Risks of Stratospheric Aerosol Injection

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ABSTRACT

Stratospheric aerosol injection (SAI) of typically sulfuric particles to increase albedo is a solar radiation management (SRM) proposal that is theoretically effective at reducing global average surface temperatures, but comes with environmental, social, and governance risk. Understanding the uncertainty associated with these risks, which have been demonstrated through computational models and understanding volcanic eruptions, will be crucial to assessing whether this technology should be considered as a climate solution, through what avenue, and to what extent. Recent literature was synthesized on the effectiveness, climate and environmental impacts, feasibility, and environmental justice concerns of SAI.

Introduction

Stratospheric aerosol injection (SAI) is a climate geoengineering strategy that has been proposed as a worst-case-scenario solution to lowering global average surface temperature without curbing greenhouse gas (GHG) emissions. SAI works by injecting aerosol particles, usually sulfur, into the stratosphere to increase the albedo effect and block solar irradiance. Alternative strategies have also been proposed, including marine cloud brightening (MCB) using sea salt to increase reflectivity, cirrus cloud thinning (CCT) to promote outgoing longwave radiation, space mirrors, and ground-based albedo modification (GBAM), though the Intergovernmental Panel on Climate Change (IPCC, 2018) states that "SAI is the most-researched [Solar Radiation Management] SRM method, with *high agreement* that it could limit warming to below 1.5°C." I will begin by describing how effective SAI is as a climate geoengineering strategy. I aim to provide a scientifically-guided analysis on the societal impact of SAI through a climate and environmental justice (EJ) lens. I will then discuss potential unintended impacts of SAI on climate and environmental systems. I will discuss the technological, economic, social, governance considerations for feasibility of adoption. Finally, I will discuss the social and EJ impacts.

Prior work has covered technical analysis and simulations on the impacts of SAI, and separate analysis on the governance and justice issues, which are referenced in the discussion. I aim to synthesize a deep, specific scientific and social analysis of SAI.

Approach

I compiled literature on the effectiveness, climate and environmental impacts, feasibility, and environmental justice concerns of SAI. This information was synthesized to draw together a narrative on these impacts, and how they tie together, to draw together a harmonious understanding.

Results and Discussion

1. Effectiveness of SAI

SAI can reduce temperature rise, rate of sea level rise, and frequency of extreme storms in the North Atlantic and heatwaves in Europe, but there is great risk of it changing precipitation, ozone concentration, and potentially reducing biodiversity (IPCC, 2018). Sulfates, which mimic particles released from volcanic eruptions, are a leading candidate for SAI. These would be emitted in the form of precursor gases such as sulfur dioxide (SO_2) and hydrogen sulfide (H_2S, or through the direct release of sulfuric acid (H_2SO_4). H_2SO_4 would be ideal because of smaller particle size, allowing for better lifetime and efficiency of release. Salts such as calcite have also been proposed due to their ability to reduce or reverse ozone depletion that would be caused by sulfates, as well as titanium dioxide, aluminum oxide, silicon carbide, and synthetic diamond particles (Keith et al., 2016; Smith 2022).

SO_2 has a lifetime of about 30 days in the stratosphere (based on measurements from the eruption of Mt. Pinatubo) compared to less than a week in the troposphere, so it is vital for aerosols to be delivered to the stratosphere (Zhu et al., 2020). Delivery methods are primarily proposed through aircrafts, but also high-altitude balloons and artillery, which would need to enter the stratosphere by entering the upper levels of the troposphere (approximately 8 km at the poles to 18 km at the equator) and provide sufficient payload. SAI It may be possible to lower the required altitude by including absorbing aerosols (i.e. black carbon) that can locally heat and loft the sulfate, but this can reduce the cooling efficiency of SAI, delay recovery of the ozone hole, disrupt the Quasi-Biennial Oscillation, and enhance the positive phase of the wintertime North Atlantic Oscillation (Haywood et al., 2022).

The IPCC (2018) recommends SAI for use as a supplement to mitigation of GHG emissions, such as dealing with temperature overshoot scenarios. With a radiative forcing efficiency of 1–4 Tg S (terragrams of sulfur) W^{-1} m^2 $yr^{-}1$, 2–8 Tg S yr^{-1} are needed for 1°C overshoot (IPCC, 2018). Figure 1 represents at net-zero by 2050 scenario, which can result in around 45 years of a less than 0.2°C overshoot above 1.5°C that can be mitigated by the gradual ramping up of sulfur to about 1 Tg S yr^{-1} and then ramping down during the overshoot. Smith et al. (2022) considers deploying SAI only in subpolar regions to mitigate ice and permafrost melt, which requires lower altitudes of deployment than the tropics, but still poses similar governance and technological feasibility challenges to general SAI. Tjiputra et al. (2015) models an optimistic and ambitious SAI scenario of 50 Tg S providing 8.5 W^{-1} m^2 that linearly increases from 2020 to 2100, counteracting Representative Concentration Pathway 8.5, or RCP8.5 (the IPCC's highest GHG emission scenario resulting in 3.7°C of warming by 2100), to maintain less than 1.5°C of warming. However, warming of 5 to 10 K still projected at high latitudes (Figure 2). In this model, termination of SAI in 2100 could cause rapid warming of 0.35 K yr^{-1}, remaining at about

0.5 K lower than RCP8.5 levels in the following 10 years. Keys et al. (2022) considers an SAI model that limits warming to 1.5°C based on the IPPC's middle-of-the-road Shared Socioeconomic Pathway 2 (SSP2)-4.5 scenario. They find that while global temperatures were stabilized, 55% of the global population would experience rising temperatures over the decade following SAI, which could cause SAI to be perceived as a failure, despite potential long-term benefits. While it is theoretically possible for SAI to limit global average warming by 1.5°C, it is riddled with differential climate and environmental impacts regionally and issues surrounding feasibility and ethics, which will be discussed.

2. Climate and Environmental Impacts

2.1 Climate

SAI can lead to increases in natural carbon uptake by land biosphere and also somewhat by the oceans (IPCC 2018). Cooler temperatures lead to increased solubility of CO_2 in seawater and delays the melting of sea ice. Tjiputra et al. (2015) finds that an aggressive SAI scenario from 2020 to 2100 will lead to ~15 ppm lower atmospheric CO_2 by 2100 due to 10% greater ocean absorption of carbon. They find that carbon uptake on land is driven by soil carbon storage due to reduced heterotrophic respiration because of lower temperatures. Unlike vegetation carbon storage, soil carbon storage lasts after termination of SAI. Further, Tilmes et al. (2022) finds reductions in springtime Antarctic total column ozone (TCO) of around 10 Dobson Units (DU) initially to 20 DU by the end of the century, but an increase of 20 DU in the Northern Hemisphere mid-latitudes. Ozone depletion may have Vienna Convention for the Protection of the Ozone Layer consequences, but the Montreal Protocol does not currently deem sulfates an ozone depleting substance.

2.2 Water Systems

Understanding how SAI effects flood and drought patterns will be crucial to understanding regional risk that can directly affect people. SAI influences thermodynamic and dynamic mechanisms controlling moisture budget. Whether SAI is deployed in Arctic or tropical regions seems to impact precipitation effects. Sun et al. (2020) finds that tropical SAI suppresses precipitation globally by 1.9%/(10 Tg S yr^{-1}), while Arctic SAI reduces Northern Hemisphere monsoon (NHM) precipitation by 2.3%/(10 Tg S yr^{-1}) and increases Southern Hemisphere monsoon (SHM) precipitation by 0.7%/10 Tg S yr^{-1}). Cooling in the northern hemisphere (NH) creates a meridional temperature gradient that induces cross-equatorial northerlies. This cooling decreases NH tropical moisture content and NHM precipitation, while having the opposite effect on SHM precipitation. Tropical SAI suppresses global monsoons due to cooling that decreases moisture content in the tropics. Figure 3 describes regional impacts on monsoons. Krishnamohan & Govindasamy (2022) simulate 12 Tg S yr^{-1} injected at 30° and 15° north and south and find that the largest precipitation changes occur in tropical regions, and that summer monsoons are increased (about +10%) by injection in the opposite hemisphere and decreased (about -10%) by injection in the same hemisphere (at 30° latitude).

North African monsoons will be significantly weakened by Arctic SAI (though they do not face significant impact from tropical SAI) due to northeasterly anomalies caused by thermal contract between North African and tropical North Atlantic Ocean. South African monsoons are decreased, to a lesser extent, by tropical SAI, but face little impact from Arctic SAI (Sun et al., 2020). There will less uncertainty regarding drought frequency, although more research should be conducted to understand SAI impacts on river basins across Africa. Abiodun et al. (2021) finds that SAI will reduce Standardized Precipitation Evapotranspiration Index (SPEI) drought frequency due to reduced temperatures lowering evaporative demand and increase Standardized Precipitation Index (SPI) drought frequency due to reduced precipitation.

South and East Asian monsoons may be generally reduced by Arctic and tropical SAI. Sun et al. (2020) finds that the East Asian Summer Monsoon (EASM) will be significantly weakened due to induced northwesterly anomalies due to meridional land-sea thermal contrast (Sun et al., 2020). However, Liu et al. (2021) finds that whether the EASM increases or decreases varies among models and geographical regions (e.g. some evidence points to an increase in the Yangtze-Huaihe River valley in eastern China). In the study by Krishnamohan & Govindasamy (2022), Indian summer monsoon precipitation decreased by 21% for 15° N and 29% for 30° N, which can pose adverse effects on population in India who rely on this crucial monsoon, which also acts as a heat source that can influence El Niño.

SAI will either not address or continue to worsen ocean acidification (IPCC 2018). Tjiputra et al. (2015) projects that SAI will accelerate deep ocean acidification in the North Atlantic (reaching a critical pH threshold 34 years earlier than the RCP8.5 reference case) due to changes in ocean circulation that strengthen deep water formation, allowing anthropogenic CO_2

to further penetrate the deep ocean. Oceans are a crucial part of our ecosystem, and damages to our oceans will greatly impact the wellbeing of humans.

3. Feasibility

3.1 Governance

Who has the power to initiate SAI? Nations that are major emitters like the US may employ the Common but Differentiated Responsibilities and Respective Capabilities principle (under the UNFCCC) to assert the deployment of SAI (Tang & Kemp, 2021). Indian policymakers raise concern that unilateral action on geoengineering could be taken by developed nations without other nations being able to stop it (Smith & Henly, 2021). For SAI to work, it must be deployed unilaterally with large-scale operations. However, Keys et al., (2022) finds that perceived failure of SAI in the short terms in certain regions, which may experience local warming in the first 10 years, may undermine this unilateral deployment (Figure 4). Sulfur may be regulated by the International Convention on Long-Range Transboundary Air Pollution (CLRTAP Convention) and nationally, the EPA Clean Air Act, may apply (IPCC, 2018). Military involvement—which can escalate geopolitical conflict—may inevitably play a role in R&D, deployment of aircrafts, and the defense of volatile SAI sites from catastrophic termination. While the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD) may prevent military involvements in SAI, this may not apply due to the non-“hostile” nature of this technology (Jayaram, 2020).

Geoengineering at a large scale poses new catastrophic risks that would require highly dependable governance and international diplomacy to mitigate. Termination shock may cause rapid temperature rise, which can lead to biodiversity loss (IPCC, 2018). Tang & Kemp (2021) discuss risks that may lead to termination shock. If a nuclear water, pandemic, cyberattack, or any large interference were to disrupt SAI, we may be at risk for a “double-catastrophe.” In the case of nuclear winter, SAI would lead to short term overcooling, following by medium- to long-term overheating due to termination shock. Further, volcanic eruptions with SAI pose moderate catastrophic risk. Given a large volcanic eruption, SAI may need to be rapidly scaled down, and in further geographical regions, scaled up within a few weeks, which can be a governance challenge. Extreme solar and space weather, though rare, may damage control systems onboard deployment aircrafts. It is unknown whether space weather that generates strong UV radiation may interact catastrophically with SAI.

3.2 Technology and Cost

Aerosols would have to be deployed are nearly double normal airliner cruising altitudes (around 20 km) to last for 12 to 18 months in the atmosphere (Smith & Henly, 2021). Smith & Wagner (2018) find that around 4000 flights will be needed per year to introduce just 0.2 Tg S yr^{-1}. This would cost about \$1500 ton^{-1} of sulfur, resulting in an average cost of about \$2.25 billion yr^{-1} after 15 years of deployment. While no aircraft design exists to handle such an altitude and payload, Smith & Wagner find that it is technologically feasible and not prohibitively expensive to develop.

4. Environmental Justice

Depending on SAI as a climate change mitigation strategy falls in line with a harmful Western philosophy: that we can continue producing and consuming as usual without changing our behavior. In fact, it is North America and Western Europe that primarily promote geoengineering through scientific research and climate strategy frameworks (Jayaram, 2020). In 2019, the U.S., along with Saudi Arabia and Brazil, opposed a U.N. resolution to assess the risks and adverse effect of carbon capture and solar radiation management, a motion backed by Switzerland, Burkina Faso, Micronesia, Georgia, Liechtenstein, Mali, Mexico, Montenegro, New Zealand, Niger, Senegal, and Bolivia (Chemnick, 2019). Geoengineering is also strongly opposed by indigenous people; the People’s Agreement in the World People's Conference on Climate Change and the Rights of Mother Earth held in Bolivia—which represented indigenous people and their supporters from over 100 countries—rejects geoengineering as a “false solution” (“People’s Agreement,” 2010).

While countries in the Global North contribute the most to climate change, and those in the Global South bear the brunt of the burden, SAI would further exacerbate issues of climate justice for vulnerable populations. Precipitation changes due to SAI disproportionately impact the tropics (as discussed in 2.2), where many people rely on agriculture and subsistence farming. Uncertainty in monsoons vital to farming can jeopardize crop yield, posing socio-political risk. Maize, wheat, and rice in China may benefit from the low-temperature, high carbon environment created by SAI, but solar dimming may reduce groundnut yields in India (Tang & Kemp, 2021).

Changes in monsoon patterns, ecology, air quality changes, and UV exposure could pose health impacts and affect disease transmission, especially for vulnerable populations, though little research has been conducted in this area (Tang & Kemp, 2021).

Meanwhile, the extraction and production of fossil fuels would continue to threaten our planet and EJ communities. Transitioning to solar may prove to be more challenging because SAI diffuses direct sunlight by 4 W for every watt reflected into space, reducing the efficiency of concentrating and passive solar (Murphy, 2009). There is speculation that SAI will disincentivizes GHG mitigation, though proving this comes with high uncertainty. Perverse incentives of SAI, like that of carbon dioxide removal, would depend on the extent to which it will be used as a strategy (e.g. to temporarily address overshoot [IPPC, 2018], or solely target subpolar regions to prevent the melting of permafrost and ice [Smith et al., 2022]). Nevertheless, these scenarios come with the many challenges posed by SAI.

Conclusions

SAI has been proposed as a SRM geoengineering method that can address climate change without having to address GHG emissions. This can be accomplished through the deployment of aerosol sulfur particles, likely from aircrafts, at high altitudes to enhance albedo and lower global average surface temperatures, which simulations demonstrate is possible. While aircrafts that can reach the necessary ~20 km altitudes have not been developed, this is technologically and financially feasible, but would require thousands of additional flights every year as SAI is scaled up. SAI may reduce the rate of sea level rise and some extreme storms and heatwaves regionally and increase carbon uptake by the land and oceans. However, it is not a substitute for the mitigation of GHG emissions.

SAI can drastically alter precipitation patterns regionally depending on where it is deployed. Monsoons in South Asia, East Asia, and North Africa have been shown to exhibit disruption, which can harm populations dependent on monsoons for agriculture. Monsoons across Africa and South Asia may be weakened, while there is high uncertainty in impacts on East Asian monsoons. SAI may also deplete atmospheric ozone, worsen ocean acidification, and because of climate and ecological changes, threaten biodiversity. More simulations and studies of volcanic eruptions should be conducted to better understand changes in precipitation.

Nations that compose the Global South and populations reliant on their environment are most at-risk in the face of SAI. These nations also have the least power to initiate SAI. Global superpowers, which are greater proponents of SAI, may require military involvement for its development and deployment, which can create geopolitical tension. If international diplomacy fails, or other catastrophic events that lead to termination shock, rapid warming to nearly non-SAI levels may occur within a decade. SAI would further exacerbate the harms of events such as nuclear war, volcanic eruptions, and space weather, though the extent of interaction of SAI with these events should be simulated using climate models.

There is an ethical concern with Western nations initiating SAI when they are also the greatest emitters. Many nations in the Global South and indigenous groups oppose SAI. Flooding and drought changes can impact agriculture, and health impacts are largely understudied. SAI may also be a perverse incentive (though not proven) to the continuation of fossil fuel extraction, while it decreases the efficiency of solar energy. SAI may also be used locally to overcome overshoot or melting ice.

Figures and Tables

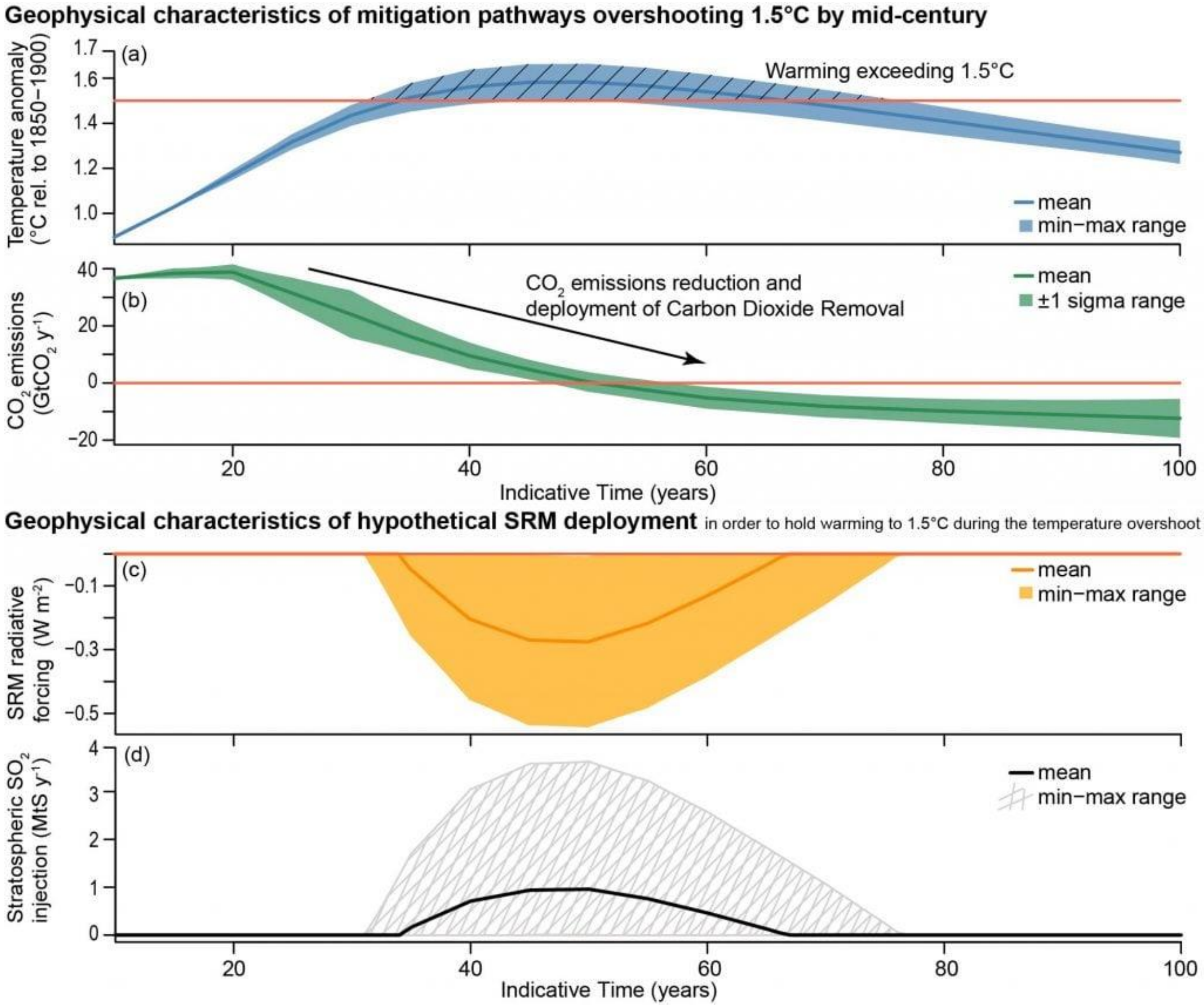

Figure 1: SAI use in response to temperature overshoot to achieve 1.5C of warming; (a) estimated temperature overshoot of ~45 years (represented by blue hatching) in response to (b) a CO_2 emissions reductions pathway reaching net-zero by 2050. The overshoot can be mitigated by (c) adaptive solar radiation modification (SRM) using (d) stratospheric SO_2 injection (IPCC, 2018).

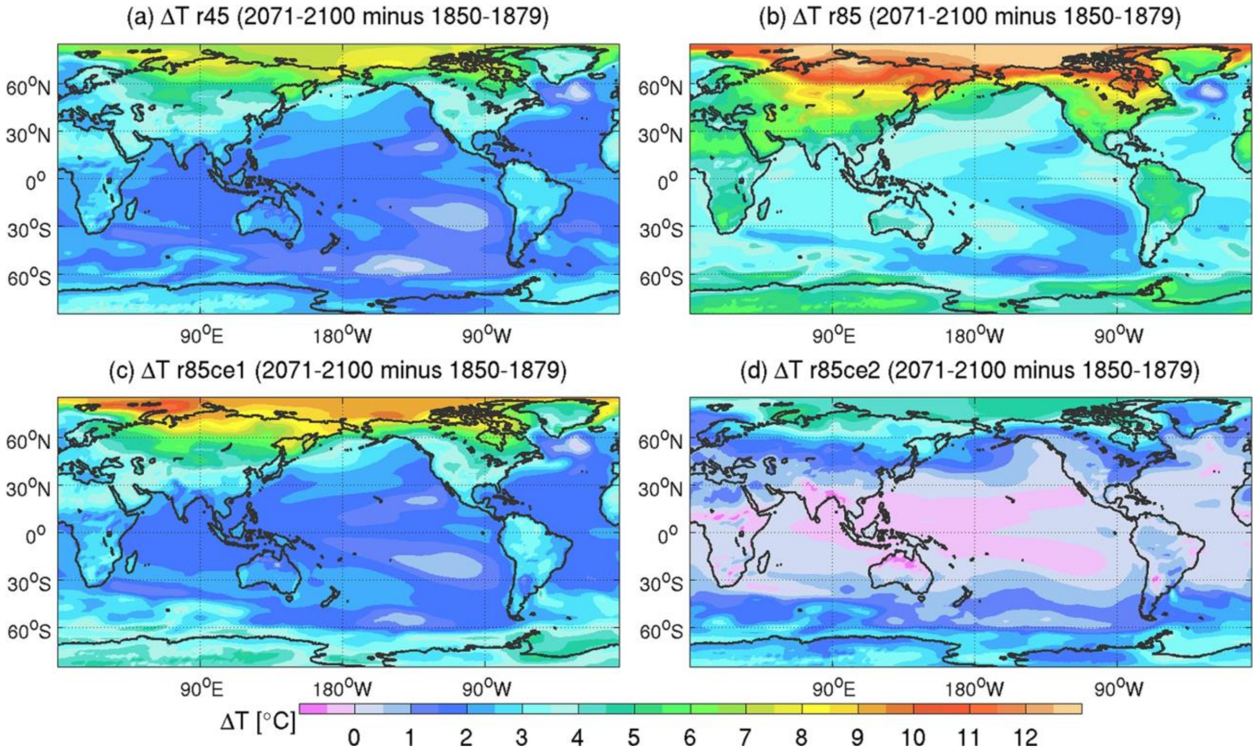

Figure 2: Changes in surface temperatures from 2071-2100 compared to pre-industrial level (1850-1879) under simulations for (a) RCP4.5, (b) RCP8.5, (c) SAI with weaker forcing (2 times that of Mount Pinatubo) to counteract RCP8.5, and (d) SAI with stronger forcing (5 times that of Mount Pinatubo) to counteract RCP8.5 (Tjiputra, 2015).

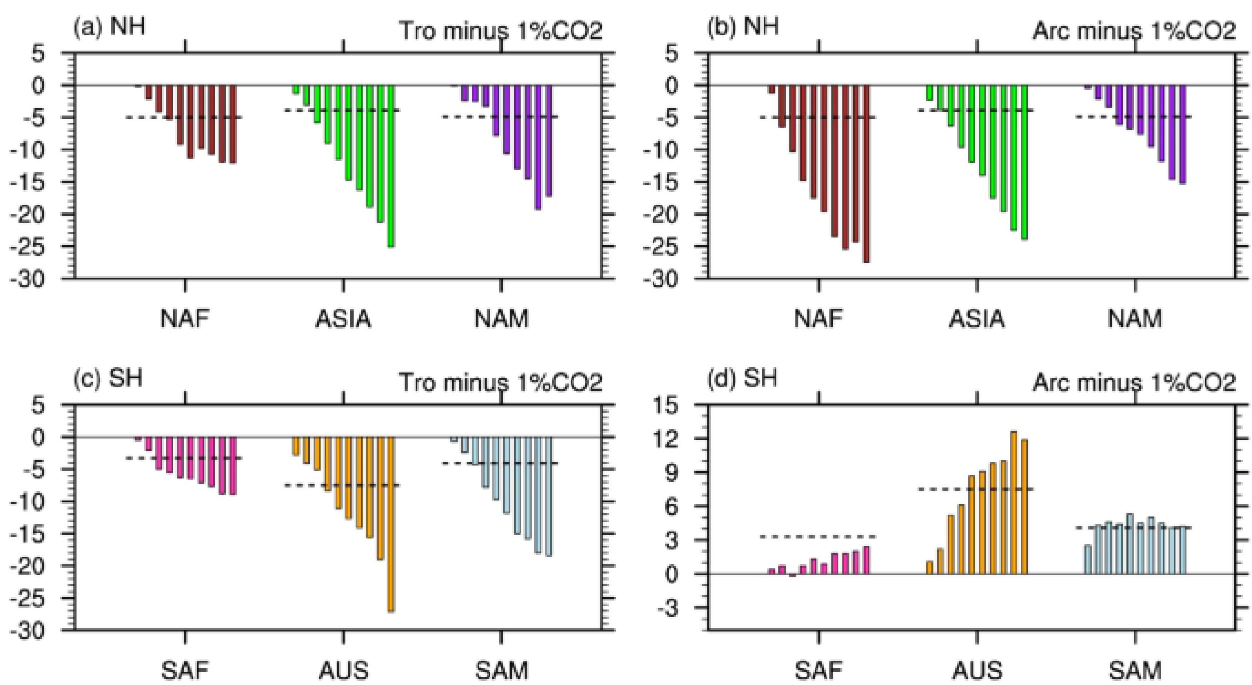

Figure 3: CHANGE Change rates (%) in last 40 years mean local summer precipitation over submonsoon region in the tropical (left) and Arctic (right) SAI experiments, relative to the 1% CO2 experiment. a, b North African monsoon (NAF), Asian monsoon (ASIA), and North American monsoon (NAM) regions. c, d South African monsoon (SAF), Australian monsoon (AUS), and South American monsoon (SAM). In each monsoon region, bars from left to right represents the 10, 20, 30, …, 100 Tg yr−1 injection

experiments, respectively. The horizontal dashed lines denote the one standard deviation of local summer precipitation in the Ctrl (Sun et. al., 2020)

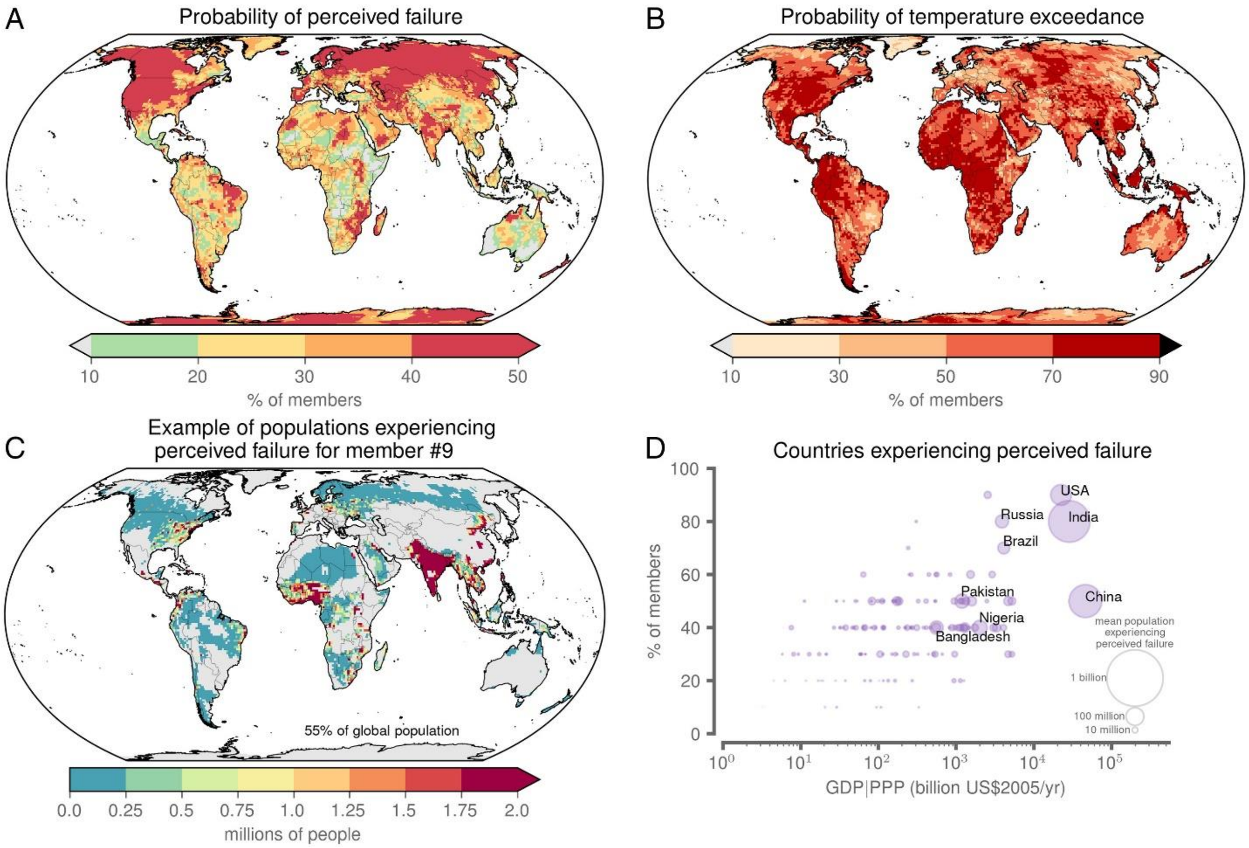

Figure 4: Perceived failure over 10 years following SAI with (a) the probability of perceived failure, (b) the probability of exceeding pre-deployment temperatures, (c) populations experiencing perceived failure, and (d) percentage of ensemble members (forecast simulations) with 10% of more of its population experiencing perceived failure following SAI deployment versus projected GDP. Perceived failure is correlated with higher GDP (Keys et al., 2022).

References