II. Response to comments and suggestions of Reviewer #2

Peer Review, Liu, et. al., 2022: PInc-PanTher estimates of Arctic permafrost soil carbon under the GeoMIP G6solar and G6sulfur experiments

Overall this is a good contribution, and most of my comments are with regards to the clarity of presentation (including the current version leaving out a few details that are important). Some of this is simply that as written it implicitly is stating the results of this study as if they were statements about solar geoengineering more generally, vs statements about this particular strategy (tropical injection) in this particular scenario (cooling back down only to SSP2-4.5 levels, so that the global mean temperature continues to increase, just more slowly). Relevant to that it might be useful to try and make some statements in the conclusions about what one might expect to see in other cases, e.g., if SRM were used to hold global mean temperature constant, what would happen; if injection was done at higher latitudes… obviously you can't actually say that without having looked at those simulations, but you could potentially comment at least enough to make it clear that the answers will ultimately depend on the implementation.

We would like to thank the Anonymous Referee #2 for all the constructive comments and valuable suggestions on the previous version of the manuscript, which have helped us to improve the quality of the manuscript. We have brought in more discussion on the more polar-targeted injection schemes that have bene published and emphasized the difference with the G6 tropical injections. For each question and comment, we gave point-by-point response and made additions and revisions to the manuscript. Please see the attached response.

1. L11, SG could slow, could also stop it if one wanted, could even reverse it if one wanted. Why implicitly exclude these other options? (This is written as a generic statement, not a statement about the specific simulations you conducted.)

- Agreed, we have revised it. "Solar geoengineering (SG) has the potential to cool the Arctic surface by increasing planetary albedo"

2. L14-15, I know what you mean but someone unfamiliar with G6 might not realize that the SG is *only* applied for the SSP585. Nor might it be clear to a reader that in these scenarios, SG is used not to stop warming but only to reduce it to SSP2-4.5 levels – this is important context for the conclusions! (Given that G6 appears to roughly restore permafrost conditions to SSP2-4.5 levels also, one might reasonably infer that had more SG been used, one could prevent any further permafrost loss should one choose to.) Nor would a non-SG reader know that G6solar is a solar reduction and G6sulfur is stratospheric sulfate aerosols. (The abstract should be interpretable by people who are not already intimately familiar with GeoMIP scenarios.)

- We have modified the abstract as suggested. "Six earth system models are used to drive the model, running G6solar (solar dimming) and G6sulfur (stratospheric sulfate aerosols) experiments which reduce radiative forcing from SSP5-8.5 (no mitigation) to SSP2-4.5 (substantive mitigation) levels."

3. L15-18, I don't think these numbers are useful to anyone who doesn't already know what G6 scenarios are (per above comment). Might be more useful to say that sufficient SG to yield global mean temperatures consistent with the SSP2-4.5 pathway under SSP2-8.5 CO2 concentrations also leads to permafrost area and soil carbon not statistically significantly different from those under SSP2-4.5, either under solar dimming or stratospheric aerosols.

- We have revised it. "By 2100, simulations indicate a loss of 9.2 ± 0.4 (mean ± standard error) million km^2 of permafrost area and 81 ± 8 Pg of soil carbon under the SSP5-8.5 scenario. In comparison, under SSP2-4.5, G6solar and G6sulfur, permafrost area loss would be mitigated by approximately 39%, 37% and 34% and soil carbon loss by 42%, 54% and 47%, respectively, relative to SSP5-8.5."

4. L21-23, (i) The first part of this conclusion is not correct as written, because it is written as if it is a generically true statement about SG rather than a statement about this particular scenario. A reader might reasonably infer that SG actually couldn't do more than this, because that is what the sentence as written (making it a generic statement) implicitly says. I would assume from your results that SG could mitigate all the area loss and carbon loss if we wanted. (ii) the last part of the sentence about an income stream for the Arctic population doesn't seem like a scientific statement but a guess. This isn't an economics or IR paper. (Personally I don't have a problem speculating on this in the conclusions, but highlighting that level of speculation in the abstract of what is otherwise a scientific paper feels a bridge too far.)

- Thanks for pointing this out. We have revised the statement and deleted the last half of the sentence. "G6 experiments mitigate ~1/3 of permafrost area loss and halve carbon loss for SSP5-8.5, averting $0–70 (mean 20) trillion in economic losses through reduced permafrost emissions."

5. L29, missing close quotation. (Plus, there's been fair criticism of continuing to call 5-85 as BAU given the existence of policy changes and pledges; labeling it BAU is inconsistent with the first line of the intro.)

- We have revised it as suggested. "lowering global temperatures from a no-mitigation baseline scenario to a moderate emissions level"

6. L48 is written as if these are alternatives; the point about speed is appropriate but wording could be improved to avoid framing as an either/or. Ditto L51.

- We have revised it and removed policy-relevant statements. "The principal advantage of SG compared with CO2 removal and substantial emission reductions is that temperatures can be reduced far faster; SG may also face fewer technical and financial hurdles (Aldy et al., 2021), however, the potential for damage by SG has not yet been fully explored (Zarnetske et al., 2021). In an earlier study, Chen et al. (2020)…"

7. L55… I think it would be worth defining GeoMIP somewhere in the definition of G4. I guess you

do in the next paragraph…

- We have moved the definition of GeoMIP to the front as suggested. "Chen et al. (2020) found that five of seven CMIP5 Earth System Models (ESMs) driven by the Geoengineering Model Intercomparison Project (GeoMIP) G4 stratospheric aerosol injection geoengineering scheme simulated significant mitigation of Arctic permafrost soil carbon loss."

8. L63… was the target of G6 the radiative forcing, or global mean temperature? (I honestly forget, and I'm on an airplane and not bothering to pay for wifi, so can't look it up.)

- We have checked and it is radiation forcing.

9. L64, repeated "more". But more to the point, this would be a great opportunity to comment on the obvious scenario dependence (including not just the amount of cooling, but things like latitudes of injection). Ultimately (future paper of course) would be good to look at some of the more recent simulations still…

- Thanks for pointing this out. We have added comment "More sophisticated SG deployment strategies are being explored such as the latitudes of injection and its seasonality (Lee et al., 2021, 2022), but are still at the single ESM simulation stage, while the G6 experiments have been simulated by six ESMs (Table 1)."

  Lee, W. R., MacMartin, D. G., Visioni, D., Kravitz, B.: High-latitude stratospheric aerosol geoengineering can be more effective if injection is limited to spring. Geophys. Res. Lett., https://doi.org/10.1029/2021GL092696, 2021

  Lee, W. R., MacMartin, D. G., Visioni, D., Kravitz, B., Chen, Y., Moore, J. C., Leguy, G., Lawrence, D. M., and Bailey, D. A.: High-latitude stratospheric aerosol injection to preserve the Arctic., Earth and Space Science Open Archive [preprint], https://doi.org/10.1002/essoar.10512047.1, 22 November 2022

10. L110, should define TSL, NPP, and GPP. (Even if I know what they are… other readers might not)

- We have explained TSL, NPP and GPP where they first appear (the caption of Table 1).

11. Figures 1-3, when I can't see the G6solar line, is it under G6sulfur?

- Yes. We have modified the colors in Figures 1-3.

12. L170, why is 2015-19 in equilibrium?

- We have added explanations. "The initial carbon flux into the soil pool is inferred from the initial steady state, which satisfies the condition that soil C loss and input are in equilibrium during the first five years (2015–2019). This initial equilibrium assumption ignores decomposition occurring in the active layer in the current climate and aims to remove the effects of decomposition that would also occur under a constant climate for predicting the response of soil carbon loss to future soil warming (Koven et al., 2015)."

13. Section 2.3 more generally… there are certainly some assumptions that go into this model; it might be useful somewhere to give some indication for which ones importantly affect results and which don't, and how significantly they affect things. (E.g., if the 2.5-fold increase for 10C change was 2.0, or 3.0, would that radically change conclusions? Is that sort of uncertainty likely?)

- This is an interesting question, but beyond the scope of this study. However, rates of chemical reactions generally double for temperature rises of about 10C but can be somewhat faster in living tissue. Hence, it would be very unlikely for the three- or five-times higher activation energies, suggested as examples by the referee to double reaction rates in 2 or 3C, to occur in decaying tissues. We have added "The parameters of PInc-PanTher model are derived from laboratory incubation syntheses and literature reviews. For a more detailed description, please refer to Koven et al. (2015)."

14. Section 2.4, there will be some rather critical assumptions in here too, which aren't even stated. Like ratio of C emitted as CO2 vs CH4. Or the discount rate. Again, it's ok to refer to published

literature, but giving some context (to save us from looking things up) would be useful, and to the extent possible worth acknowledging degree of uncertainty.

- Thanks for this point. We have clarified the proportion of CH_4 emissions in section 3.4. "We assume that CH_4 emissions are 2.3% of the overall soil respiration rate based on available studies and expert assessments (Schuur et al., 2013; Schneider Von Deimling et al., 2015; Gasser et al., 2018), and that the remaining soil carbon is emitted as CO_2."

  And we have added notes on the PAGE-ICE parameters. "Finally, the estimated climate …, converting changes in consumption to utility through the elasticity of marginal utility (EMUC) to correct for regional income differences, and discounting aggregates based on the pure time preference (PTP) rate. In PAGE-ICE, both PTP and EMUC follow triangular distributions ranging from 1 (0.1–2) and 1 (0.5–2) respectively."

15. L205-6, minor quibble, but could you put the RCP8.5 and 4.5 in the same order as in the previous sentence?

- We have removed the comparison with McGuire et al. (2018) here, as suggested by reviewer #1, because the time span of the study is so different.

16. L211-214, not sure the G6solar vs sulfur results are even statistically significant, but worth saying more here. When people ran the simulations to achieve SSP2-4.5 temperatures (or RF), were the global mean values for G6solar the same as G6sulfur? (That is, some effect could simply be how well they executed the G6 protocol.) Or, if the modelers perfectly balanced RF in each case, did that also manage temperature equally well in both cases? Second, for same global mean temperature under the two, is the typical overcooling of tropics / undercooling of high latitudes the same for the solar and sulfur simulations? (Given that AOD is likely higher in the tropics for the specific G6 protocol, I might expect more tropical overcooling than for G6solar, leading to a physical reason why G6sulfur as specified might be worse than G6solar for permafrost, but that would be a result of the G6 specification, not a feature inherent to SAI vs solar reduction, indeed SAI would presumably give more flexibility to alter latitudinal dependence.) Or, is any difference between G6solar and G6sulfur due to something associated with the aerosols themselves somehow? (E.g., assumptions in the land model and

how it handles direct to diffuse light.) I think it would be both easy and important to check the first two possible sources of difference. It would also be worth pointing out somewhere that G6sulfur assumes tropical injection, which tends to undercool high latitudes relative to low, and that that is a choice; that other choices for injection latitude might do relatively more cooling at higher latitudes.

- Visioni et al., 2021 report detailed analysis of the surface climate response for the 6 ESMs running the G6 experiments. For the purposes of this answer, we focus on surface temperatures only, while remembering that other elements of the system also are affected. From Visioni et al., 2021: “All models successfully reduce global mean surface air temperatures to within 0.2 ∘C of SSP2-4.5 levels on average throughout the century with both geoengineering methods, but the amount of geoengineering required to do so varies across models.”

  So, we can answer your first question: “how well they executed the G6 protocol / manage temperature equally well in both cases?” We conclude that all models performed the G6 experiments adequately since residual surface temperature differences G6-SSP245 are significantly larger than 0.2 ∘C of SSP2-4.5 in various locations.

  The second question: “for same global mean temperature under the two, is the typical overcooling of tropics / undercooling of high latitudes the same for the solar and sulfur simulations?”

  No, it is different. G6sulfur has more residual temperature differences than G6solar just as the referee expects. There is also far more across-ESM variability under G6sulfur than G6solar (see fig 7 in Visioni et al., 2021).

  The third question: “is any difference between G6solar and G6sulfur due to something associated with the aerosols themselves somehow?”

  The response in the Arctic under G6sulfur is clearly due to the aerosols. Probably due to stratospheric heating (Visioni et al., 2021 and references therein). The differences between ESM may well be due to different initial states of long-period variations in the ocean or sea ice, but changes in the land vegetation have not been explored to date. As the referee suggests, the fact that G6 specifies tropical injection, and also specifies the target of global mean temperatures is very important in producing the strongly undercooled polar regions.

We added text: "It is perhaps surprising that the simulated permafrost area loss (and carbon loss, see next section) are so similar under both G6 scenarios, given that G6sulfur has more residual temperature differences and across-ESM variability than G6solar (Visioni et al., 2021). Under both G6 experiments, but especially G6sulfur, the polar regions are undercooled as is the boreal permafrost zone. This is not inherent to stratospheric aerosol injection, but a consequence of the G6 specification of tropical injection and global radiative forcing (hence temperature) target. The bias correction procedure for TSL removes much of the across-ESM differences and offsets from observational data at the start of the simulation period (Fig.1 and Table 2). G6sulfur produces a weaker response with larger uncertainty than G6solar…"

17. L273-274, is that RPE statement for all cases? (It follows a sentence about G6; unclear whether it is intended to be specific to that)

- We have revised the wording. "Specifically, RPE will increase the net loss of soil C, causing additional permafrost emissions of about 6 to 10 Pg C between 2020 and 2100 under the four scenarios".

18. L281… the changed direct and diffuse ratio is only present in G6sulfur yet the sentence talks about both. (Also, relevant to that, do you know how the land models in the various models handles direct to diffuse ratio for driving vegetation?)

- Thanks for pointing it out. We're not quite sure how the land models handle the direct and diffuse radiative forcing, and changes in precipitation under SG will also affect NPP. The expression has been modified. "Increasing input C flux allows more carbon to be retained in the permafrost soils, thus the lower C loss and larger uncertainty under the G6solar and G6sulfur scenarios compared with SSP2-4.5 is mainly caused by the large across model spread in NPP change (Fig. 8)."

19. And Figure 9… wow, that's remarkable! I suppose not really that relevant here, but noting that

CESM G6sulfur does show the "over" cooling in summer as suggested by Jiang et al.

- Thanks. Good to know.

20. L319, are the conclusions very sensitive to this highly-uncertain numbr?

- Methane emissions are presumed to be 1.5%-3.5% of overall soil respiration rates, with the most common value taken as 2.3% (Schuur et al., 2013; Schneider Von Deimling et al., 2015; Gasser et al., 2018). The uncertainty in the methane emission estimates is therefore much smaller than that in the economic impact assessment.

21. L326, whoa… I think you need to say more than just "various". What parameters did you change, and why, and for what range? Are you coming up with a range of carbon emissions (in which case, shouldn't it be in the previous section)? Or just a range of economic damages for a given carbon? (in which case, are you missing the dominant uncertainties?)

- We have revised the wording. "All reported results are derived from an ensemble of 100,000 Monte Carlo simulations to perturb model parameters related to GHG emissions, climate modelling, economic damages and discounting, explore uncertainties in the economic impacts of climate damages, and establish probability distributions of the results."

22. L356, again, the statement here is worded as a generic thing (as if "implementation of SG" was a binary choice, rather than something that one could do more or less of, as well as depending on latitude of injection)

- Agreed, we have revised the wording. "Implementation of G6 experiments on the basis of the SSP5-8.5 scenario could…"

23. L358, but now, for costs, you specify G6 and then say it depends on scenario? This is not well worded… (that is, the "G6 scheme" I think means specifically following G6, i.e., for SSP5-8.5 emissions, with a target of 2-4.5 levels, using tropical injection. If you meant SAI more generally, you should say that).

- Thanks. We have revised the wording. “The implementation cost of stratospheric aerosol injection is strongly dependent on injection scenario specified, but for high greenhouse gas emission and a consequent degree of cooling, comparable to the G6sulfur scenario, is estimated at $30-70 billion/year (Smith, 2020). Our experiments thus show that SG, at least as defined by G6, but also likely including other schemes that target polar regions more specifically, has considerable global economic benefits even if only the permafrost carbon is included in the calculations.”

24. L360… considerable economic benefits even if only the permafrost carbon is included in the calculation!

- Yes!