July 15th, 2024

Reviewer comment regarding How Does the Latitude of Stratospheric Aerosol Injection Affect the Climate in UKESM1? submitted to Atmospheric Chemistry and Physics by Matthew Henry, Ewa M. Bednarz, and Jim Haywood

General Comments

This study examines five sets of simulations of different stratospheric aerosol injection (SAI) strategies carried out with the UK Earth System Model (UKESM1). The strategies are designed to be similar, with the primary difference being the latitude of sulfur injection; the strategies include equatorial injection; hemispherically symmetric injection at 15°N/S, 30°N/S, and 60°N/S; and the four-latitude injection strategy prescribed by the ARISE-SAI-1.5 protocol. The study considers the required sulfur injection rates to maintain a global mean temperature of PI + 1.5°C with each strategy, as well as some changes to surface and stratospheric climate.

Overall, the manuscript is sound, and I recommend minor revisions before it is formally published. My main comments are as follows:

- Many of the figures need more detail, either in the labeling, the data they present, or both. Many tend to show only ensemble means, zonal means, and 10-year averages; I would like to see more data from individual ensemble members represented, as well as more full maps and timeseries where appropriate. I would also like to see more information about the baseline/reference/target state to which the strategies are compared (see specific comments below).
- The authors assert in several places that the 30°N + 30°S strategy is the "best" or "optimal" strategy, and they claim that 30N+30S has the least overall "unwanted side effects," while equatorial injection has the most. While the authors are of course entitled to their opinion about which strategy is optimal or what constitutes a "negative" side effect (and I do not necessarily disagree!), such subjective assertions are unscientific; I would much rather see objective statements about the magnitude of disruptions to circulation or precipitation (the conclusion does a much better job of this).
- I disagree with the authors' decision to simulate year-round 60°N + 60°S injection at 22 km altitude. Past simulations of high-latitude injection with which I am familiar - Bednarz, et al.

(2023)[1]; Zhang, et al. (2024)[2]; Lee, et al. (2023)[3] - choose to inject around 15 km altitude (a short distance above the tropopause) rather than at the same altitude as subtropical injections; additionally, they choose to inject only in the polar spring, rather than in all months of the year. While I understand the authors' decision to prioritize consistency with the other strategies, consistency in the injection distance above the tropopause would have been more relevant than absolute altitude - I don't think an analysis of year-round 60°N + 60°S injection at 22 km is particularly meaningful, because at the current state of the research, this is not a strategy that would be considered either for inter-model comparison or in real life. Additionally, if one of the study's primary goals is to compare these strategies in UKESM and CESM, that cannot be done for the 60°N+60°S strategy if they were implemented so differently.

While I think the manuscript would suitable for publication without this change, I strongly encourage the authors to consider running at least one ensemble member of the 60°N + 60°S strategy with injection at a lower altitude (either 15 km, to be consistent with other studies, or the same distance above the tropopause in this model as the subtropical injection strategies), and ideally with injection only in the polar spring as well. I don't know what constraints the authors have on computational resources, or whether they are constrained by length limits for this journal, and this may not be feasible for them. However, I do not think the 60°N + 60°S strategy presented here will receive as much attention because there are no similar simulations (to my knowledge) by other models, and I do not expect there will be. If the authors are able to add what I consider to be a more realistic implementation of 60°N + 60°S injection, I think it would significantly increase the impact of this paper.

Specific Comments

- Lines 6-8, "many undesirable side effects" - I don't disagree, but I advise against using subjective words like "undesirable" and try instead for objective words (perhaps "disruptive"). Additionally, be careful to discriminate between the impacts of SAI, and the impacts of global warming which SAI does not prevent - for example, equatorial SAI "leading to" residual Arctic warming may be

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[1] Bednarz, E. M., Butler, A. H., Visioni, D., Zhang, Y., Kravitz, B., and MacMartin, D. G.: Injection strategy – a driver of atmospheric circulation and ozone response to stratospheric aerosol geoengineering, Atmos. Chem. Phys., 23, 13665–13684, https://doi.org/10.5194/acp-23-13665-2023, 2023.
[2] Zhang, Y., MacMartin, D. G., Visioni, D., Bednarz, E. M., and Kravitz, B.: Hemispherically symmetric strategies for stratospheric aerosol injection, Earth Syst. Dynam., 15, 191–213, https://doi.org/10.5194/esd-15-191-2024, 2024.
[3] Lee, W. R., MacMartin, D. G., Visioni, D., Kravitz, B., Chen, Y., Moore, J. C., et al. (2023). High-latitude stratospheric aerosol injection to preserve the Arctic. *Earth's Future*, 11, e2022EF003052. https://doi.org/10.1029/2022EF003052

technically correct, but I would prefer to see wording such as “substantially undercools the Arctic”.

- Lines 11-13, “we demonstrate that the 30N+30S strategy has, on balance, the least negative side effects” - this is a long way away from being shown. While this may be the authors’ opinion concerning the five SAI strategies simulated with this model and the impacts considered in this paper, such a subjective blanket statement is unscientific; there are many, many more impacts to consider than just the ones examined here, and as the results do not show that the 30N+30S strategy is universally better than the others (for example, 15N+15S and ARISE-SAI-1.5 have smaller injection rates at the end of the experiment), and others may read this study and form a different opinion.
- Section 2 in general: please clarify which simulations are being presented here for the first time, and which were first presented in other studies - from what I can tell, the ARISE-SAI-1.5 and SSP2-4.5 simulations were first presented in Henry, et al. (2023)[4], and the other four SAI simulations are new here. As a whole, I think this section would be easier to interpret if you introduced SSP2-4.5 and ARISE-SAI-1.5, and the reference period and temperature targets, first, and then explained that you’re presenting four new simulations which only target global mean temperature.
- Lines 69-70, “the global mean surface temperatures value in UKESM1 exceeds its preindustrial value by 1.5K” - this needs a citation, since the presented temperature data in Figure 1 only goes back to 2020 (I assume these numbers, and the temperature targets, were first presented in Henry, et al. 2023).
- Table 1: I would add a line to include SSP2-4.5, which is a unique set of simulations you are considering, and in line with my comment above, you could add a “first presented in” column with a citation/source for each simulation, even if it just says “Henry, et al. (2023)” for SSP2-4.5 and ARISE-SAI-1.5 and “here” for the rest. These changes would make it easier for a reader who is less familiar with the literature to follow along.
- Figure 1: the plot needs to be labeled better - clearly, the y-axis is relative to the preindustrial, but this is not stated. Additionally, the dashed black line is probably shown to represent the reference/target temperature, but it is not included in the legend.
- Figure 1: I would really like to see the individual ensemble members represented on this plot, not just the ensemble mean.

[4] Henry, M., Haywood, J., Jones, A., Dalvi, M., Wells, A., Visioni, D., Bednarz, E. M., MacMartin, D. G., Lee, W., and Tye, M. R.: Comparison of UKESM1 and CESM2 simulations using the same multi-target stratospheric aerosol injection strategy, Atmos. Chem. Phys., 23, 13369–13385, https://doi.org/10.5194/acp-23-13369-2023, 2023.

- Figure 1: I would also like to see actual numbers for global mean temperature somewhere, not just relative to the reference period - right now, the numbers are buried in the text; adding a right-side axis with the actual temperature values in °C or K, or adding the target value as text next to the dashed black line, would help give the reader another point of reference.
- Figure 1: the target and ARISE-SAI-1.5 both in black is a bit confusing - I would either pick a different color for one of them, or make the dashed line for the target thinner to more easily differentiate.
- Line 82 - saying Figure 2 "summarizes the climate response" is a bit strong… climate response is a lot more than zonal mean surface temperature and precipitation
- Line 85, "the most latitudinally homogeneous AOD is achieved by injecting at 30N+30S" - is it? The ARISE-SAI-1.5 AOD looks pretty similar to me. Additionally, you should clarify that this is out of the five strategies you considered here, and that this isn't a blanket truth for SAI
- Line 90, "the most efficient injection strategies" - 60N+60S isn't that different from the other three; certainly, the difference between 60N+60S and any of the other off-equatorial strategies is much larger than the difference between equatorial and off-equatorial
- Lines 93-94 - I disagree with this characterization as "optimal," for the same reasons as above
- Lines 99-100, "The larger injection rates for 60N+60S, on the other hand, arise due to faster removal of aerosols when injected near the descending branch of the Brewer Dobson Circulation (BDC)" - this needs a citation or other evidence to support it. This is one plausible contributing factor, but no analysis of aerosol lifetime is presented; polar SAI could simply cool the planet less efficiently because you're mainly inducing forcing changes over a relatively smaller fraction of the planet, and you're also injecting in winter when there's no sunlight to reflect
- Figure 2, all panels: again, I would really like to see individual ensemble members, not just ensemble mean
- Figure 2a: does "AOD" refer to 550nm AOD in the stratosphere only, or the whole atmosphere?
- Figure 2a: we need to see at least some information about the baseline SSP2-4.5 AOD here. I would plot raw AOD instead of ΔAOD, and show the SSP2-4.5 in yellow as well; if SSP2-4.5 AOD is so small that it wouldn't even show up on this graph (e.g., order 0.01 or lower), you could just omit it entirely, and say in the text or figure caption that the baseline is several orders of magnitude smaller than the changes under SAI.
- Figure 2b: I would really like to see timeseries instead of 10-year averages. Additionally, there is no description of what the errorbars represent; however, I would rather just see individual ensemble members here too.

- Figures 2c and 2d: using a black line for both target and ARISE-SAI-1.5 is a bit confusing - please either change the color of one, or make the line for the target thinner to differentiate
- Figure 2d: while zonal mean surface temperature changes are probably okay, I think precipitation would be much better shown as a map. I know this would take up a lot of space, but you have maps for each strategy in figures 4-6; I don't know if you are constrained by length limits or number of figures, but it might be better to have one figure for AOD and injection rates (perhaps merged with Figure 1), and have a second figure containing temperature and precipitation. If this isn't feasible, I encourage you to add maps of precipitation changes to the supplementary.
- Lines 110-111, "no pattern of AOD from SAI is able to entirely offset the forcing from greenhouse gasses in the model" - firstly, this paragraph discusses temperature change, not forcing; secondly, this is only shown for the five patterns considered here
- Lines 133-134 - more detailed methodology is needed here; are you interpolating between grid boxes to compute this? Is this a linear interpolation, or a cubic one?
- Line 141 - I am not convinced this relationship is linear. You have fit a linear trend to the data, but that does not mean the relationship is linear
- Figure 3: how are you computing the dashed line? More details are needed here
- Figure 3: rather than using the bars to denote ensemble spread, I suggest just using different color dots for each of the individual simulations, as the number of individual simulations is relatively small
- Lines 156-158 - there is already at least some literature on this; see Lee, et al. (2020)[5]
- Figure 4 (and Figure 6) - height in km, or pressure in hPa, would probably be easier to read than height in m
- Line 171 - if age of air cannot be measured directly, can you elaborate on how it is presented here? Do you compute it from the model output, or is it computed and saved directly as model output during the simulation?
- Conclusion, in general: the results here are primarily compared to similar experiments in CESM2, but I am also curious about the robustness of these results in UKESM - for example, Wells, et al. (2024)[6] looked at equatorial injection vs. a four-latitude controller strategy similar to ARISE-SAI-1.5, but with a different background; if that study presented any of the same

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[5] Lee, W., MacMartin, D., Visioni, D., and Kravitz, B.: Expanding the design space of stratospheric aerosol geoengineering to include precipitation-based objectives and explore trade-offs, Earth Syst. Dynam., 11, 1051–1072, https://doi.org/10.5194/esd-11-1051-2020, 2020.

[6] Wells, A. F., Henry, M., Bednarz, E. M., MacMartin, D. G., Jones, A., Dalvi, M., and Haywood, J. M.: Identifying climate impacts from different Stratospheric Aerosol Injection strategies in UKESM1, Earth's Future, 12, e2023EF004 358, 2024.

diagnostics as this study (ITCZ position, circulation changes, ozone depletion), it would be a useful point of comparison.

- Conclusion, in general: I like the objectivity of this section a lot more than the abstract/introduction; rather than saying that 30N+30S is the “best” strategy, evidence is presented that certain possibly unwanted impacts are smaller or absent. The equatorial strategy is still described as having “the most negative side effects” in lines 252 and 270, which I would advise rewording. Lastly, in line 272, I might choose a word such as “supports” instead of “confirms”.