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Quantifying and understanding uncertainties in regional impacts of solar geoengineering

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1. Project overview

The overall scientific objective of our project is to quantify and understand the uncertainty, detectability and robustness of regional impacts of solar geoengineering scenarios, particularly over land. We will concentrate on solar radiation management , more specific on stratospheric aerosol intervention (SAI) by study the simulated climate impacts of an artificial sulfate aerosol layer in the stratosphere. Many SAI studies have shown large differences between the simulated climate impacts. The stratospheric aerosols scatter solar radiation and, consequently, cool the Earths' surface. The global cooling efficiency of a certain amount of sulfate differs between models. Even stronger are differences in regional impacts. This raise questions about our ability to predict regional impacts of solar geoengineering scenarios, particularly over land. What are the robust (agreed upon across climate models) regional impacts of solar geoengineering? Do regional climate discrepancies exacerbate or mitigate these impacts? How does physical-science uncertainty associated with known (small-scale parameterized physics, natural variability) and emerging (atmosphere-ocean coupling) factors cascade into uncertainty in regional impacts of solar geoengineering?

The parameterization of small-scale physical processes, e.g. clouds, convection, aerosols and turbulence that couple the atmosphere, land and ocean, is another well-known source of uncertainty often referred to as structural uncertainty. Structural uncertainty is typically quantified using a perturbed parameter ensemble (PPE). To date only a few PPEs have been performed for anthropogenic climate change scenarios because they are computationally intensive.

The work will be done in cooperation with the group of Tiffany Shaw, Department of the Geophysical Science, University of Chicago and the Climate System Engineering Initiative (CSEi) in Chicago. The project began in late summer of 2025 with one out of three positions filled. Two positions are still unfilled. Consequently, many tasks planned for the allocation period from July 2025 to June 2026 have not yet been completed.

2. First results

We use ICON in the climate model version (XPP) for the PPE (Mueller et al, 2025). In the first phase of the project, the model was tuned to realistically represent the period from 2010 to 2024. Our planned PPE is based on the G6-1.5K-SAI scenario (Visioni et al, 2024) of the Geoengineering Model Intercomparison Project (GeoMIP). We ran the SPP2-4.5 scenario until 2050 when our simulation reached a 1.5 K increase above the estimated pre-industrial climate level. To reduce the global temperature by 1K we introduced an artificial layer of sulfate aerosols into the stratosphere by specifying their optical properties. ECHAM was used to simulate the aerosol microphysical processes and dispersion of the sulfate. We processed the output using CMIP7 processors for use as input in ICON XPP. We tested 3, 4, and 5 Tg(S)/yr injections, each with a small ensemble (Fig. 1b). The 3 Tg(S)/yr injection produced results that were closest to the assumed 1 K global temperature reduction.

The PPE will focus on altering cloud, radiation, and turbulence parameters that clearly impact top-of-atmosphere radiation and surface temperature in ICON-XPP. We have identified eight tuning parameters within ICON's cloud, radiation, and turbulence parameterization schemes that we want to disturb within specific value ranges. Currently, we are testing different value ranges for these combinations of parameters. Previous simulations with ICON-XPP for tuning and ENSO tests provided possible ranges for these values.

Using Latin hypercube sampling, we calculated 50 combinations of these parameters (Fig. 1 a). For five combinations of these parameters, we simulated two scenarios over 20 years: a control scenario

A) Latin hypercube for 4 parameters **B) Control simulations and sulfur injection tests**

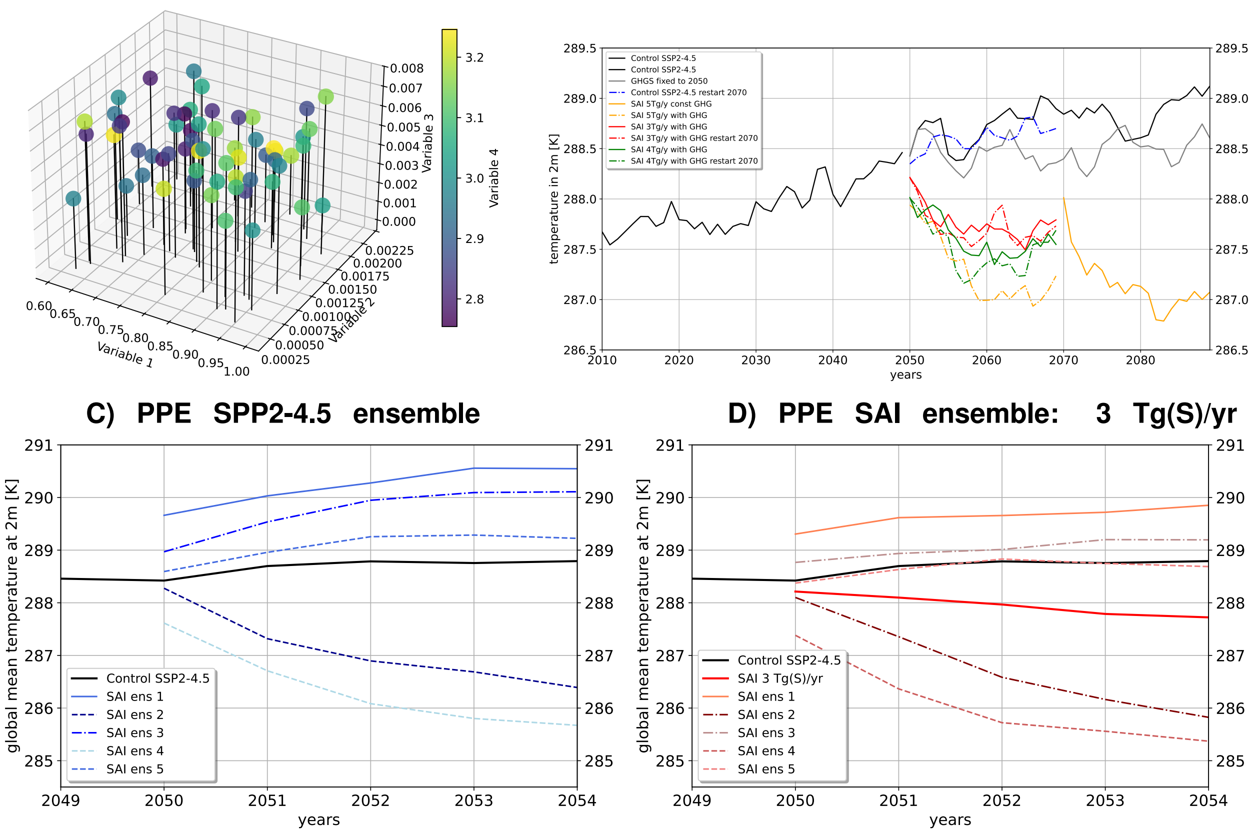

Figure 1: A: The parameter space of the identified tuning parameters was calculated using Latin hypercube sampling. These values were then used in single PPE simulations. Four of the eight parameters are shown here. B to D: Time series of the global mean 2-meter temperature. B: Simulations following SPP2-4.5 (black) and SAI simulations with sulfur injection starting in 2050 (colored lines). C and D: Five PPE simulations for SPP2-4.5 (left) and the SAI ensemble (right). The range of the simulated temperature response is still quite large, from +2 to -3 K compared to the tuned control simulation (solid black and red lines).

under SSP2-4.5 conditions and a SAI scenario (e.g., the injection of 3 Tg(S)/yr). However, when the tuning parameters are combined in a hypercube setup, the impact of changes to each parameter is compounded. This can result in relatively unrealistic climate states with significant global temperature changes. For example, the global temperature could increase by 5 K despite the injection of 3 Tg(S)/yr into the stratosphere. Therefore, we reduced the range of possible values for each parameter and performed again five simulations with different combinations of tuning parameter values. The results are shown in Figures 1c and 1d. In three of the simulations, the temperature continues to increase. In the other two simulations, the temperature drops an additional 2 K compared to the SAI control run (red line in Figure 1d). ICON's response to the different PPE parameter sets remains strong, requiring us to reduce the range again.

Literature

Müller, W. A., Lorenz, S., Pham, T. V., Schneidereit, A., Brokopf, R., et al.: The ICON-based Earth System Model for climate predictions and projections (ICON XPP v1.0), Geosci. Model Dev., 18, 9385-9415, https://doi.org/10.5194/gmd-18-9385-2025, 2025.

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