Author comments, "Exploring divergent long-term stratospheric aerosol injection scenarios with the G2-SAI and ARISE-hybrid experiments," submitted by W. R. Lee et al. to Earth System Dynamics

We would like to thank two anonymous peer reviewers for their feedback on our manuscript. We respond to each reviewer below in blue.

Author response to Peer Reviewer #1

This manuscript introduces a new set of long term experiments, G2-SAI, to better isolate and understand the impacts of stratospheric aerosol injection (SAI), and propose them as new GeoMIP experiments. Using CESM2, the authors show that the commonly used feedback algorithm, when adjusted, can result in the scenario meeting the same temperature targets using different injection location magnitudes. These different injections can produce fundamentally different climate states, especially through their influence on the AMOC, whilst still achieving the same temperature targets. The study highlights the importance of longer simulations to capture slower climate feedbacks, and shows that small changes in the feedback algorithm can change the resulting climate impacts.

This paper is very well written and formulated. The revision of the ARISE simulations are particularly interesting. I recommend it for publication and have only a few comments below.

We thank the reviewer for their time and comments, and respond to individual comments below.

General comments

Section 2.2: Please could you clarify the algorithm used for G2-SAI-hybrid. You discuss in this section that I0 determines the injection for 15°N+15°S and its I1 and I2 which determine how much is injected in 30°N+30°S, how does the hybrid scenario determine injection at 30°N+30°S if I1 and I2 are turned off? It might be worth expanding on your explanation of this scenario in this section. It was not immediately clear that the three temperature targets were still being used when you discuss turning off the feedforward terms.

The other reviewer also commented on this. We have clarified our methods in this section - specifically, the ℓ_0, ℓ_1, and ℓ_2 loops each have a feedforward and feedback component; in the hybrid case, the ℓ_1 and ℓ_2 feedforwards are turned off, but all three feedbacks are still turned on. We have split Section 2.2 into two parts, and the new Section 2.3 hopefully makes these differences more clear.

Section 3.2:

I really like how you have displayed the figures as "per degree of warming" but I think the way you have done this could be better explained in the opening paragraph. I think you get to some of that in the figure caption but this section would benefit from further explanation in the main text as to how you calculate the "per unit warming". Personally, the addition of the global mean

temperature increase values in the figure caption helped me understand what you had done, so perhaps adding that to the main text would help. Lines 259-261 discussing the average of the maps added confusion for me personally, so might benefit from further explanation.

Thank you for the feedback - we have edited the text, and hopefully it better clarifies what we're plotting.

Regarding the precipitation changes, I agree that a detailed investigation would be beyond the scope of the study. But it might be worth mentioning again that for the G2-SAI simulations you are only looking at one ensemble member and precipitation is highly variable and would benefit from multiple ensemble members to determine any specific impacts.

Good point; we say this now.

Specific comments

All of the comments below have been addressed; we especially thank the reviewer for catching the mismatched figure references.

Line 149: remove "above"

Fixed

Lines 150-152: "Feedback gains, which adjust the injection rates each year based on the error (the difference between the actual and desired model behavior) over the course of the simulation."

Fixed

Figure 1: It might be worth adjusting the width of the ensemble mean lines, it looks quite messy with the variation, in particular the black lines. This is an aesthetic judgement which the authors should feel free to ignore.

Fixed

Line 196: 4f not 4f-g

Fixed

Lines 200-201: "AOD distributions in years 16-35 of injection likewise have similar shapes." Please add a reference to 4g here.

Added

Lines 225-228: Figure references should be 5 not 4.

Fixed

Line 229: Figure reference should be 4 not 3.

Fixed

Line 272: Should that read “compare Figs 5a and 8**d**”?

Yes; fixed

Author response to Peer Reviewer #2

In the work, Lee et al. propose an updated version of the earlier iteration of the GeoMIP G2 experiment which originally involved a “time dependent insolation decrease to offset the radiative flux perturbations from a scenarios in which CO_2 concentrations increase by 1% per year from pre-industrial levels” [Kravitz et al. 2013]. Authors use this background emissions scenario to test three unique SAI injection strategies:

1. Injection at 30N, 15N, 15S and 30S to manage global average surface temperature large scale meridional temperature gradients
2. Injection at 30N and 30S to manage global mean surface temperature

Authors find that while all scenarios meet the same surface temperature objective …achieving this state with injection dominated at 15S fails to slow the decline of the AMOC; ultimately challenging the idea of linearity used in contemporary strategy design. These findings are used to revisit the ARISE-SAI-1.5 simulations.

In general, I find this work an important addition to the literature by providing evidence to support the need to better understand potential non linearities in the climate response under the same surface temperature response. Ultimately, I think this work will provide motivation to the SRM community to invest in further mechanistic and process levels studies to improve assessment of *why* such non-linearities exist. Additionally, assessment of the AMOC response to SAI with a higher control on background CO_2 emissions represents a timely investigation given recent literature to suggest the first observed decline in AMOC strength; making such simulations important to the global tipping points discussion. One major comment to the authors is consideration of splitting out the discussion of the revision of the ARISE-SAI-1.5 into a separate work and expanding the AMOC related findings from the G2 simulations, more robustly building out this section. The presentation of the G2 simulations alone is well founded and generates a substantial amount of results that constitute a clear addition to the literature as a stand-alone study. The introduction of the ARISE SAI revisit makes sense but it does make more work for the reader and I worry it could reduce visibility of your already very interesting and important findings from the novel G2 work. I leave this choice up to the authors. Below I discuss several additional minor comments.

We thank the reviewer for their time and feedback. We considered splitting this work into two papers, but ultimately decided to leave them as one work. We respond to individual comments below.

Minor Comments:

Line 135: It remains somewhat unclear what the G2-SAI-hybrid setup refers to. It is clear from the current text that it is one of two 3-DOF scenarios which seeks to maintain targets T0, T1, T2, but it is unclear what differentiates it from the G2-SAI-3DOF scenario when first introduced. I would suggest the authors add a bit more text to make this more clear. This comment extends to the abstract, where I would suggest making more clear the differences between the two 3DOF simulations. As it reads now I initially thought one 3DOF simulation sought to control for T0 and the other sought to control T1, T2. This can be made more clear. One might consider moving information from line 170 “the term hybrid is chosen to reflect the combined aspects of both the 3DOF and 1DOF strategies,” higher in the text when the G2-SAI-hybrid is introduced.

The other reviewer also commented on this; we have re-written this section and split it into another section, and hopefully our methodology is more clear.

Table 1: in the same way, I would recommend an additional column in Table 1 to help the reader understand the differences between G2-SAI-3DOF and G2-SAI-hybrid, which otherwise look identical from the table as is.

This is a good idea; we have added a column to Table 1 which highlights the different injection strategies.

Line 185/Figure 2b: Changes in the slope of plots of Tg-SO2 per year vs. deg. C cooling are estimated to say that for G2-SAI the injections cool less efficiently above 10 Tg/year. I wonder if authors could provide some measure of or correction to the interannual variability in the cooling efficiency in the context of these estimated slopes? In addition to a lessoning of the efficiency, is there also greater year to year variability in the later years of the simulation? If so why might this be?

This is a good question; as a preliminary analysis of interannual variability, we have divided the 150-year simulations into six 25-year chunks, and computed mean and standard deviation of injection rate and mean and standard deviation of cooling per injection for each chunk. The variability of cooling per injection decreases as the simulations go on, and variability of injection rates as a percentage of injection size also decreases as the simulations go on. At first glance, this suggests decreasing relative uncertainty with larger injection rates. However, it is important to remember that injection rates here are chosen by the feedback algorithm based on the behavior of temperature in the model, and therefore long-term variability in the injection rates are likely to be a function of the controller gains as well as temperature fluctuations under several degrees of global warming + SAI, and separating out these influences would require deeper investigation. For posterity, we have added a table with this information to the Supplementary Material, and we mention it in the appropriate place in the main text.

Figure 4 : I might try to make the panels under “Stratospheric 550 nam per Tg SO2 / yr” and “Residual d near -surface T” slightly larger. This figure was an extremely useful visual representation of the inter-scenario differences and would merit taking up more room on the

page. For ease of reading I would also suggest thickening the lines and moving the legend which covers both sub sections to the bottom to be a bit clearer.

Thank you for the feedback - we have increased the panel size, font size, and line width of the bottom two rows of this figure, which should improve readability.

Section 3.2 : authors may consider creating separate sections for AMOC response and the surface temperature/precipitation response. I would recommend showing the reader the surface temperature/precipitation plots before an in depth discussion of the AMOC response which then helps to explain why the G2 – 3DOF scenarios differ in responsive injection latitudes as a function of temperature itself. I realize section 3.1 was results of the G2 SAI scenarios, but I would consider breaking out the section discussing AMOC separately as it is discussed in comparison with the other pre-existing simulations. I acknowledge one relies on the other – the northern hemisphere temperature changes are dependent on the decline of the AMOC. It may be useful to tie these sections together by providing overlapping time vs. metric plots of norther hemisphere T change vs. some metric of the AMOC – as a visualization of this relationship.

We have split this subsection into two parts, with the AMOC behavior now in its own section. We have also added additional temperature maps and a diagram to Figure 5, which is slightly different from what the reviewer suggested, but we think it works well.

Line 264: might be more specific and say “warming patterns across the two background ghg scenarios” … this section is good but was just a lot to digest as the reader keeping track of all the simulations so wherever possible being super specific is helpful – (which in general I think the authors have achieved).

Changed

Figure 6-7: For visual clarity for these large multi -panel plots, authors might consider making clear rows for the different simulations (eg moving the labels G2-SAI-1DOF) to the far left highlighting that all members of that row are the same simulation. The repetition of labels and colorbars makes the reader have to parse if there are differences in every single map. Reducing visual noise here could really help simplify for the viewer.

We have rearranged Figs. 6 and 7 to reduce visual clutter; we tried several different variations, and we hope the one we selected improves the readability.

295-300: It would be really clarifying to include in the supplementary material a plot of latitude (x axis) vs. d-precip (yaxis) for each scenario. This helps to easily summarize the descriptions and similarities discussed in this section which otherwise do take quite a bit of time to get to. I think this would help the important results of your work sink in for folks a bit more.

We agree that this would be helpful; we have added such a plot.