

Dear editor and reviewer,

We greatly appreciate your thoughtful and valuable comments and suggestions in both rounds of the review, which have been crucial in improving our manuscript. Now, according to your latest feedback,
5 this manuscript has been further revised. We have provided a marked-up version of the manuscript showing all changes made (using track changes in Word). Following is a point-by-point response to the comments.

With warm regards,

10 Ou Wang, on behalf of all co-authors

Response to comments by referee #1:

General comment:

15 The authors have worked hard to improve the manuscripts and addressed many of my previous concerns. However, some inconsistencies remain in the text and some fairly major changes are still necessary before this article can be accepted for publication.

Response:

20 Thank you very much for your comments. We have carefully considered each of the comments, and most of them have been adopted in improving our manuscript. Responses to all the comments are given point by point as follows.

I have not checked the ms beyond L270 as my comments are largely repetitive: The point of the G6 simulations is not whether they arrive at a “better” future than SSP5-8.5, a better future would be SSP1.19.
25 Rather the point is whether using SAI to hold temperatures in line with SSP2-45 will have any other unforeseen consequences. Thus all results comparing back to SSP5-85 need to be removed, and statistical significance tests should be between SSP2-45 and G6 simulations. Please revise the remainder of the manuscript to reflect this.

Response:

30 We understand your suggestion that the G6sulfur simulations should only be compared against SSP2-4.5. This type of analysis highlights any differences that the impact of stratospheric aerosol injection (under the assumptions implicit within the G6sulfur strategy) might have when compared to a greenhouse gas warming scenario with the same global mean temperature.

While we acknowledge that this is important, and has been the focus of many SRM publications, 35 including those using both SAI (e.g. Wells et al., 2024) and MCB (e.g. Haywood et al., 2023), this type of analysis does not directly present a ‘risk-risk’ analysis – i.e. the risk of unmitigated global warming (SSP5-8.5) against a world where greenhouse gas emissions are essentially unmitigated, but SAI is used to counter-balance a proportion of the global warming.

While we agree that the academic community may be interested in the residual climate impacts 40 between a greenhouse gas world and a (GHG+SAI) world, the first-order impact of SAI is often overwhelmingly positive – at least when viewed as a physical risk-physical risk analysis. This fact is, unfortunately, often overlooked in the, largely more academic, presentations on SRM. Questions that the public and policy-makers ask are along the lines of i) Could SAI be effective in reducing the impacts of climate change? and ii) What are the residual climate impacts? Ignoring the first-order impacts (i.e. point 45 (i)) and presenting only the second-order impacts (i.e. point (ii)) would distort the policy-relevance of the studies.

It is important to acknowledge that the G6 experiments (G6sulfur and G6solar) are based on SSP5-8.5; i.e., the external climate forcing of SAI is applied to the GHG emission scenario (Tilmes et al., 2022). Their comparisons to SSP5-85 directly quantify the role of aerosol-climate interaction in the effect of SAI 50 on climate. It is important not only for the policy-makers but also for climate scientists who are interested in aerosol-climate feedback.

Studies such as those by Liang and Jim. (2023) have investigated the combined effects of GHG+SAI, demonstrating the simulated SAI strategy is effective at partly mitigating the projected future increase in atmospheric rivers (ARs) activity under SSP5–8.5 over the study region, while it induces significant 55 increases (by up to 0.15 %) in the AR frequency over north-eastern China. These findings provide essential insights for shaping climate policies. They help policymakers understand how SAI can influence

precipitation patterns regionally, aiding in the formulation of evidence-based decisions for climate adaptation and mitigation strategies.

By presenting G6 against SSP5-85, we provide important information to the policy-makers. This is of particular interest and of relevance to policy-makers in China, who have not had a great deal of exposure to the science of SRM via SAI. Given the narrative and arguments laid out above, we respectfully request that the reviewer reconsider their insistence in removing this analysis; we feel it is too important to ignore.

At a general level please ensure you choose either precipitation or rainfall and stick with that terminology. Similarly for “global warming” “anthropogenic global warming” “warming at the global scale”.

Response:

For the terms "precipitation" or "rainfall," different references use different words, but we have consistently used "precipitation" throughout the Abstract and main text and have ensured that all instances are correct. Additionally, we have checked and ensured that only "global warming" is used consistently throughout the text.

I remain unconvinced about the need to present the comparison with APHRODITE data. Your analysis centres around extreme precipitation, for which the models are not appropriate as they overestimate the maximum intensity. Furthermore, you do not (and do not need to!) bias correct the results; and I do not see where else the comparison to observations is used (not line 230-255 as stated in your response). You could instead simply state that the model has been effectively evaluated for adequacy elsewhere citing relevant papers (including your own paper Liang and Haywood 2023!). If you really wish to keep it, I suggest putting a summary of the analysis as an Appendix.

Response:

We agree that the validation should be moved to the Supplement. While it may not be highly relevant for these theoretical simulations, it provides reassuring that the model performs satisfactorily. We also refer to Liang and Haywood (2023) and other relevant articles. We have added the statement, please see lines 219-222.

The presentation of the results is still confusing. In all cases you present changes and statistical significance with respect to the control period, but state that SAI is approximately successful. I recommend breaking this up to illustrate both the changes with respect to the control period, and the differences at the end of the century from SSP2-45. Discuss the results with respect to these differences
90 from SSP2-4.5 as that is the target. As the pattern of changes is largely the same for all indices, you don't need to show the results for the changes relative to control, but could explain that the patterns are similar to those seen in other indices and cite other literature for UKESM/CMIP6 and focus on the effects of SAI.

Response:

We understand your suggestion to break up the analysis to illustrate both the changes with respect
95 to the control period (CP) and the differences at the end of the century from SSP2-4.5, as well as not to show the results for the changes relative to the CP but to explain that the patterns are similar to those seen in other indices. While we recognize the importance of this approach, we believe that presenting changes relative to the CP allows for a more straightforward visualization of future changes under different scenarios, providing clearer insights into the effectiveness of SAI in mitigating climate effects.

100 Additionally, we have included comparisons between G6solar and SSP2-4.5 for all indices and discussed the differences in results among various simulations. We have also added, for example, details on the mechanisms and reasons for SAI's effects relative to SSP2-4.5 in lines 254-256, as this information is crucial for understanding its effect.

105 We believe that this comprehensive approach provides a balanced view of the effect, addressing both the need for direct comparisons with SSP2-4.5 and the benefits of understanding changes relative to the control period. This dual perspective ensures that the policy relevance and scientific robustness of our findings are maintained.

Specific Comments:

110 [L24 G6sulfur is.](#)

Response:

Thank you. Already added the space "G6sulfur" and "is".

L26 delete “, under future simulations (SSP 5-8.5 and SSP2-4.5),”.

115 **Response:**

Thank you. Deleted.

L28-29 As stated for the previous version of the ms, this is not appropriate and should be reframed as matching the target FOR THIS MODEL only similar to L31

120 **Response:**

The sentence has been revised to “The G6sulfur and G6solar experiments show statistically similar results to those under SSP2-4.5 in extreme precipitation intensities of China in UKESM1. These results are encouraging.” Please see lines 28-30.

125 L30-31 These sentences don’t make sense.

Response:

Thank you. Deleted, as this sentence “the G6sulfur and G6solar show encouraging potential abatement of the impacts from detrimental extreme events which are similar with the lower emissions target of SSP2-4.5, there are some exceptions. For instance,” is similar to before “The G6sulfur and
130 G6solar experiments show statistically similar results to those under SSP2-4.5 in extreme precipitation intensities of China in UKESM1.”.

L34 Should really highlight that although only one model, small ensemble etc., the hydrological effects are not as beneficial as those indicated for temperature and more research recommended. Leave
135 statements about deployment to policy people.

Response:

Thank you for this important comment. The sentence has been changed to: “Given the limitations of the current model and the small ensemble size, and considering that the hydrological effects are less beneficial than those indicated for temperature, it is recommended that further, more comprehensive

140 research be performed, including using multiple models, to better understand these impacts.” Please see
line 35-38.

L43 insert space after “2020,”

Inserted.

145

L43-52 You could still reduce the level of historical events as the focus of the article is not on these
impacts. e.g. start a new paragraph at “Extreme precipitation...” then “For example severe flooding
affected southern, eastern and parts of central China in the summer of 2020 (Jia et al 2020); extremely
intense hourly and daily precipitation also occurred over Zhengzhou (southeast? China) in 2021 (Zhao et
150 al, Dong et al). Further extreme precipitation occurred over southern China in 2022, together with
flooding in the west of the Yangtze; and finally record-breaking precipitation occurred in 2023 across at
least 15 cities and provinces in north-eastern China” Could cite the WMO State of the Climate report here
to back up the record-breaker. WMO (2023) Provisional State of the Climate in 2023. World
Meteorological Organization. Available at: <https://www.nature.com/articles/nclimate3063> (Accessed: 15
155 February 2024).

Response:

Thank you for the thoughtful suggestion. The sentence has been revised to “Extreme precipitation
events appear to have impacted China more frequently in recent years. For example, severe flooding
affected southern, eastern, and parts of central China in the summer of 2020 (Jia et al., 2022); extremely
160 intense hourly and daily precipitation also occurred over Zhengzhou (central China) in 2021 (Zhao et al.,
2021; Dong et al., 2022). Typhoon Doksuri in 2023 resulted in significant flooding in China, setting
records near Beijing, while Yunnan province experienced its most severe drought since 1961 (WMO,
2024). These events suggest a potential expansion of regions that could be influenced by increasing
precipitation under the changing climate. On a global scale, climate change has been influencing
165 hydroclimatic conditions (Donat et al., 2016; Pendergrass and Knutti, 2018).” Please see lines 45-58.

L50 Remove “Although not statistically robust” and “might tentatively” Dunn et al. (2020) and de Vries et al. (2023) show a robust signal in Rx1day globally.

170 De Vries, I.E. et al. (2023) ‘Robust global detection of forced changes in mean and extreme precipitation despite observational disagreement on the magnitude of change’, *Earth System Dynamics*, 14(1), pp. 81–100. Available at: <https://doi.org/10.5194/esd-14-81-2023>.

Dunn, R.J.H. et al. (2020) ‘Development of an Updated Global Land In Situ-Based Data Set of Temperature and Precipitation Extremes: HadEX3’, *Journal of Geophysical Research: Atmospheres*, 125(16). Available at: <https://doi.org/10.1029/2019JD032263>.

175 **Response:**

Removed. We thank the reviewer for recommending these helpful references.

L61 Change ‘forecasted’ to ‘projected’.

Response:

180 Thank you. Changed.

L63 Again this is a policy statement best left to policy makers. The projections show an urgent need to mitigate (i.e. reduce carbon emissions) to avoid worse changes, and to adapt. However, as you go on, some have suggested that climate interventions may also support those actions to further abate the impacts from climate change.

185

Response:

Thank you for pointing out this problem. The sentence has been revised to “An increase in precipitation forecasted by current climate models, particularly that projected over the populated areas in East Asia, such as China (Liang and Haywood, 2023), indicates an urgent need for mitigation efforts (i.e., reducing carbon emissions) to prevent worsening impacts from climate change. However, it has been suggested that climate interventions could complement these actions in further mitigating the impacts of climate change.” Please see lines 67-71.

190

L65 Technically this should be a reference to COP 15, UNFCCC rather than the IPCC special report.

195 **Response:**

Thank you for pointing out this mistake, the reference has been corrected. Please see lines 73-75.

L73-75 Move “Numerous studies....” To L69 before G6Sulfur - to give better background on the idea of a “natural analogue” in the form of volcanoes.

200 **Response:**

The sentence has been moved. Please see lines 79-81.

L71 Zarnetske also points out the negative consequences; it is worth making more of that to make this paper a balanced contribution.

205 **Response:**

Thank you for your advice. We have added “Thus, SAI would come with some adverse consequences, including stratospheric polar ozone depletion leading to increased surface UV radiation, and increased sulphate deposition to the surface (acid rain). Moreover, the potential risks of abrupt termination also reveal significant changes in temperature and precipitation velocities, with potential severe impacts on ecological systems (e.g. Trisos et al., 2017). Despite the numerous drawbacks (e.g. Robock et al., 2015), its potential climate regulation effects make it arguably a plausible strategy to address escalating climate change challenges.” Please see lines 87-92.

L75 New paragraph for “The latest phase of ...”.

215 **Response:**

This section has been moved to start a new paragraph at line 93.

L79 Description of model specifics (I.e. SSP) belongs in the Methods section.

Response:

220 Lines 79-83 has been removed to Method section. Please see lines 133-136.

L83 rephrase “Previous studies from a range of modeling experiments innate that SAI will exert....”

Response:

The sentence has been rephrased in line 97.

225

L84 This is too generalised. Instead “reduce mean surface air temperature and may reduce global mean precipitation”.

Response:

Thank you for your suggestion. The sentence has been revised. Please see lines 98-99.

230

L86 change to “when stratospheric sulfur is used to moderate global mean temperatures”.

Response:

The sentence has been revised in lines 100-101.

235 L87 Remove “However, as suggested by some studies,” and change to “can effectively moderate global mean temperature increases, it cannot...”.

Response:

Thank you for the comments. The sentence has been changed to “Although SAI can effectively moderate global mean temperature increases, it cannot fully offset the effects at regional scale (Niemeier et al., 2013; Tilmes et al., 2013; Tye et al., 2022).” in lines 102-104.

240

L92 geoengineering is redundant here.

Response:

The word “geoengineering” has been removed.

245

L93 maybe differences instead of changes? And “between scenarios of projected warming alone, and warming with solar geoengineering”

Response:

250 The sentence has been revised to “our study explores the differences in frequency and intensity of extreme precipitation between the scenario of projected warming alone and warming with solar geoengineering (G6sulfur, G6solar).” Please see lines 109-111.

L98 This should be 2100?

Response:

255 The number has been corrected in line 112.

L117 remove “Tier 1” this is confusing.

Response:

Removed.

260

L125 Define the control period here instead of calling it “Historical”.

Response:

We've defined the control period as suggestion. Please see line 146.

265 L131 maybe “was created from spatial interpolation of gauge...”

Response:

The sentence has been revised in line 153.

L132 change “has been a” to “is a”

270 **Response:**

Changed. Please see line 155.

L140 include the references that are also in the Table caption here.

Response:

275 The references have been included on line 162.

L162-190 This section does not describe changes and so doesn't go with the title. It would be better removed altogether as stated above.

Response:

280 This sentence has been removed to the Supplement. As mentioned in the previous response, we have added the statement in lines 219-222.

L192 Should be "In all four simulations, most of the region is."

Response:

285 Revised. Please see line 224.

L193-195 See my general comment and consider removing these lines.

Response:

As stated in our response to the general comment, we need to retain these lines.

290

L205 some areas of southern China seem wetter than SSP2-45, and drier in the west for G6. See general comment. Even if statistically significant this still doesn't categorically show that SAI "effectively mitigates the increase" it demonstrates that it works for this set up in this model.

Response:

295 Thank you for pointing that out. The sentence has been revised to "This indicates SAI somewhat mitigates the increase in mean precipitation from the high GHG SSP5-8.5 scenario to the medium GHG SSP2-4.5 scenario across most of China. It is important to note that this finding is based on a single model, and future studies could validate these results using multiple models." in lines 245-248.

300 L212 space between R95p, for

Response:

Thank you, the space has been added.

L220 Should be SSP5-8.5

305 **Response:**

Thank you. It has been corrected.

[L223 Why is this noteworthy? It seems to be the same location in all four panels.](#)

Response:

310 Thank you for pointing that out. 'Noteworthy' was not accurately used; we have revised it to 'observed' in line 276.

[L227 Presumably the combination of water vapour and south-westerly winds brings more frequent ARs as you demonstrated?](#)

315 **Response:**

We agree that the increases in the north-eastward water vapour transport can facilitate the increase in AR frequency and partially the increase in extreme precipitation. However, not all the occurrences of extreme precipitation and their future changes can be attributed to ARs, particularly in southern China where precipitation extremes are linked to different types of weather systems (e.g. tropical cyclones and easterly waves). Thus, A short statement relevant to this has been added to lines 285-287. We also stated that “the synoptic mechanisms behind these signals of increase still require further investigation” in lines 287-288.

[L228 Spelling check all UK or all US throughout.](#)

325 **Response:**

Thank you. The spelling has been checked throughout the paper to make sure the language is UK English.

[L231 is this a statistically significant decrease with respect to SSP5-8.5?](#)

330 **Response:**

Thank you for pointing out this issue. Strictly speaking, this sentence may not be accurate and has been removed.

L238-252 Figure 5 This would make more sense with SSP2-4.5 - G6sulfur, SSP2-45 - G6solar, and
335 G6sulfur-G6solar because the description is about how areas are wetter than SSP2-45; and your reference
point is whether the difference between SSP-2.45 and G6 are statistically distinguishable and what the
consequences might be. Update the narrative to match the figures as suggested.

Response:

As our response to the general comment, as well as your suggestion, we have included ‘G6solar-
340 SSP2-45’ and updated the description to match the figures. Please see lines 298-330.

L248 Change “effectively mitigates”

Response:

The sentence has been revised to “G6sulfur mitigates RX5day under SSP5-8.5, particularly in the
345 eastern and south-western regions under UKESM1.” Please see lines 317-318.

Table 3 as noted above, more compelling would be the difference in results between SSP2-4.5 and G6.
Can SAI hold the space without having other consequences?

Response:

350 As suggested, we have included the difference in results between SSP2-4.5 and G6 (Table S3 and
Table S4) in the Supplement. We have also added some related discussions, such as in lines 355-360 and
lines 517-519.

L270 You still have not included in the article how the CDFs were established for each region!

355 **Response:**

Thanks for pointing out this issue. We have added a more detailed explanation: “To establish the
CDFs for an extreme precipitation index, firstly, the yearly mean extreme precipitation index was
calculated over the three ensemble model members and the 30 years at each grid point. Then, for each
region and the whole of China, the empirical CDFs (ECDFs) of the extreme precipitation index were
360 statistically established as histograms, based on the values over all the grids. To achieve a smooth

representation of the distribution, we applied a Gaussian smoothing technique. By doing so, we were able to obtain smoothed representations of the empirical distributions, which provided clearer insights into the underlying patterns of the data.” Please see lines 180-185.

365 [L286 Four G6 scenarios?](#)

Response:

Thank you for pointing this out; we have corrected it to "four simulations."

Reference

- 370 Haywood, J. M., Jones, A., Jones, A. C., Halloran, P., and Rasch, P. J.: Climate intervention using marine cloud brightening (MCB) compared with stratospheric aerosol injection (SAI) in the UKESM1 climate model, *Atmospheric Atmos. Chem. Phys.*, 23, 15305-15324, <https://doi.org/10.5194/acp-23-15305-2023>, 2023.
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- 375 Robock, A., Jerch, K., & Bunzl, M.: 20 reasons why geoengineering may be a bad idea. *Bull. Atom. Sci.*, 64, 14–59, <https://doi.org/10.1080/00963402.2008.11461140>, 2008.
- Tilmes, S., Visionsi, D., Jones, A., Haywood, J., Séférian, R., Nabat, P., Boucher, O., Bednarz, E. M., and Niemeier, U.: Stratospheric ozone response to sulfate aerosol and solar dimming climate interventions based on the G6 Geoengineering Model Intercomparison Project (GeoMIP) simulations, *Atmos. Chem. Phys.*, 22, 4557–4579, [https://doi.org/10.5194/acp-](https://doi.org/10.5194/acp-22-4557-2022)
- 380 [22-4557-2022](https://doi.org/10.5194/acp-22-4557-2022), 2022.
- Trisos, C. H., Amatulli, G., Gurevitch, J., Robock, A., Xia, L., and Zambri, B.: Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination, *Nat. Ecol. Evol.*, 2, 475-482, <https://doi.org/10.1038/s41559-017-0431-0>, 2018.

Wells, A. F., Henry, M., Bednarz, E. M., MacMartin, D. G., Jones, A., Dalvi, M., and Haywood, J. M.: Identifying climate
385 impacts from different Stratospheric Aerosol Injection strategies in UKESM1, *Earth's Future.*, 12, e2023EF004358,
<https://doi.org/10.1029/2023EF004358>, 2024.