes et al., 2018; Visioni et al., 2023; Bednarz et al., 2022; 2023) or a pair of equatorial vs multiobjective strategies (Kravitz et al., 2019; Visioni et al, 2021). While single-latitude injection strategies at mid-high latitudes are useful for understanding underlying physical processes, those are unlikely to represent responsible long-term deployment strategies due to the expected

large effect on ITCZ. While the second set of studies (Kravitz et al., 2019; Visioni et al., 2021) demonstrate that the importance of injection location also holds for more complex strategies, it is paramount to explore a broader range of such injection strategies.

As noted earlier we agree that "comprehensive" was not the correct word choice. Nonetheless, as we expect (in this model, and at least plausibly in others) that there are of order 6-8 distinct choices, the linear combination of a relatively small number of distinct strategies would span the range of possible climate responses. The selection of these four injection strategies is based on the conclusion in Zhang et al. (2022), and is explained in Line 33-66, and Line 76-111. This set of strategies would include the 4 new strategies simulated and evaluated here, the multi-objective one also evaluated here, and some more asymmetric strategies. We have rewritten the more general motivation in the introduction, and the specific motivation for these particular choices in Section 3.

7. *"The paper is very long and detailed, going through many variables from the climate model simulations they did. I lost interest before I got halfway through."*

We believe it is important to assess how the strategy affects a range of climate outcomes. Different strategies affect different climate variables differently. For example, a strategy may overcompensate some climate variables but undercompensate others. It is important to not only look at one or two climate variables, but a larger set of climate variables, and evaluate how these strategies studied here affect each climate variable.

8. *On line 65 the paper says, "The understanding that comes from the analysis of the differences between these strategies lays the foundation for future work." That is what a technical report should be doing, not a journal article which needs new science to justify publication.*

We do not agree with this comment. New research is always built upon the understanding and scientific knowledge from existing research; any good research paper should both have new science and lay a foundation for future work; the latter being true is a good thing. This study shows how the choice of SAI strategies impacts surface climate responses, which is necessary and novel knowledge that future research on evaluating the benefits and risks of SAI needs to be built upon.

9. *In several places, "We note that" is in the text and should be deleted. Every sentence should be noted or it should not be in the paper.*

We deleted "We note that" in Line 87 and Line 108.

10. *There are 45 additional comments in the annotated manuscript. If the authors chose to reply to this review, a response of "we addressed all the comments" would not be sufficient. Each comment should be listed with a specific response.*

Below are our responses to the additional comments in the annotated manuscript:

    1. Line 2: Change "Different injection strategies" to "Different stratospheric aerosol injection strategies". After "therefore, making informed future decisions on SAI requires an understanding of the range of possible climate outcomes", add ", in addition to other considerations".

2. Line 3: “therefore, making informed future decisions on SAI requires an understanding of the range of possible climate outcomes” is changed to “therefore, understanding the range of possible climate outcomes is crucial to making formed future decisions on SAI”.
3. Line 6: The scope of this study is limited to climate goals. We have acknowledged that there are other possible goals in the discussion session.
4. Line 9: this is the name of the strategy.
5. Line 11: before “We…”, we added “These strategies are simulated using the Earth system model CESM2(WACCM6-MA) with the global warming scenario SSP2-4.5”., in response to the comment on line 18.
6. Line 14: delete “notable”.
7. Line 15: Replace “Among other findings” with “In addition”.
8. Line 15: replace “in” with “in the”.
9. Line 31: This sentence is meant to briefly explain how SAI works. As the reviewer suggested, there are many metrics for evaluating and quantifying the state of a climate. Because many metrics can be used to evaluate the effects from climate change and from SAI, we need to consider multiple metrics when evaluating the SAI strategies, which is exactly what we did in this paper.
10. Line 33: we thank the reviewer for valid points. However, other potential risks are beyond the scope of the current manuscript.
11. Line 39: “these two studies” are MacMartin et al. (2022) and this manuscript.
12. Line 41: change “can” to “could”.
13. Line 42: use “would” in this sentence. “would overcool the tropical region and undercool…”, and “would primarily cool…”.
14. Line 51: change “do” to “potentially would”.
15. Line 63: change "are” to “is”.
16. Line 70: In line 71-73, we have described the chemistry in this model. In line 73, we have added the following sentence, “The ocean component is based on the Parallel Ocean Program Version 2 (POP2), the land component is Community Land Model Version 5 (CLM5), and the sea ice component is CICE5 (Danabasoglu et al., 2020).”
17. Line 79: We have modified the sentence as “Although the estimate of 6-8 distinct injection choices was made using CESM1(WACCM) simulations, the conclusion is expected to hold relatively well in CESM2(WACCM) due to similarities in the stratospheric circulation and aerosol microphysics between the two model versions. This is demonstrated by the results of a set of fixed-amount single-latitude injection simulations (Fig. S1 in supplementary material)”. Using a completely different model is outside of the scope of this single-model study. However, we agree that cross-model validation should be done in future work.
18. Line 81: The word “pragmatic” here was intended to mean that we consider the strategies that are more likely to be considered for future deployment, in contrast to highly-asymmetric strategies that would notably change T1 and shift ITCZ. One can find many possible sets of 7 strategies that span the AOD design space of the same 7 degrees of freedom found in Zhang et al. (2022), which are single

latitude injections at 7 different latitudes: 60°N, 30°N, 15°N, the equator, 15°S, 30°S and 60°S. We chose this particular set of strategies based on not just the goal of spanning the same AOD design space, but also to focus only on strategies that would not result in large shifts in ITCZ. We agree that the word “pragmatic” was not a great choice of word as this word is somewhat subjective; different people may reach different conclusions regarding pragmatic. We have deleted this word in the manuscript.

19. Line 81: We thank the reviewer for the valid point. However, testing different altitudes or different particles is beyond the scope of this manuscript.
20. Line 94: both are grammatically correct.
21. Line 98: The sign of the hemispheric asymmetry in injection rates that would be needed to maintain T1 varies among different climate models. For example, in CESM1 more injection was required in the NH and in CESM2 more injection was required in the SH to compensate T1. We have rewritten this paragraph to better explain our motivation.
22. Line 102: The radiative forcing from CO2 is roughly hemispherically symmetric, and thus to first order one might reasonably expect a hemispherically symmetric injection would compensate both T0 and T1. However, other effects - the fast cloud-adjustment to increased CO2, as well as changes in AMOC and in tropospheric aerosol concentrations lead to changes in T1 that require asymmetric injection to compensate. These, however, are strongly model dependent (e.g., in CESM1 more injection was required in the NH and in CESM2 more injection was required in the SH to compensate T1). This model-dependency of the sign of the asymmetry in injection rates (NH-dominated or SH-dominated) is one reason we focus here only on symmetric strategies. Also see our responses in #21. We have rewritten this paragraph to better explain our motivation.
23. Line 104: These hemispherically-symmetric strategies that only target T0 are simpler to implement in many other climate models. It is relatively straightforward to tune one variable (overall injection rate) to meet one objective (T0) by hand. Simultaneously tuning multiple variables is more challenging without explicitly coding a feedback control algorithm. Simulations such as GeoMIP G6 demonstrate that modeling centers can adjust injection to meet one goal without needing to code a control algorithm. We have reworded the text to clarify.
24. Line 108: change “will” to “would”.
25. Line 112: same response as in #1.
26. Table 1: We have added explanations for MAM and SON in Table 1 caption. T0, T1, and T2 are explained in line 91-92. We have changed “T0/T1/T2” to “T0, T1, T2”.
27. Line 131: We have changed according to the reviewer's comment.
28. Line 142: We have changed according to the reviewer's comment.
29. Line 147: We have changed according to the reviewer's comment.
30. Line 159-163: We have removed our hypothesis on the overcompensation of T1.
31. Figure 1: We have increased the Font size in all figures.

32. Line 204: we have added citation: Butchart, 2014; Lee et al., 2021; Visioni et al., 2023.
33. Figure 6: We have added a Jan column after Dec.
34. Line 363-365: we thank the reviewer for valid points. However, the analysis of the above aspects is beyond the scope of the current manuscript. We have added “including” after “a series of deliberate decisions”.
35. Line 366: We have changed the original sentence to “…a set of five SAI strategies…”
36. Line 396: same response as in #1.