Using the FRIDA Framework to Evaluate Endogenous Human-Climate Responses to Climate Intervention Scenarios

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Abstract

The gap between current greenhouse gas (GHG) mitigation efforts and the objective of limiting warming to 1.5°C persists because mitigation is often delayed, incomplete across sources, constrained by carbon-intensive infrastructure, unevenly distributed globally, and insufficiently responsive to non-CO_2 GHGs, land-use change, and climate feedbacks; consequently, climate intervention technologies might be required to complement mitigation efforts. Solar Radiation Modification (SRM) has been proposed as a complementary approach that cools the planet by reflecting a fraction of incoming solar radiation, notably through Stratospheric Aerosol Injection (SAI). Because SRM has not been deployed, assessment relies predominantly on modeling; however, Earth System Models and Integrated Assessment Models (IAMs) face limitations in representing dynamic climate–human feedbacks and are computationally intensive for extensive scenario exploration. This study adapts the system dynamics FRIDA framework—a fully coupled model integrating radiation balance, carbon and water cycles with demographics, economy, land use and agriculture, energy, resources (concrete), and behavioral change—to simulate SRM, focusing on incorporating SAI. Overall, the adapted FRIDA model can reproduce the intended physical effect of SAI within an integrated assessment framework; however future work should extend SAI-linked feedbacks across all human-system modules to evaluate impacts beyond direct climate outcomes.
Keywords: Climate Intervention, Solar Radiation Modification, Stratospheric Aerosol Injection, Climate Change.

1. Introduction

The climate gap refers to the discrepancy between current greenhouse gas (GHG) mitigation efforts and the ambitious goal of limiting global warming to 1.5°C above pre-industrial levels. While reducing GHG emissions is critical, focusing solely on mitigation overlooks several key factors that contribute to this gap.

These include delayed implementation of policies, incomplete coverage of emission sources, and persistence of carbon-intensive infrastructure. Additionally, the uneven global distribution of emissions and varying national capacities to mitigate climate change exacerbate this gap, making it difficult to achieve the 1.5°C target through mitigation alone. Moreover, mitigation strategies often fail to address non-CO2 greenhouse gases, land-use changes, and feedback loops within the climate system that can accelerate warming. The climate gap also highlights the importance of integrating adaptation, carbon removal technologies, and systemic socioeconomic transformations alongside mitigation. Without a comprehensive approach that includes these elements, mitigation efforts risk falling short, leaving the world on a trajectory that surpasses the 1.5°C threshold despite emission reduction commitments.

Solar Radiation Modification (SRM) is an innovative geoengineering strategy designed to mitigate the effects of climate change by intentionally cooling the planet, with the goal of alleviating global warming (Robock et al., 2009). Unlike traditional methods that focus on reducing greenhouse gas (GHG) emissions (i.e., mitigation), SRM employs techniques to reflect a small fraction of solar energy back into space to counteract global warming (Irvine et al., 2019; Ricke et al., 2010).

Two main SRM techniques have been proposed: (i) injecting SO2 into the stratosphere to mimic volcanic eruptions, known as Stratospheric Aerosol Injection (SAI), and (ii) increasing the brightness of marine clouds to enhance their reflectivity, known as Marine Cloud Brightening (MCB).

With respect to SAI, the goal is to inject aerosols into the stratosphere between 7 and 15 km above sea level. One of the most studied aerosols is SO2, following empirical evidence showing that SO2 injected into the stratosphere by natural volcanic eruptions increased solar reflectivity and reduced global temperatures by 0.5 °C (C2G, 2020). An annual injection of 1–5 Mt of sulfur could halve the effects of the 240 billion metric tons of carbon accumulated since the Industrial Revolution (Keith, 2013), with particles remaining in the stratosphere for years and cooling effects visible within less than one year after deployment.

In the context of MCB, clouds over the oceans can be modified to become more reflective, thereby increasing the amount of solar radiation redirected back into space and leading to cooling effects (Lin, 2013). In marine atmospheric areas with relatively low dust levels, it has been shown that increasing the number of cloud condensation nuclei (particles around which water droplets gather to form clouds) can significantly increase cloud reflectivity and potentially extend cloud lifespan (Albrecht, 1989).

However, these technologies are not without challenges and ethical implications. Critics have highlighted that SRM could disrupt regional climate patterns, trigger unpredictable consequences in ecosystems, and crucially, fail to address the root cause of climate change—excessive GHG emissions—a phenomenon often referred to as "mitigation displacement" (Degrees, 2023).

Studies such as those by Haywood et al. (2013) have examined the asymmetric impacts of SAI, showing how it can unevenly affect rainfall in the Sahel region of Africa, demonstrating the complexity and possible unwanted side effects of this technology. Thus, issues such as unintended changes in precipitation patterns, shifts in regional climates, and adverse impacts on biodiversity remain significant concerns. Finally, the deliberate alteration of the climate raises profound questions about equity, justice, and the distribution of risks and benefits among different populations (Irvine et al., 2011).

Given that to date, no SRM technology has been deployed, mathematical models are the predominant method to anticipate the benefits and harms of these technologies, as they assist in simulating the potential impacts of SRM on various climatic and ecological variables (Keith & Irvine, 2016). The Geoengineering Model Intercomparison Project (GeoMIP) is the main climate modeling project used to study the impacts of SRM, particularly the SAI and MCB strategies. GeoMIP involves collaboration among various institutions and is designed to systematically compare and analyze climate responses to idealized SRM scenarios across multiple state-of-the-art Earth System Models (Visioni et al., 2023).

Although it is a promising initiative for analyzing the effects of SRM, GeoMIP poses some important limitations. Earth System Models (ESMs) are primarily designed to simulate the physical, chemical, and biological processes within the climate system, such as atmospheric dynamics, ocean circulation, and biogeochemical cycles. However, they face challenges in accurately representing the interactions between climate and human systems, as they often treat human systems as external or overly simplified boundary conditions rather than as dynamic components. This separation limits their ability to capture the complex interactions in which human behavior, policy decisions, and socioeconomic factors both respond to and influence climate variables in a feedback loop. Furthermore, the spatial and temporal scales of human activities and societal changes often do not align with those modeled in ESMs, hindering the integration of rapidly evolving human responses.

IAMs are designed to connect economic, social, and environmental systems; however, they encounter challenges in accurately depicting the interactions between climate and human systems. These models often rely on simplified portrayals of human behavior, policy implementation, and technological change, which can miss nonlinear, emergent, or region-specific responses. They frequently assume rational decision-making and uniform policy adoption, failing to fully capture real-world complexities, such as political inertia, equity considerations, or cultural influences. Additionally, IAMs may inadequately represent the feedback from climate impacts on human systems, such as how climate-induced disruptions affect economic productivity, migration, or social stability, thereby limiting their ability to predict realistic pathways toward climate targets, such as 1.5°C.

Another significant limitation for conducting modeling studies such as those required by GeoMIP is the enormous volume of data generated by these models and the substantial processing capacity required to run additional scenarios (Muñoz-Sánchez et al., 2025).

Together, these limitations in ESMs and IAMs hinder the comprehensive modeling of the climate gap discussed earlier, in which the interplay between mitigation efforts, socioeconomic transformations, and climate system responses is critical. Addressing these gaps requires enhanced coupling of models that integrate detailed human decision-making processes, equity considerations, and adaptive capacities alongside physical climate dynamics.

The FRIDA model is an integrated assessment model developed using the system dynamics method, with a focus on capturing feedback loops between human and climate dynamics (Schoenberg et al., 2025). This study adapts the FRIDA model to simulate climate intervention scenarios, particularly SAI, to evaluate their potential socioeconomic feedback loops.

This adaptation facilitates a thorough evaluation of the potential impacts of SAI deployment on economic activities, policy responses, and social dynamics, while considering the intricate interactions previously discussed in relation to climate–human feedback and the limitations inherent in traditional models. By incorporating SAI-specific mechanisms into FRIDA, the model can more effectively guide decision making regarding geoengineering strategies within the broader framework of climate mitigation and adaptation.

2. The FRIDA Model

The *Feedback-based knowledge Repository for IntegrateD Assessments* (FRIDA) model is a feedback-based, fully coupled global integrated assessment model designed to integrate Earth's radiation balance, carbon cycle, and water cycle alongside human demographics, economics, agriculture, and energy use (Mauritzen et al., 2023). In its most recent version (2.1), it contains seven interconnected modules (Schoenberg et al., 2025), as shown in Figure 1.

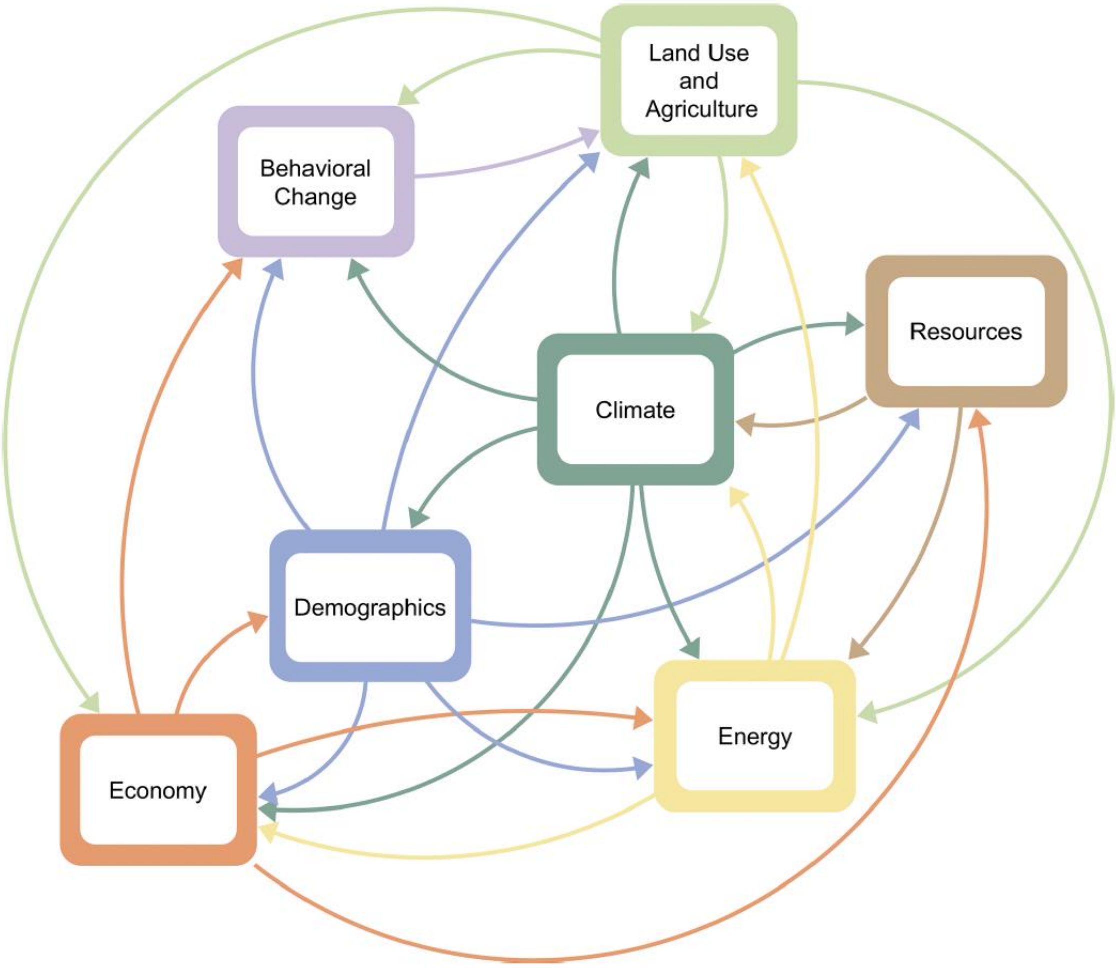

Figure 1. The seven modules of the FRIDA model. Source: Schoenberg et al. (2025)

FRIDA fully integrates the purposes of both traditional ESMs and IAMs by modelling the co-evolution of human processes contributing to emissions and climate processes that transform emissions into climate change.

Given the importance of the climate module in this paper, as it will be explained later, we will initially introduce the other modules in a bulk section and later describe the climate module in more detail, including the adaptations we made.

2.1 The Human Processes Modules

FRIDA's human system is divided into six distinct modules, each dedicated to a particular area of study: Demographics, Economy, Land Use and Agriculture, Energy, Resources (Concrete), and Behavioral Change (Schoenberg et al., 2025).

The demographics module illustrates the evolution of the global population over time by utilizing a continuous cohorting system (Sterman, 2000) divided into seven age groups. Birth rates are determined by a calculated fertility rate derived from a calibrated regression that uses GDP per capita and female literacy levels as variables. This reflects the trend that improvements in living standards and women's education significantly lower birth rates (Schoenberg et al., 2025).

The Economy module models the global economic system as a stock-flow consistent monetary framework encompassing production, consumption, finance, and government activities, all within a Schumpeterian context (Schoenberg et al., 2025). The financial sector determines investment levels based on profitability, lending standards, and bankruptcy dynamics, whereas the corporate sector invests to expand production and hires workers as necessary. FRIDA's economic module also considers climate change, which affects economic growth through four primary pathways. First, rising temperatures diminish labor productivity. Second, sea-level rise damages infrastructure and assets. Third, financial instability increases as investment failures rise, hindering economic dynamism. Finally, maintaining climate-affected public infrastructure places a strain on government budgets (Schoenberg et al., 2025).

The Land Use and Agriculture module details the process-based aspects related to human requirements for food, including both plant and animal products, as well as other products derived from the land. It monitors the effects of these production processes on the Earth's system, with a particular focus on the climate system. This module categorizes land into four types: mature and maturing forests, grasslands, croplands, and degraded lands. Vegetation growth is modeled based on climate conditions, and for croplands, it also considers agricultural management practices (Schoenberg et al., 2025).

The energy module simulates, in a process-oriented way, human requirements and desires for energy and the impact of these processes on the climate. The framework of the energy supply submodule is based on the Model of Investment and Technological Development (MIND), which incorporates learning by doing and the effects of resource scarcity. It distinguishes between three fossil fuel types (coal, oil, and gas), four renewable energy sources (biofuel, hydropower, solar, and wind), and nuclear power (Schoenberg et al., 2025).

Energy demand is influenced by GDP per capita, with higher GDP resulting in greater energy demand, although the increase in demand diminishes marginally. Both energy production and consumption are influenced by the climate module. Energy demand increases with an increase in cooling degree days and decreases with a decrease in heating degree days (Schoenberg et al., 2025).

The behavioral change module is designed to simulate the detailed processes that influence individual choices regarding dietary habits. These choices, which encompass both calorie consumption and the composition of one's diet, are crucial environmental behaviors that lead to increased food production and associated greenhouse gas emissions (Schoenberg et al., 2025).

2.2 The Climate Module

FRIDA's climate system model is an adaptation of FaIR v2.1, altered in three ways: (i) substituting FaIR's carbon cycle emulator with a process-based representation of land and ocean carbon cycles, (ii) significantly narrowing anthropogenic climate forcers to only those explicitly modeled in other modules, and (iii) recalibrating the entire model according to established procedures (Schoenberg et al., 2025). The climate module simulates Earth's response to global-scale forcings. Inputs to the climate module from the human components of the model include population, GDP per capita, energy production, concrete production, food production, and land use changes. These inputs are utilized to determine global emissions of greenhouse gases and sulfur dioxide, alterations to the land carbon cycle, changes in land albedo, and freshwater usage (Schoenberg et al., 2025).

The climate module accounts for eight chemical species of emissions. Among these, CO_2, CH_4, N_2O, SO_2, and HFCs are the primary species, with emissions directly calculated from human activities. The remaining three (CO, NO_x, and VOC) are modeled internally using relationships derived from historical data (Wells et al., 2026).

The module structure is shown in Figure 2 and includes the terrestrial carbon balance, emissions, radiative forcing, ocean carbon, energy balance model, and sea level.

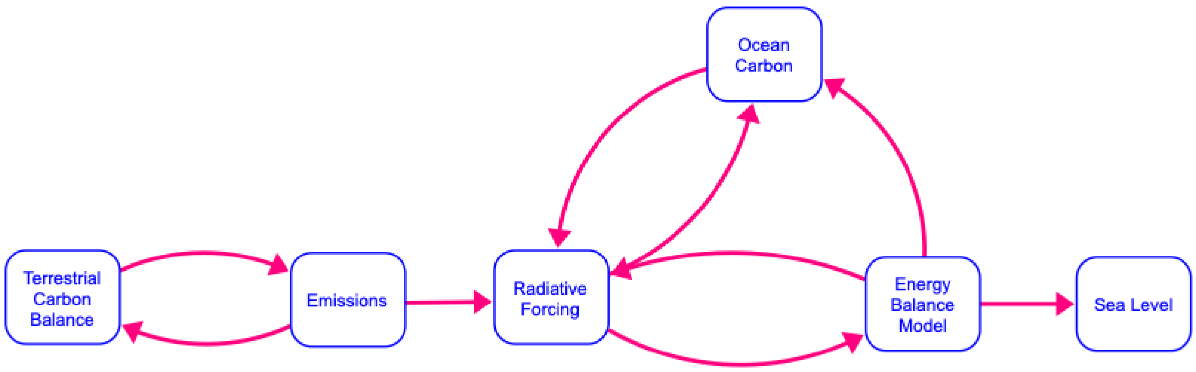

Figure 2. The sub-modules of the Climate Module

Among the various sub-modules, this study focuses on the 'Radiative Forcing' sub-module. In this context, the FRIDA model computes both natural and anthropogenic radiative forcings.

Anthropogenic radiative forcing was calculated by including nine different forcing types: carbon dioxide (CO_2), nitrogen (N_2O), methane (CH_3), stratospheric water vapor, other minor greenhouse gases, ozone, black carbon on snow, land use, and aerosol forcings, as shown in Fig. 3.

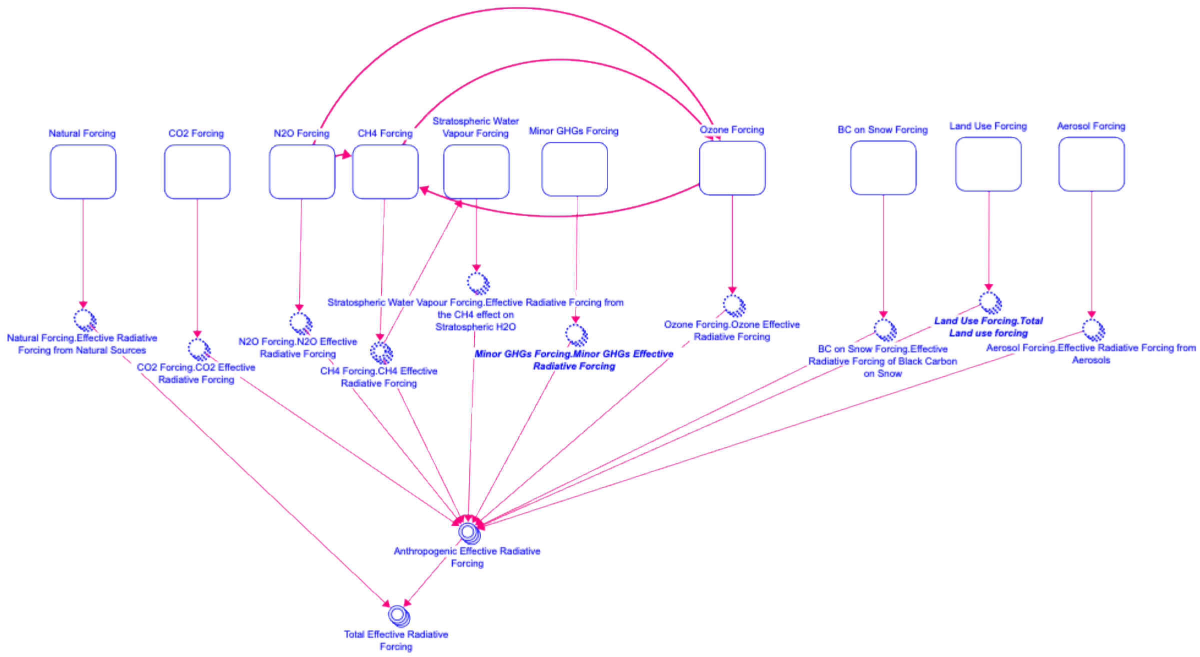

Figure 3. The structure of the Radiative Forcing sub-module

2.3 The SAI Sub-module

In the radiative forcing submodule, we integrated a balancing feedback loop designed to generate negative forcing, thereby mitigating the forcing effects induced by anthropogenic activities. Figure 4 shows a simplified causal loop diagram (CLD) that elucidates this concept, and Figure 5 depicts the stock–flow structure.

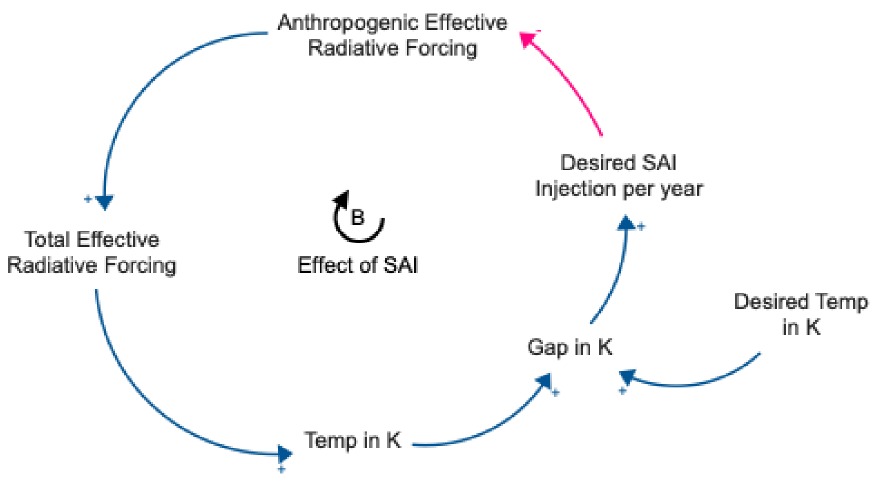

Figure 4. Balancing Loop explaining the effect of SAI on the Anthropogenic Effective Radiative Forcing

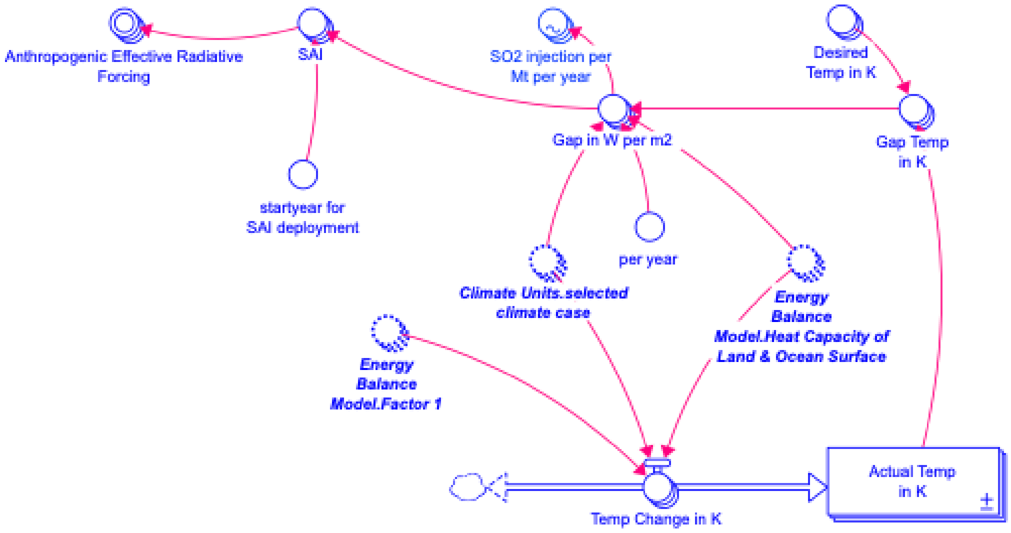

Figure 5. Stock-Flow structure of the new SAI sub-module

Regarding the deployment rate, i.e. the amount of Mt of SO2 to be injected by year, the relationship between sulfur aerosol injection and the resulting cooling effect in W/m² is inherently nonlinear. As the amount of SO_2 injected into the stratosphere increases, the initial increments lead to significant increases in aerosol concentration, which enhance solar reflectivity and thus produce a strong negative radiative forcing.

However, this effect does not scale linearly with continued injection; at higher injection rates, the marginal cooling effect diminishes due to saturation in aerosol optical depth and complex atmospheric chemical interactions (Robock, 2020). This nonlinear behavior is reflected in the graphical function used in the FRIDA model's SAI sub-module (Figure 6), where increases in SO_2 injection yield progressively smaller increments in negative radiative forcing.

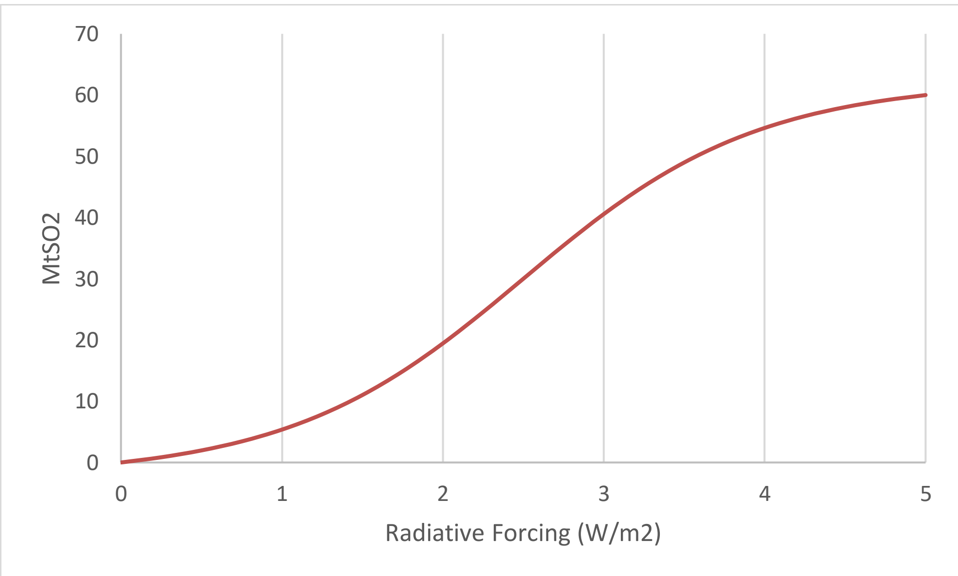

Figure 6. Proposed relationship between radiative forcing and SO2 injection over Mt/yr. Source: Robock (2020)

Such nonlinearity arises because aerosol particles can coagulate, sediment, or be removed through chemical processes, thereby limiting the persistence and reflectivity of aerosols and thus reducing the efficiency of additional SO_2 injections in producing proportional cooling.

3. Results and Discussion

First, we ran the model with predefined parameters and compared the results of an SAI vs. No-SAI scenario, as shown in Figure 7.

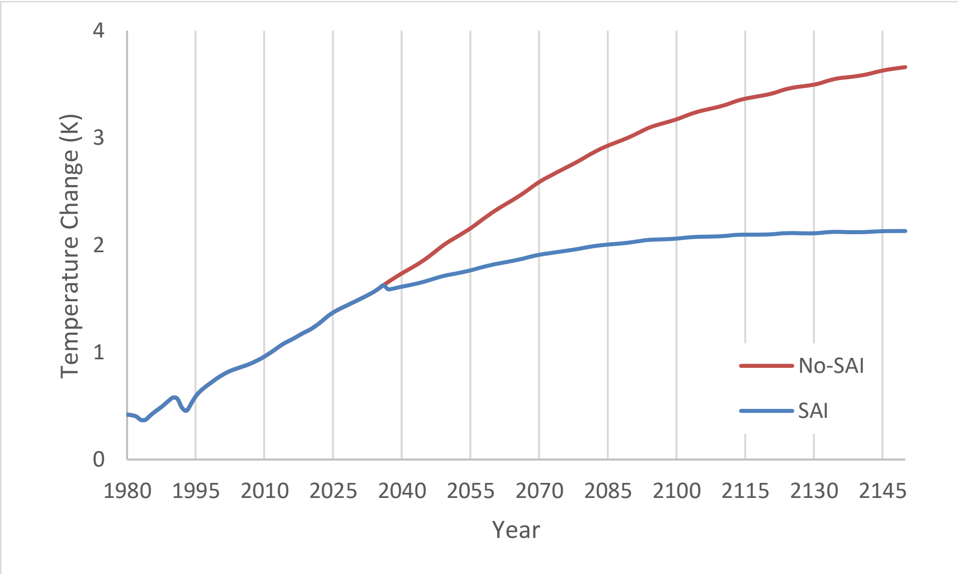

Figure 7. Change in Surface Temperature in (K)

Figure 7 illustrates the change in surface temperature (in Kelvin) comparing the scenarios with and without Stratospheric Aerosol Injection (SAI). The results demonstrate a clear cooling effect in the SAI scenario relative to the no-SAI baseline, reflecting the negative radiative forcing generated by sulfur aerosols injected into the stratosphere. This temperature reduction aligns with the model's representation of SAI as a peak-shaving intervention designed to limit warming below critical thresholds. In our base run, SAI reduced the temperature to approximately 2 K.

Next, we show the deployment rate (i.e., aerosol injection in MtSO2 per year) in Figure 8.

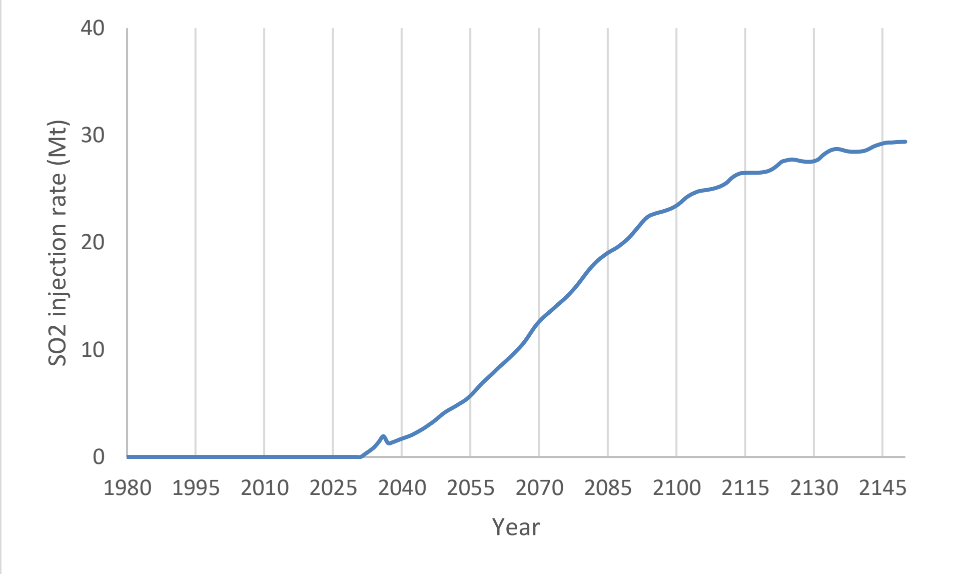

Figure 8. Injection rate of SO2 per year (in Million Tons)

As illustrated in Figure 8, the injection rate increases in tandem with the rise in anthropogenic radiative forcing, thereby stabilizing the temperature at 2 K (as previously shown in Fig. 7). By the end of the century, the model estimates more than 20 Mt of SO2 injection per year. These increasing injection rates indicate escalating pressure over time because of radiative forcings induced by human activities.

When analyzing economic outputs, our initial results show a progressive increase in GDP per capita when SAI is deployed (Fig. 9).

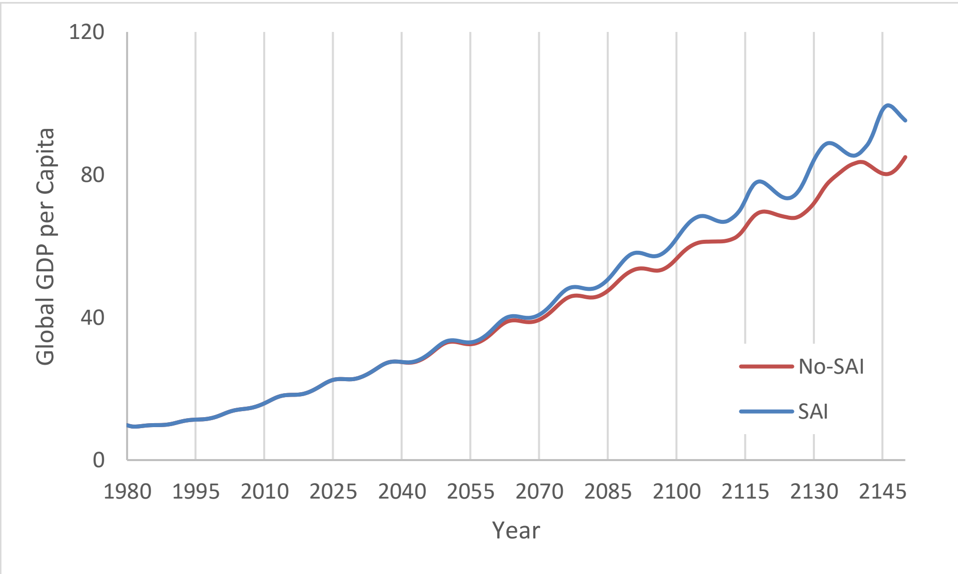

Figure 9. GDP per Capita in Bi USD per Million people per year

These results confirm the capacity of the FRIDA model to simulate the climatic impact of SAI deployment, supporting its use for evaluating potential strategies within integrated assessment frameworks.

4. Conclusions and Policy Implications

The conclusion emphasizes that the FRIDA model effectively demonstrates the physical feasibility of the proposed climate intervention strategies, confirming from a scientific and technical standpoint that these measures can be implemented.

However, the overarching challenge does not stem from physics or engineering constraints but from governance-related issues. In particular, the political risks associated with termination shock—a sudden cessation of interventions leading to rapid and potentially catastrophic climate consequences—represent the most significant bottleneck. This highlights that the critical barriers to success lie in managing political will, social acceptance, and international coordination, rather than in technological limitations. Addressing these governance challenges is essential to ensure the safe and sustained deployment of such interventions.

Future work should expand the FRIDA model to include feedback loops linking SAI to demographics, economy, land use and agriculture, energy, resources (concrete), and behavioral change modules. This expansion will significantly increase the potential usefulness of the model in assessing impacts beyond direct climate impacts.

5. Acknowledgements

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