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Informative risk analyses of radiative forcing geoengineering require proper counterfactuals

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The study "Radiative forcing geoengineering under high CO_2 levels leads to higher risk of Arctic wildfires and permafrost thaw than a targeted mitigation scenario" by Müller, et al.[1] examines three scenarios of radiative forcing geoengineering as simulated by the Norwegian Earth System Model. The authors compare high-latitude boreal summer maximum temperatures and winter minimum temperatures in the geoengineering scenarios – stratospheric aerosol injection, marine cloud brightening, and cirrus cloud thinning – to high-warming and moderate-warming scenarios without geoengineering. They conclude that all three geoengineering interventions, which use the high-warming scenario as the baseline, worsen the risk of wildfire and permafrost thaw relative to the moderate-warming scenario because they cool the Arctic somewhat less than the global mean in their experiments. We have significant concerns about how this paper's results and conclusions are framed.

First and foremost, Müller et al. claim that geoengineering increases the risk of wildfires and permafrost thaw; instead, what the authors show is that geoengineering *reduces* these risks, but not as much as an equivalent scenario and emissions cuts. We note that the original title, "Radiative forcing geoengineering causes a higher risk of wildfires and permafrost thawing over the Arctic regions", made this claim more explicit than the revision, which is an improvement. However, both framings of "risk" suffer from the fundamental defect of comparing geoengineering to an inappropriate baseline: the three geoengineering scenarios use RCP8.5 (a high-emissions, high-warming scenario) as the background, but the authors primarily compare the geoengineering scenarios to RCP4.5 (a moderate-warming scenario) instead of the more appropriate counterfactual of higher emissions without geoengineering. Secondly, the authors overgeneralize from a limited set of simulations even though it is now well known that regional impacts are highly dependent on the specific geoengineering strategy employed[2].

Our first concern relates to how Müller et al. characterize "risk". All three geoengineering interventions were simulated in the context of RCP8.5 emissions and designed to achieve the same global radiative balance as RCP4.5. It is clear from Fig. 1 of Müller et al. that the interventions substantially reduce global and Arctic mean temperatures relative to RCP8.5 by 2100. While it may be the case that, relative to RCP8.5, the greenhouse gas mitigation represented by RCP4.5 more efficiently reduces risk than any of the geoengineering interventions (assuming they were used as a substitute for that mitigation), the study misattributes the impacts of increased GHGs plus geoengineering to geoengineering alone; their Figs. 2–6 present results with respect to RCP4.5, which is not, on its own, a suitable frame of reference to determine the impacts of geoengineering. International assessments of geoengineering underscore that such methods should not be considered as a substitute for emissions reduction[3], not least because the environmental consequences of GHGs and aerosols can be very different[4]. Thus, to have a clear and accurate sense of their potential consequences, an assessment of geoengineering's potential climatic risks must consider them in relation to, not isolated from, the counterfactual risks of a world where warming is unabated by geoengineering (in this case, RCP8.5). In Fig. 1, we plot July maximum (T_{Xx}) and January minimum (T_{Nn}) temperature differences for each geoengineering realization to both RCP8.5 and RCP4.5. The authors' data show a *reduction* in the risk of wildfires and permafrost thaw in the geoengineering intervention scenarios compared to a world with the same CO_2 concentrations but without geoengineering (in line with other studies[5,6]). Müller et al. imply that geoengineering is at least in part responsible for the increased risk relative to RCP4.5; this is a mischaracterization because they compare against the wrong baseline, ignoring the appropriate counterfactual (RCP8.5) in which climate risks increase due to rising CO_2. To clarify, it is not our position that RCP4.5, or any other scenario, is not an appropriate baseline for geoengineering analysis in general; rather, an evaluation of the risks of geoengineering based on a comparison to RCP4.5 is inappropriate in this specific instance because RCP8.5 was the baseline used for the geoengineering simulations in this study.

Our second concern relates to the specifics of the geoengineering interventions considered in this study: the impacts of any geoengineering intervention depend on the strategy employed, but the authors only consider one strategy for each method of intervention. While the authors make some effort in the text to acknowledge other potential strategies, their title implies that the conclusions of this study apply universally to geoengineering interventions. For instance, for SAI, multiple studies have demonstrated that

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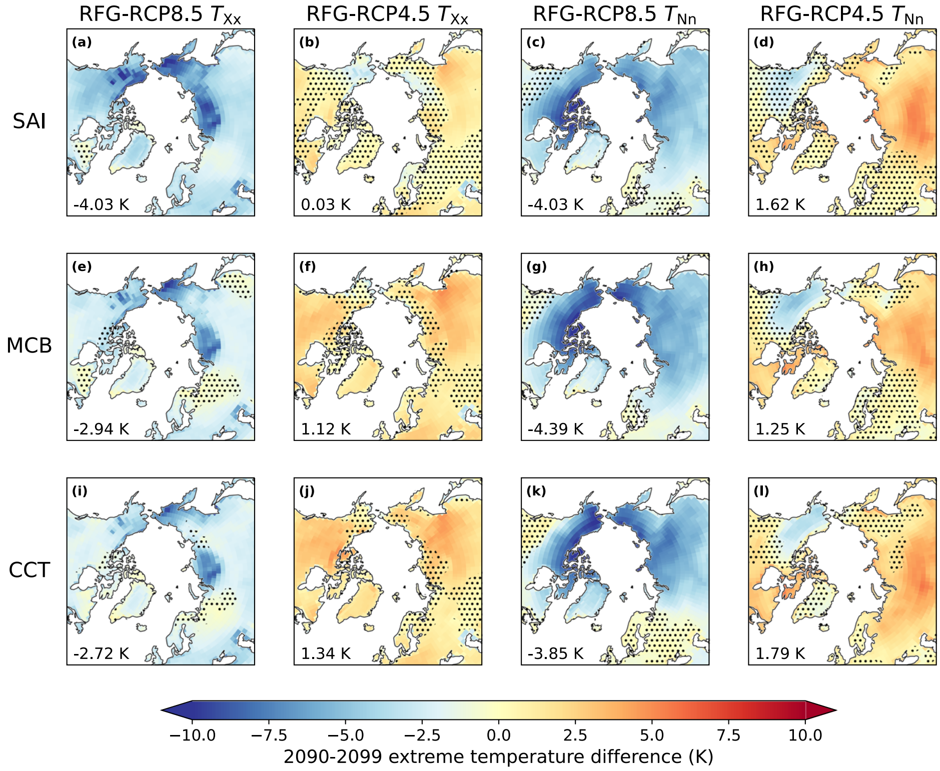

Fig. 1 | Simulated changes in T_{Xx} and T_{Nn} under geoengineering scenarios relative to RCP8.5 and RCP4.5 scenarios. Maps of changes in summer maximum (T_{Xx}) and winter minimum (T_{Nn}) high-latitude temperatures over land for stratospheric aerosol injection (SAI; **a**–**d**), marine cloud brightening (MCB; **e**–**h**), and cirrus cloud thinning (**i**–**l**) scenarios relative to RCP4.5 and RCP8.5 scenarios, averaged over the 2090-2099 period in the Norwegian Earth System Model. Stippling indicates statistically insignificant differences based on a two-tailed *t*-test at 95% confidence. Averages over the >50°N domain are shown as text in the lower left corner of each panel.

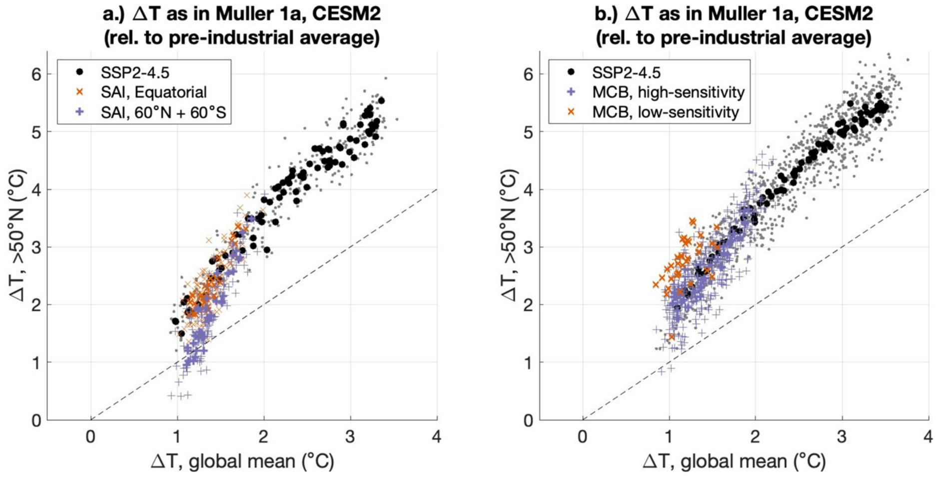

Fig. 2 | Simulated temperature changes for different SAI and MCB strategies and SSP2-4.5 relative to the historical period. Changes in global mean temperature and high-latitude (>50°N) temperature over land as in Müller, et al.[1] Fig. 1a for CESM2 simulations of (**a**) SAI at different latitudes, and (**b**) MCB in different regions, alongside SSP2-4.5 (both panels) relative to the historical period averaged over 1850-1899. Faint markers denote individual years of individual ensemble members; bold markers denote individual years of ensemble averages or of a one-member simulation. Note that these SAI and MCB CESM2 simulations use different atmospheric configurations (described in refs. 2 and 10, 11, respectively); hence, historical and SSP2-4.5 baselines are different in each panel.

equatorial injections are sub-optimal for high-latitudinal climate, not because of an innate characteristic of stratospheric aerosols, but because injections in the tropical stratosphere tend to overconfine aerosols to lower latitudes, thus over-cooling the tropics and under-cooling the poles[2,7,8]. This is not to say that any simulation of equatorial SAI is inherently useless or inferior[9]; however, a conclusion drawn from simulations of only one strategy should always be framed in the context of the community's understanding of the existence (and in many respects, optimality) of other strategies.

To demonstrate this point, in Fig. 2, we reproduce the analysis of Müller et al.[1] Figure 1a with output from multiple geoengineering strategies simulated using the Community Earth System Model (CESM2). In Fig. 2a, we compare equatorial SAI, high-latitude SAI, and the moderate-warming scenario SSP2-4.5 (the baseline for these SAI simulations[2]); the SAI simulations use a feedback algorithm to choose injection rates to maintain the global mean surface temperature of 1.0 °C above preindustrial. This analysis shows that: (1) in CESM2, equatorial and high-latitude SAI that produce the same amount of global cooling cool the Arctic to varying degrees; (2) this instance of equatorial SAI does not undercool the Arctic relative to SSP2-4.5; and (3) the high-latitude strategy overcools the Arctic relative to SSP2-4.5. In the right panel, we compare two MCB interventions (which also use the SSP2-4.5 baseline) in which clouds in different regions of the ocean are brightened by directly increasing the cloud droplet number concentration: one in which the "most sensitive" 5% of the ocean is brightened[10], and one in which the "least sensitive" 30% of the ocean is brightened[11]. These two strategies provide approximately the same amount of global cooling but affect Arctic temperature differently. These results demonstrate that, in addition to the chosen frame of reference, the geoengineering strategy and model used will affect the conclusions reached, and care should be taken to avoid attributing results from one strategy to all possible strategies when that conclusion is not merited.

Geoengineering proposals are controversial, and there are significant uncertainties regarding their potential, risks, and limitations. To decide whether and how to develop these proposals, a clear sense of their potential consequences is necessary. Therefore, researchers have a responsibility to carefully review the language they use to describe their findings for accuracy. Given the severe expected impacts of climate change—especially in already-vulnerable regions—and geoengineering's potential capacity to reduce many climate risks[12,13], scientists should carefully communicate their conclusions in ways that are most informative to assessment, evaluation, and decision-making, and avoid misinterpretations that unjustifiably magnify risks beyond what the results actually show[14]. Because geoengineering is researched and evaluated as part of a potential response to climate change, analyses are most informative when its effects are isolated by comparing geoengineering scenarios against those with the same underlying greenhouse gas emissions. Comparing a world with geoengineering and no mitigation to one with mitigation is analogous to conflating a treatment's side effects with the symptoms of the underlying disease. In this case, an analysis that compares the geoengineering scenarios to the appropriate counterfactual (i.e., RCP8.5 without geoengineering) and a title such as "Radiative forcing geoengineering *reduces* the risk of wildfires and permafrost thawing over the Arctic regions, albeit less than mitigation" would have been more accurate and informative.

Data availability

Data from the Norwegian Earth System Model, plotted in Fig. 1, is described by ref. 1. The RCP4.5 and RCP8.5 model outputs are available at https://doi.org/10.11582/2019.00007[15], while the geoengineering model output is available at https://doi.org/10.11582/2023.00004[16]. Data from the Community Earth System Model (CESM2) with the Whole Atmosphere Community Climate Model as the atmospheric component, plotted in Fig. 2a, is described by ref. 2. Data from CESM2 with the Community Atmosphere Model as the atmospheric component, plotted in Fig. 2b, is described by refs. 10,11. All CESM2 data are available at https://doi.org/10.5281/zenodo.13905902[17].

Code availability

Code used to generate Figs. 1 and 2 are available at https://doi.org/10.5281/zenodo.13905902[17].

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Author contributions

All authors contributed to the conceptualization of the manuscript. W.R.L. and M.S.D. analyzed data and generated figures. All authors contributed to the initial draft of the manuscript. W.R.L. revised and edited the various versions of the manuscript, with assistance from all other authors.

Competing interests

The authors declare no competing interests.

Additional information

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