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Commentary: Safeguarding the polar regions from dangerous geoengineering: a critical assessment of proposed concepts and future prospects

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A Commentary on
Safeguarding the polar regions from dangerous geoengineering: a critical assessment of proposed concepts and future prospects
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1 Introduction

Research into polar climate intervention is understandably controversial. The deliberate manipulation of Earth's climate has deep physical, political, and ethical challenges. However, the dangers we face from a warming planet require us to reckon with these challenges. A recent study from Siegert et al. (2025) argued that five polar geoengineering ideas are "environmentally dangerous", "not feasible", and that "research into these techniques would not be an effective use of limited time and resources".

Several responses to Siegert et al. (2025) have already arisen (Haaslahti et al., 2025; Moore et al., 2025). We agree with many of the arguments put forward in these pieces, including that it is misleading to portray climate intervention techniques as an alternative to emission reductions when the research field is united in exploring them only as a potential supplement to those reductions, and that the risks of interventions must be compared against the risks of climate change (Doherty et al., 2024; Wieners et al., 2023).

Here, we address specific claims made by Siegert et al. (2025) about stratospheric aerosol injection (SAI), our field of study. We argue that their study presents a one-sided view of the state of knowledge on polar climate interventions, which mixes legitimate and important criticisms of implausible ideas, with premature dismissals of other ideas, particularly SAI. From the outset, we highlight that we agree on two critical points: (1) rapid and sustained decarbonisation is an absolute priority and (2) all proposed climate interventions need rigorous scientific scrutiny.

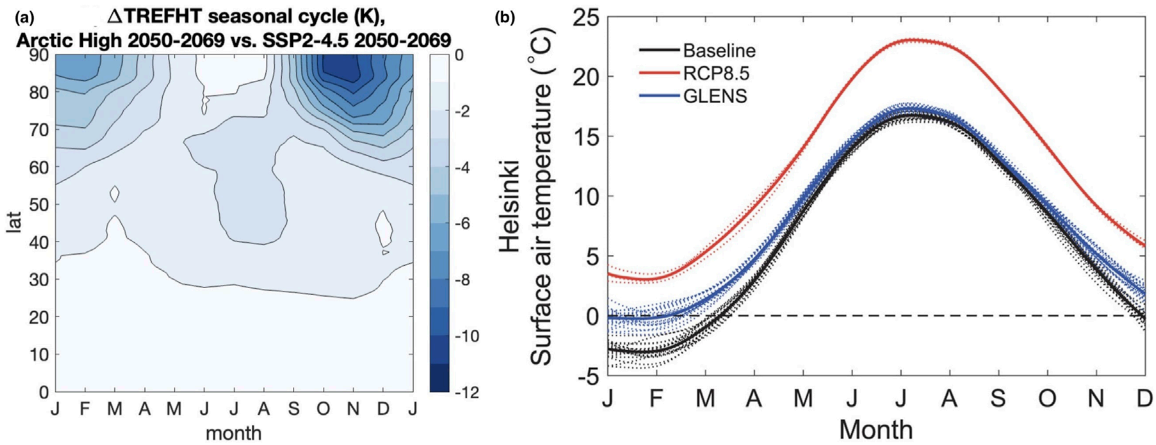

FIGURE 1
(a) Change in surface temperature in CESM2 between a middle-of-the-road greenhouse gas emission scenario (SSP2-4.5) and a stratospheric aerosol injection scenario where aerosols are injected at 60° North in the months of March, April, and May. The figure shows amplified cooling in the Arctic in winter, and is reproduced from a paper cited by Siegert et al. (2025) (Lee et al., 2023). **(b)** Seasonal cycle of temperature in Helsinki for the baseline climate (RCP8.5 in 2010–30), a high emissions scenario (RCP8.5 in 2075–95), and a scenario with injection of SO_2 at 15° and 30° North and South (GLENS). The figure shows that even injection at low latitudes can significantly cool polar regions including in winter (difference between red and blue lines), and is reproduced from a paper cited by Siegert et al. (2025) (Jiang et al., 2019).

2 Polar cooling under SAI

There are two notable inaccuracies regarding the impact of SAI on the polar regions in the assessment of Siegert et al. (2025): first, that SAI is ineffective in the polar winter (or more inscrutably, that SAI is only effective during March-April-May, as shown in their Figure 1), and second, that polar injection locations would be needed to produce an impact in the polar regions.

The first claim, that SAI would not cool polar winters, while intuitive, is inconsistent with the earth system modelling of SAI (Henry et al., 2024). Figure 1a (reproduced from Lee et al. (2023) which is cited by Siegert et al. (2025)) shows the cooling from SAI as a function of latitude and month, and clearly shows cooling from SAI in the Arctic winter in CESM2.

It is indeed true that, without sunlight to reflect, the radiative forcing from SAI is non-existent, or possibly even positive (Duffey et al., 2025), in polar winter. However the overall cooling effect of SAI is actually amplified, both relative to the rest of the planet and relative to polar summer. This amplification is likely driven by the reduced ocean heat uptake in summer leading to less ocean heat release in winter, combined with a cooling signal confined near the surface due to high atmospheric stability, though no research clearly shows this yet. This feature of Arctic cooling has been simulated for SAI with Arctic injection (Lee et al., 2023), global SAI (Jiang et al., 2019, also cited by Siegert et al., 2025), SAI with equatorial injection (Berdahl et al., 2014; Visioni et al., 2021), and in Arctic marine cloud brightening simulations (Henry et al., 2025). The "residual warming" referenced by Siegert et al. (2025), and often discussed in the SAI literature (e.g., Jiang et al., 2019; Duffey et al., 2023) refers to warming relative to a world with the same global-mean temperature as the SAI scenario, at lower greenhouse gas forcing (e.g., the present day, or a time slice of a simulation at the "target" warming level). It does not refer to the absolute effect of SAI, which is to cool all regions of the planet in all seasons.

With regards to the second claim, that polar cooling relies on "a highly specific deployment" (i.e., a high-latitude injection scenario): all earth system modelling shows polar cooling under SAI even with equatorial injection (e.g., Visioni et al., 2021, their figure 6). Indeed, this result, that the temperature response to SAI can be close to opposite that of greenhouse gases, even when the forcing patterns are quite different, was a key early finding in the climate modelling of SAI (Govindasamy and Caldeira, 2000). It is supported by simple climate dynamics arguments (as well as 1D energy balance models) which explain how low latitude forcings are transported to and amplified in the polar regions, particularly the Arctic. It is also shown in Figure 1b, which is reproduced from Jiang et al. (2019), a paper cited by Siegert et al. (2025). The lines show the seasonal cycle of temperature in Helsinki for the baseline climate (RCP8.5 in 2010–30), a high emissions scenario (RCP8.5 in 2075–95), and a scenario with injection of SO_2 at 15° and 30° North and South (GLENS). The temperature in Helsinki is around 5 °C colder under the GLENS scenario in which aerosols are injected at low latitudes when compared to RCP8.5. With respect to winter cooling, our first argument, Figure 1b also highlights that while the seasonal cycle of temperature in polar regions is not perfectly restored, it would be inaccurate to claim that SAI is ineffective in the winter at high latitudes.

3 A balanced account of the impacts of SAI on polar regions

In our opinion, these specific inaccuracies are representative of a limited account of the current understanding of SAI. For example, the important limitation that SAI cannot solve ocean acidification driven by atmospheric CO_2 concentration is noted, but the fact that SAI could reduce other stresses on systems subject to this acidification is not. SAI has been modelled to help maintain coral reefs (Couce et al., 2013) and reduce bleaching events (Kwiatkowski et al., 2015) despite the pressure on that ecosystem from unabated acidification (Irvine et al., 2016). Similarly, the fact that SAI with sulphate aerosols would reduce stratospheric ozone is noted, but quantitative assessments of the impact, which show that this is a serious but likely manageable side-effect (Haywood et al., 2022), are not included. Human health concerns arising from inhalation of sulphate aerosols are noted, but no reference is made to the quantitative assessments which have been made of the estimated human health impacts (e.g., Harding et al., 2024).

Most notably, Siegert et al. (2025) include a section on "Negative Consequences" but no countervailing assessment of the potential benefits. Such a section might have included the restoration, albeit imperfect, of polar temperature and its seasonal cycle (as shown above), sea-ice cover, permafrost extent, and the surface mass balance of the Greenland and Antarctic Ice Sheets (as discussed in Lee et al. (2023), cited by Siegert et al. (2025)). It might also have noted reductions in tipping risks associated with the Atlantic Meridional Overturning Circulation (Bednarz et al., 2025), Boreal permafrost (Chen et al., 2020) and the West Antarctic Ice Sheet (Goddard et al., 2023). We do not claim that SAI necessarily would reduce change in all of these systems, merely that such a reduction is plausible and has been simulated in at least one modelling study.

4 Discussion

After rebalancing their account of the polar impacts of stratospheric aerosol injection to include potential benefits as well as risks, and to address the inaccuracies in Siegert et al. (2025), we challenge their assertion that further research into geoengineering "would not be an effective use of limited time and resources". We emphasise that there are significant risks associated with climate intervention, some of which were discussed in Siegert et al. (2025). However, given the feasibility and potential effectiveness of SAI, and the profound risks of unchecked climate change, we believe it is a scientific and societal imperative to conduct further climate intervention research. Doing so is not advocating for deployment, but rather for a fuller understanding of the benefits, limitations, and risks to inform future decision making. The urgent necessity to cut greenhouse gas emissions is undisputed, but the argument that we already know enough to cease all further research into climate interventions is not tenable. The key question is not to choose between emission cuts or climate intervention, but whether interventions could supplement greenhouse gas emission cuts to reduce the harmful consequences from climate change.

Author contributions

MH: Conceptualization, Writing – original draft, Writing – review and editing. AD: Writing – review and editing, Conceptualization, Writing – original draft.

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