Identifying stable and effective solar geoengineering coalitions

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Abstract

We develop a novel framework to assess solar geoengineering outcomes under limited international cooperation, combining a high-resolution Integrated Assessment Model (RICE50+) with a climate emulator for stratospheric aerosol injection (SAI). Our approach integrates deep uncertainty quantification, global sensitivity analysis via optimal transport indices, and game-theoretic coalition stability concepts. We systematically explore over 1,800 representative coalition scenarios, capturing heterogeneity in physical responses, economic preferences, and deployment rules. This methodological innovation enables joint analysis of climatic and institutional dimensions of SAI, revealing key trade-offs between effectiveness and stability. Our results inform the design of viable, equitable geoengineering governance in an uncertain world.

Introduction

As climate overshoot becomes increasingly likely, solar geoengineering (SG) is gaining attention as a potential interim measure to reduce climate risk during decarbonization and the scale-up of carbon dioxide removal. Among SG methods, stratospheric aerosol injection (SAI) is the most studied, promising cost-effective reduction of climate risk. However, the climate impacts of SAI depend critically on deployment strategy[1], and its low cost raises governance concerns, notably the possibility of unilateral deployment by a single country or small coalition[2].

In previous work (under review), we showed that while global cooperation yields significant benefits, unilateral deployment increases climate risk, particularly for equatorial and tropical regions. Yet, the binary framing of full cooperation vs. non-cooperation overlooks a wide spectrum of intermediate arrangements. Limited cooperation among major powers may be more realistic and consequential.

To explore this broader space, we develop a novel methodology that integrates physical and governance uncertainties to evaluate the outcomes and stability of small SAI coalitions. Our goal is to identify configurations that approximate global-optimal outcomes under imperfect cooperation.

Methods

Our framework integrates a high-resolution, country-level Integrated Assessment Model (IAM) with a climate emulator to simulate the coupled socio-economic and climatic effects of SAI under a wide range of coalition structures and uncertainties. The modeling approach enables robust exploration of governance–climate interactions under imperfect cooperation.

Model Structure. We use RICE50+[3], a top-down IAM that resolves 155 countries, coupled with a climate emulator trained on outputs from state-of-the-art Earth System Models simulating multi-latitude SAI deployment. The emulator captures changes in regional temperature and precipitation due to SAI and GHG-induced forcing. These climate variables feed into empirically calibrated economic damage functions[4–6], enabling estimation of income losses under different climate futures. The IAM solves an open-loop Nash equilibrium in which coalitions—ranging from singletons to large alliances—optimize over both mitigation and geoengineering, interacting through shared climate variables.

Scenario Design. We assume that only coalition members can deploy SAI, and non-members are singletons. To reduce the vast space of possible coalitions ($\sim 10^{30}$), we restrict attention to coalitions with the following features:
(1) A maximum of four countries, reflecting empirical insights that smaller coalitions are more likely to be stable and feasible.
(2) Membership limited to the top 20 countries by GDP and/or population, ensuring that

members have sufficient geopolitical weight to meaningfully influence the scenario outcome.
(3) Inclusion of at least one major power (USA, China, India, or Brazil), which are assumed to be the only actors with the capacity to independently develop and deploy SAI technology[7].

These criteria yield 438,204 unique coalitions covering up to 40% of global GDP and population. We then draw a representative sample of these coalitions, stratified by geographic distribution and socio-economic diversity, to construct a tractable yet comprehensive scenario set. Each coalition is evaluated under different realizations of deep uncertainties, including (i) deployment rules (e.g., latitude-constrained[8] vs. unconstrained injection[1]), (ii) physical climate response parameters, and (iii) heterogeneity in economic preferences over climate outcomes.

Results analysis.

The scenarios so obtained are analyzed using the following techniques:

- *Global Sensitivity Analysis (GSA):* We apply optimal transport-based sensitivity indices[9] to assess the influence of uncertain parameters on key outcomes (e.g., GDP loss). This method captures nonlinear interactions and dependencies among inputs, offering a robust diagnostic of system behavior.
- *Game-Theoretic Stability Analysis:* We evaluate coalition stability under two key concepts: γ-core stability (where a defection dissolves the coalition) and internal stability (where remaining members can continue)[10]. Crucially, we distinguish between major powers (who may defect and act unilaterally) and others (who forfeit access to SAI upon defection). This allows us to assess the potential trade-off between coalition effectiveness and institutional durability.

Results

Preliminary analysis of 1,833 scenarios highlights two main determinants of 2100 GDP loss: (1) the specific world powers included in the coalition and (2) the coalition's mean population-weighted latitude.

Under free-latitude deployment, we observe a convex relationship between GDP loss and latitude: coalitions centered near the equator (0–15°N) consistently outperform others, avoiding economic losses beyond those in a 1.5°C warming scenario. Coalitions with multiple world powers (excluding USA–China pairs) tend to be welfare-improving.

These findings suggest that small, strategically composed coalitions—including countries from the Global South—can produce outcomes close to global optima. Ongoing work will extend the scenario set, deepen the uncertainty characterization, and assess the stability–effectiveness trade-off more rigorously.

Figures

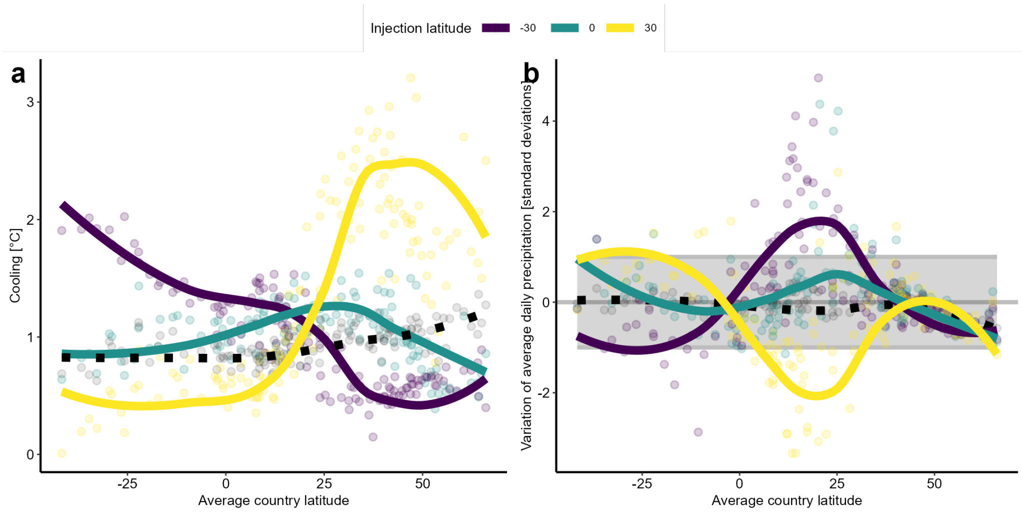

Figure 1. Outcomes of the climate emulator for temperature and precipitation. (a) temperature decrease for each country (dots) mapped by their average latitude for different injection latitudes (colors) for an injection of 12 Tg-SO2/yr relative to the SSP2 4.5 baseline climate. (b) precipitation variation for each country (dots) mapped by their average latitude for different injection latitudes (colors) for an injection of 12 TgS/yr, expressed as number of standard deviations relative to the historical country mean over the period 1990-2014. Colored lines identify the population-weighted median response per latitude and injection latitude across countries. Dotted black dots indicate the pattern of cooling/precipitation variations obtained with emission reductions leading to an equivalent amount of avoided global warming. Grey band area identifies variations in precipitation below +/- 1 standard deviation of historical variability.

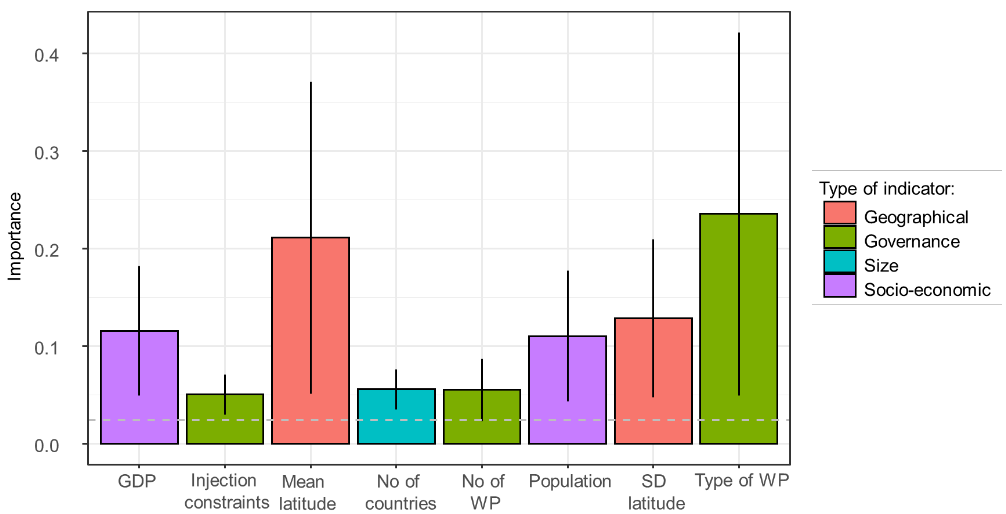

Figure 2. Relative influence of input parameters using optimal transport index. The bar represents the importance of the input in determining global GDP loss in 2100, and the errorbar represents the standard error associated with the index. Dotted grey line represents the minimum threshold of significance for an input.

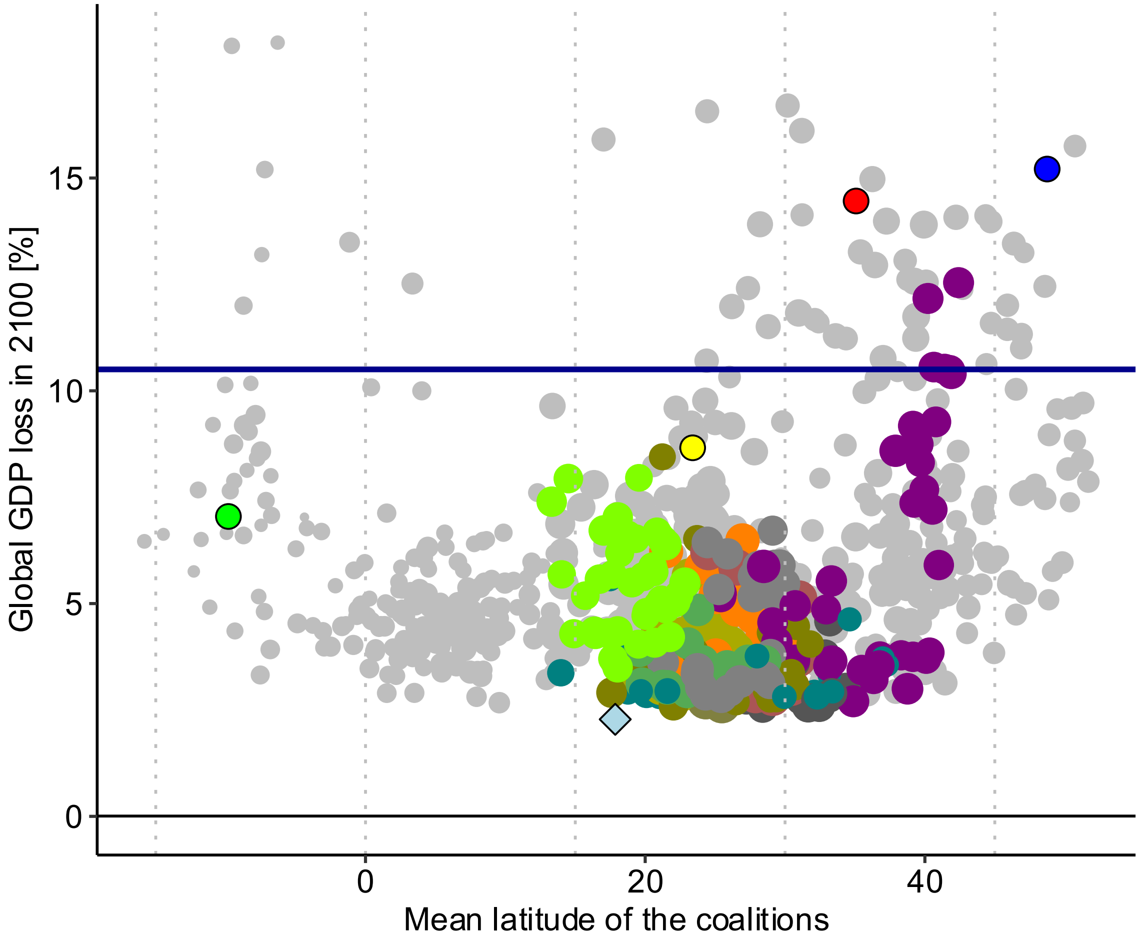

Figure 3. Global GDP loss in 2100 by scenario. Each point represents a scenario, and the x axis identifies the latitude of the coalition implementing SAI in that scenario. The light blue diamond highlights the grand coalition, black circled colors the unilateral implementation scenarios by USA (red), China (red), Brasil (green) and India (yellow). Grey points represent coalitions containing only one world power (USA, China, Brazil or India), while colored points represent coalitions containing two or more world powers, coded as the sum of the colors that identify the WP (for example, light green -> green + yellow, Brasil + India, purple -> red + blue, China + USA). The size of the dot represents the share of GDP of the implementing coalition. Horizontal blue lines highlight the GDP loss in a global cooperative scenario without geoengineering, that reaches 1.5°C in 2100.

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