Quantifying Feedbacks of Climate Intervention Under Climate Change

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Introduction

- The increasing severity of the effects of climate change, especially strengthening extreme events and wildfire, is theatening built infrastructure, utilities, and national and economic security.
- Loss of life and property is motivating serious consideration of approaches for **climate intervention** or **geoengineering**.
- In addition to efforts to scale up **carbon dioxide removal (CDR)** through **direct air capture (DAC)** and other means, interest in growing in methods to reduce or stabilize Earth's surface temperature.
- **Solar radiation management (SRM)** is one approach to partially reduce warming by reflecting a portion of incoming solar radiation to maintain resilience of the Earth system.
- **Stratospheric aerosol intervention (SAI)**, through direct injection of sulfur into the lower stratosphere, is considered the most feasible scheme.
- Many questions remain unanswered regarding the feedback effects of SAI on the Earth system.

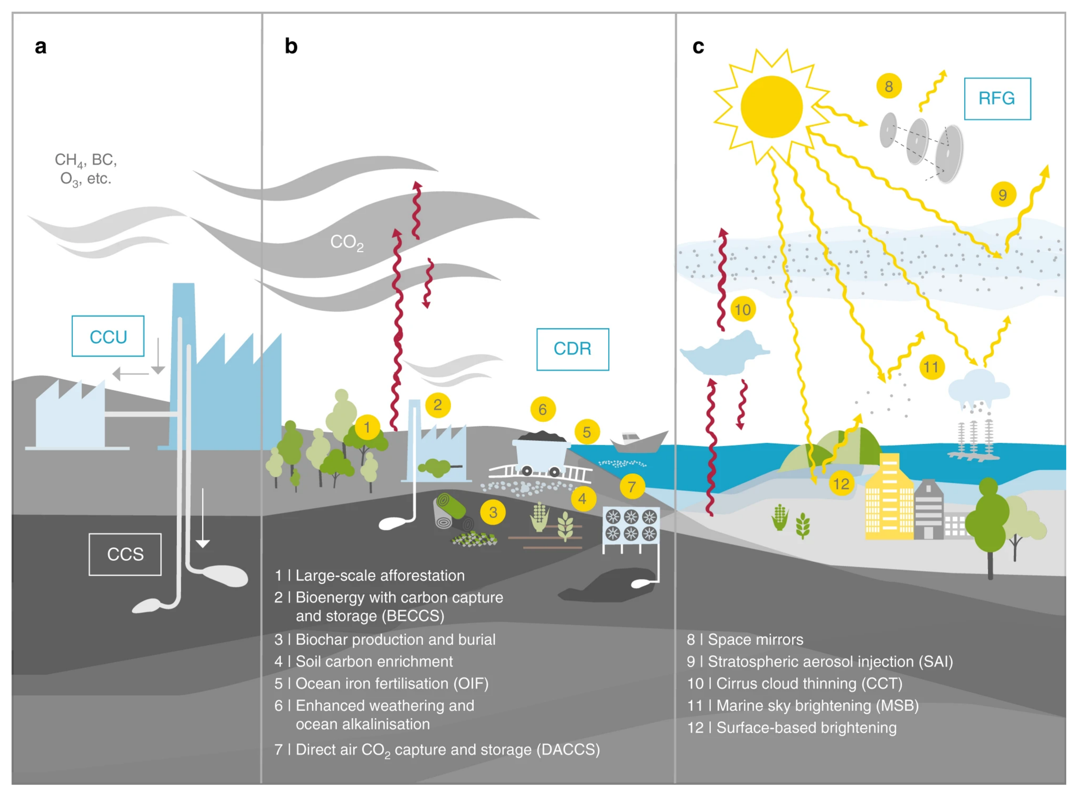


Figure 1: *Proposed climate geoengineering techniques placed in the context of mitigation efforts. Adopted from Lawrence et al. (2018).*

Potential Ecological Impacts of Climate Intervention

- While climate science research has focused on predicted climate effects of SRM, **few studies have investigated impacts that SRM would have on ecological systems**.
- Impacts and risks posed by SRM would vary by implementation scenario, anthropogenic climate effects, geographic region, and by ecosystem, community, population, and organism.

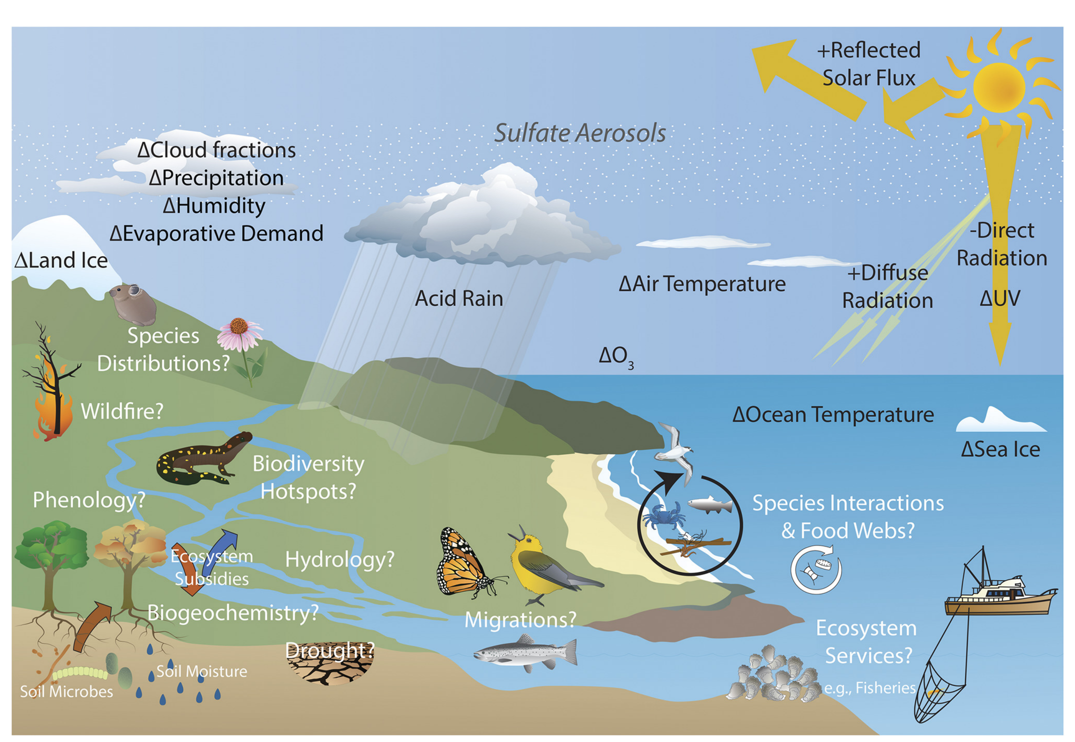


Figure 2: *Although some effects of SRM with SAI on the climate are known from certain SAI scenarios (indicated with + for likely increases, − for decreases, Δ to indicate change), the effects of SAI on ecological systems are largely unknown. Adopted from Zarnetske et al. (2021).*

- Models used for projecting responses to SAI are often the same Earth system models (ESMs) used to study anthropogenic climate change effects without SAI.
- These models must additionally be able to represent complex stratospheric aerosol processes and ecological responses and feedbacks.
- **A transdisciplinary approach, increasing collaboration between ecologists and climate scientists, is essential** for understanding the benefits and risks of SAI on climate and to ecological systems.

Terrestrial Biogeochemical Feedbacks In a Strategically Geoengineered Climate

- To characterize terrestrial ecosystem (vegetation and soil) responses and feedbacks resulting from SAI, we analyzed an ensemble of global coupled ESM climate change simulations.
- The simulations employed the Community Earth System Model (CESM) and were performed for the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) project at the National Center for Atmospheric Research (NCAR).
- The ensemble simulations followed the Fifth Phase Coupled Model Intercomparison Project (CMIP5) Historical and RCP8.5 simulations from 1850–2100.
- The baseline experiment period, called ***BASE***, ran for 2010–2019, and the control, called ***CTRL***, ran for 2020–2097, following the standard CMIP6 protocol.
- A third set of ensemble members, called ***GEOENG***, ran for 2020-2097 with simulated SAI mitigation designed to stabilize global temperatures at those for the year 2020.

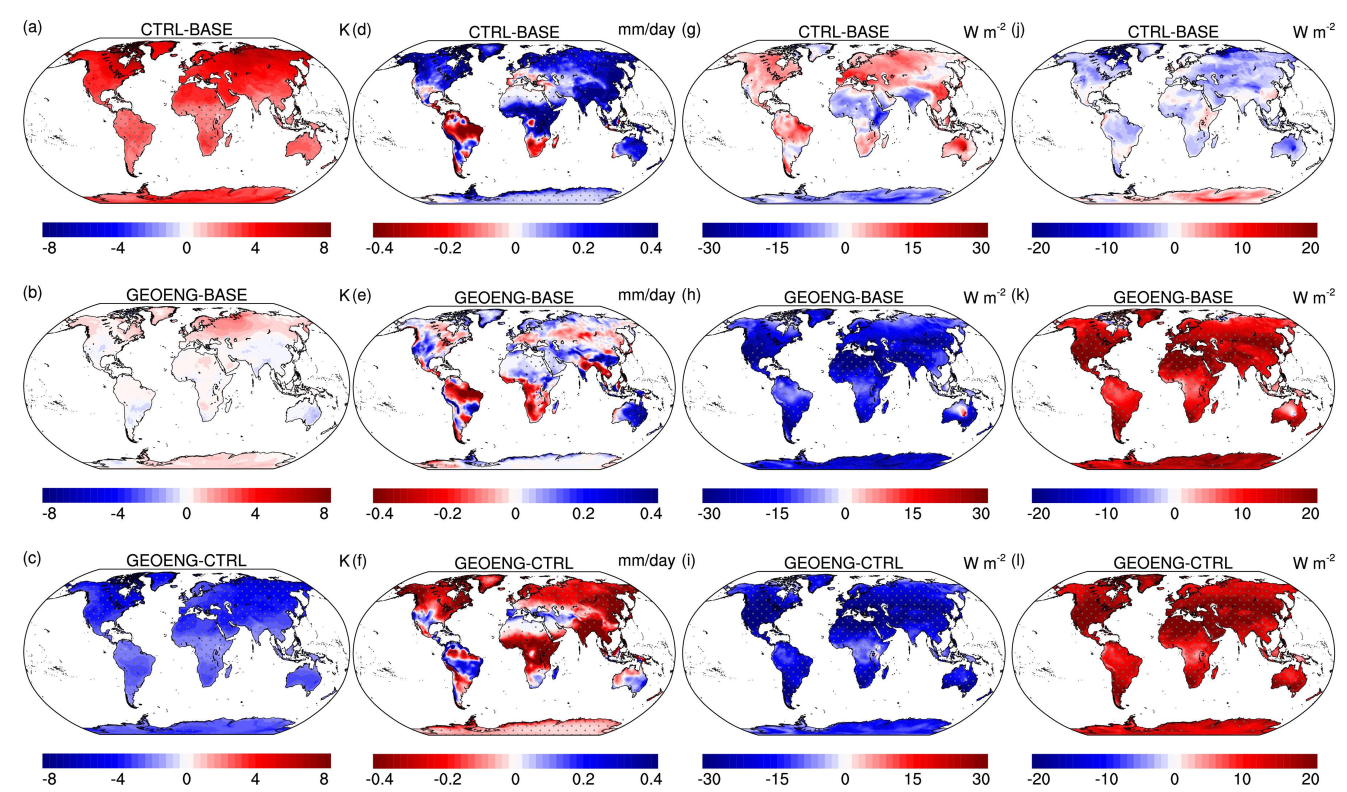


Figure 3: *Changes of spatial distributions between CTRL and BASE (top row), between GEOENG and BASE (middle row), and between GEOENG and CTRL (bottom row) for surface temperature (K, (a)–(c)), precipitation (mm day^{-1}, (d)–(f)), total downward direct solar radiation at the surface (W m^{-2}, (g)–(i)), and total downward diffuse solar radiation at the surface (W m^{-2}, (j)–(l)). The spatial distribution of CTRL is from the 2020–2097 time-averaged results without geoengineering while that of GEOENG is from the 2020–2097 time-averaged results with geoengineering applied. The spatial distribution of BASE is from the 2010–2019 time-average results. Light grey stippling (dots) indicates regions where the change is significant using the Student's t-test ($p < 0.1$).*

- Differences in climate variables (surface temperature, precipitation, and downward direct and diffuse solar radiation at the surface) were evaluated (Figure 3).
- Similarly, differences in terrestrial productivity variables (photosynthesis rate, gross primary production, net primary production, and net biome production) were assessed to characterize responses and feedbacks of the SAI treatment (Figure 4).

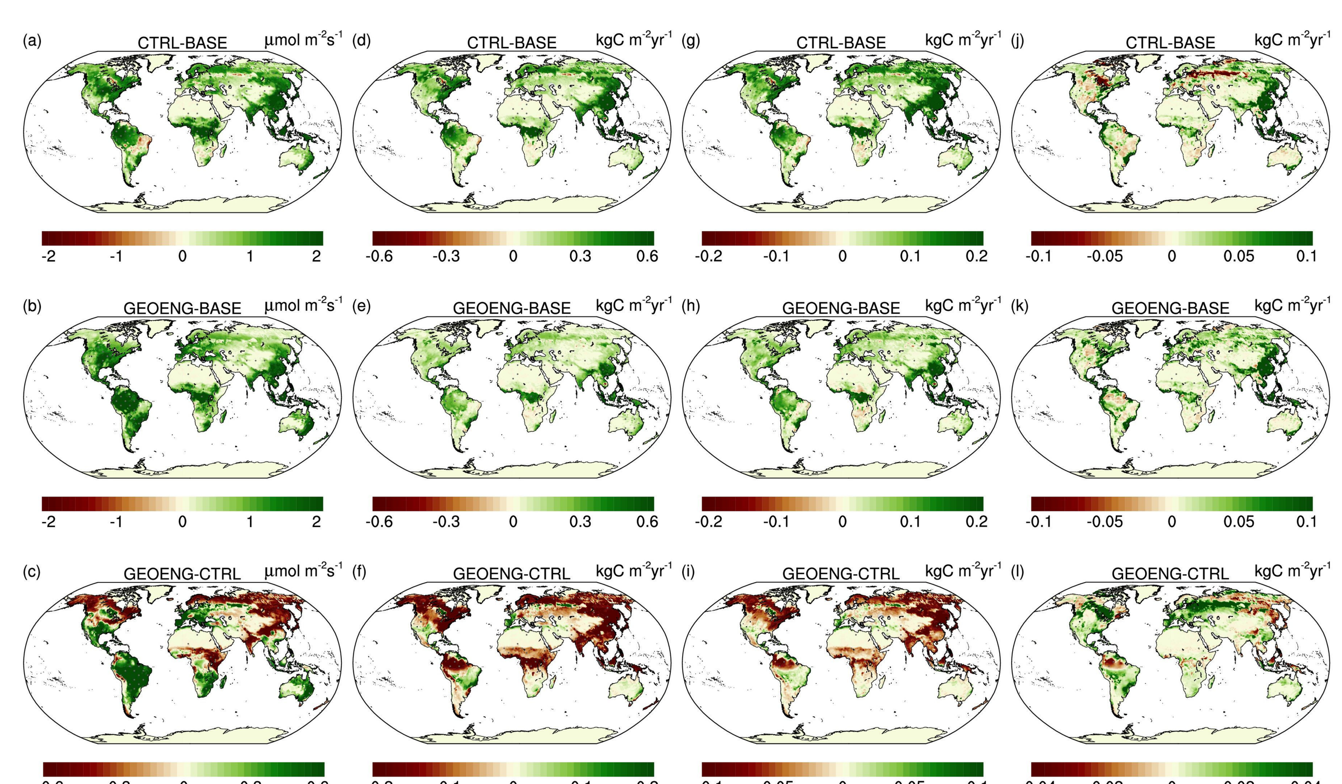


Figure 4: *Changes of spatial distributions between CTRL and BASE (top row), between GEOENG and BASE (middle row), and between GEOENG and CTRL (bottom row) for photosynthesis rates (µmol m^{-2} s^{-1}, (a)–(c)), gross primary production (kg C m^{-2} yr^{-1}, (d)–(f)), net primary production (kg C m^{-2} yr^{-1}, (g)–(i)), and net biome production (kg C m^{-2} yr^{-1}, (j)–(l)). The spatial distribution of CTRL is from the 2020–2097 time-averaged results without geoengineering while that of GEOENG is from the 2020–2097 time-averaged results with geoengineering applied. The spatial distribution of BASE is from the 2010–2019 time-average results. Light grey stippling (dots) indicates regions where the change is significant using the Student's t-test ($p < 0.1$).*

- The carbon sink strength on land increased under the SAI geoengineering treatment, accumulating an additional 79 ± 6 Pg C on land between 2020 and 2097 (Figure 5a).
- If the simulation had been coupled in a way that the atmospheric CO_2 trajectory responded to that difference in terrestrial carbon uptake, the atmospheric CO_2 mole fraction would have been 872 ppm instead of 909 ppm at the year 2097, absent ocean feedbacks not incorporated into the simulations (Figure 5b).
- Using a simple linear model, we estimated that the additional land carbon sink in the simulation would have lowered surface temperature by about 0.14°C at 2097, again assuming no ocean interactions (Figure 5c).
- We further estimated that sulfur injection rates could have been slightly adjusted to instead maintain a constant global temperature (Figure 5d).

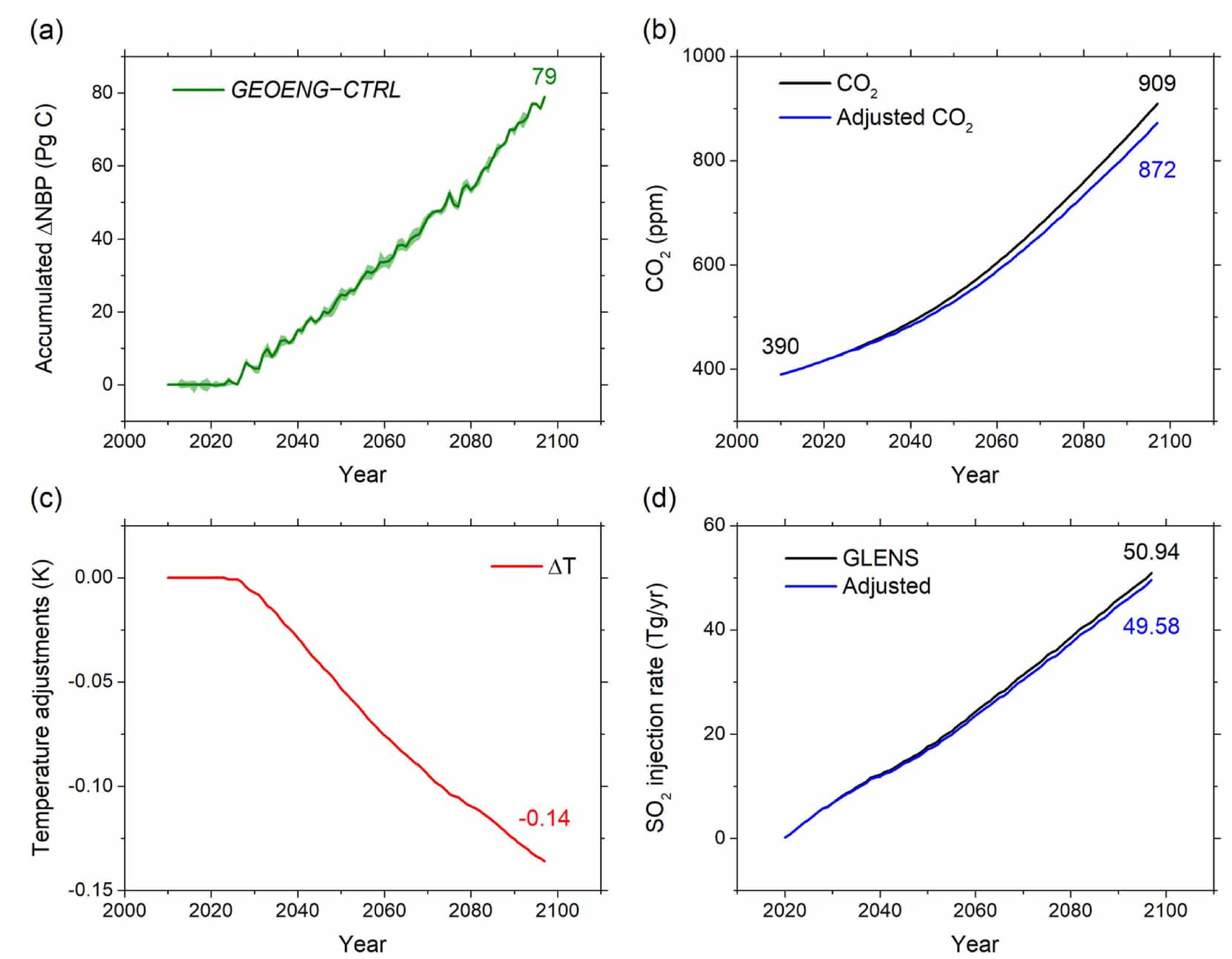
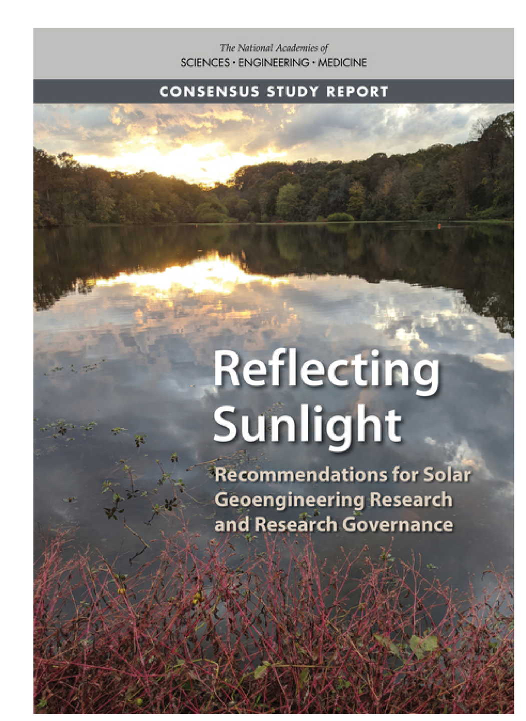


Figure 5: *The trajectories of (a) accumulated global carbon sink strength changes (Pg C) due to geoengineering, (b) the atmospheric CO_2 mole fraction (ppm) during 2010–2097 for BASE+CTRL (black line) and the adjusted atmospheric CO_2 mole fraction due to terrestrial BGC feedbacks under geoengineering (blue line), (c) surface temperature responses (K) due to atmospheric CO_2 adjustments, and (d) sulfur injection rates (Tg yr^{-1}) in GLENS (red) and adjusted injection rates due to terrestrial BGC feedbacks (blue).*

- This study showed that a geoengineering mitigation strategy with SAI under a high greenhouse gas emission scenario would have increased land carbon storage by 79 Pg C globally, primarily as a result of lower ecosystem respiration and diminished disturbance effects under the SAI treatment.
- **Fully coupled emissions-forced simulations with interactive terrestrial and marine biogeochemistry are required to quantify competing feedback effects.**

National Academies Report Calls for Climate Intervention Research



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*A 2021 report from the National Academies of Sciences, Engineering, and Medicine (NASEM) concludes a **strategic investment in research is needed** to enhance policymakers' understanding of climate response options. The United States should develop a transdisciplinary research program, in collaboration with other nations, to advance understanding of solar geoengineering's technical feasibility and effectiveness, possible impacts on society and the environment, and social dimensions such as public perceptions, political and economic dynamics, and ethical and equity considerations.*

Large-Scale Simulation Approach to Informing Policymakers

- To fill the nationally recognized research gap in understanding potential Earth system feedbacks of SAI on ecosystems, regional atmospheric circulation, and biogeochemical cycles, we will conduct a series of increasingly complex geoengineering simulations, using **DOE's Energy Exascale Earth System Model (E3SM)**.
- **These simulations will mimic the effects of CDR, SAI, and CDR plus SAI in combination.**
- We will start with the well-defined SSP5-3.4-OS mid-range overshoot CO_2 trajectory from CMIP6, which prescribes a drawdown of atmospheric CO_2 due to CDR, large reductions in emissions, or both.
- In that scenario, global surface temperatures rise by $>$2.5°C around 2040, **well above the 2°C threshold that may induce irreversible impacts**.
- A second set of simulations would introduce SAI to simultaneously cool the surface, or **"shave" the temperature peak**, until drawdown is sufficient to assure $<$2° warming at any time as illustrated in Figure 6B.

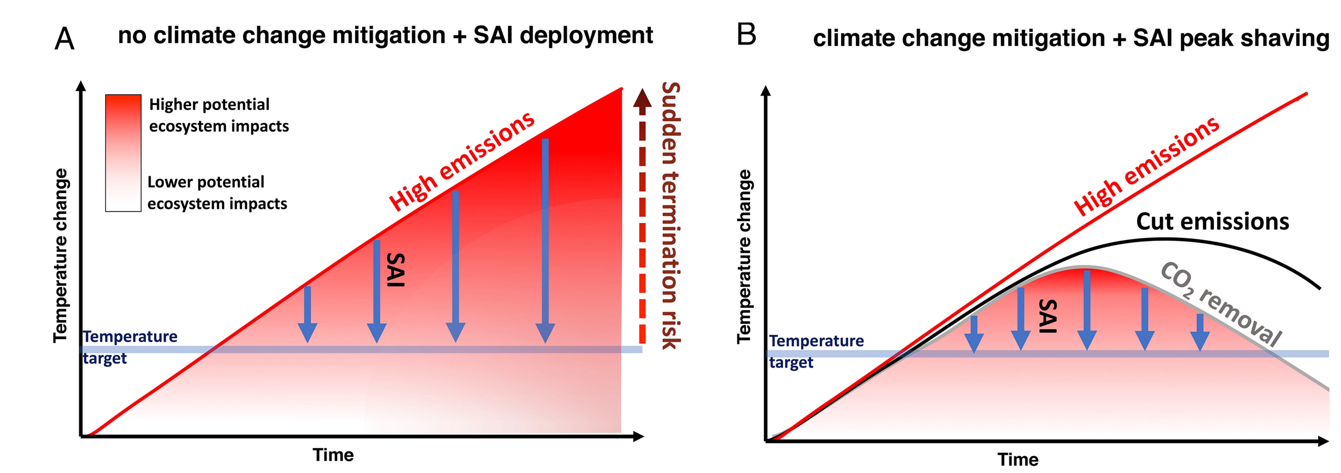

Figure 6: *Potential temperature change over time for two different SAI scenarios. (A) In a future with no climate change mitigation and with SAI deployment, high emissions result in rising temperatures (red line). Increasing amounts of SAI would have to be deployed to reduce temperature (blue arrows) to a specific temperature target (blue line). The risk of sudden SAI termination also increases (red arrow). (B) In a future with climate change mitigation and SAI "peak shaving," temperature changes are first reduced by a combination of emission reduction (black line) and CDR (CO_2 removal, gray line), then further reduced by SAI (blue arrows). The red shaded areas below the two curves indicate the potential overall risk for ecological systems from increased temperature and SAI deployment; carbon emissions alone would not create the same degree of risk reduction as shown in B. We note that SAI is not akin to a global thermostat that would only control global temperatures to remediate GHG-induced warming. GHGs add energy to the system at the surface and throughout the atmosphere, whereas reducing sunlight with SAI only changes the energy balance at Earth's surface. Furthermore, GHGs operate 24 h a day and all year long, whereas reducing sunlight primarily has a direct impact during the daytime and more so in summer than winter. Adopted from Zarnetske et al. (2021).*

- **These and other scenario simulations must be performed and analyzed to determine the effects of reduced radiative forcing despite increasing atmospheric CO_2 levels on Earth's climate, regional atmospheric dynamics and aerosol-cloud interactions, and terrestrial and marine carbon sink strengths.**
- **This research will better characterize and reduce scientific and societal uncertainties concerning the benefits and risks of solar geoengineering deployment, so that informed decisions can be made in the future about possible implementation.**

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