Regional Economic Impacts and Emission Responses under Solar Radiation Modification

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Abstract

Solar Radiation Modification (SRM) has been proposed as a potential tool to limit increases in global or regional temperatures caused by anthropogenic greenhouse gas emissions. While previous research has extensively examined the climate system's response to various SRM strategies, as well as their aggregate economic consequences, the regional distribution of economic impacts has received less attention. In this study, we use NorESM2-DIAM—an Earth System Model coupled to a high-resolution integrated assessment model—to assess the economic impacts, measured in GDP per capita, in an idealised SRM scenario where incoming solar radiation is reduced by 1%. Our results suggest that, relative to a baseline without SRM, most countries experience economic gains under SRM, with only a few countries facing negative impacts. Low-income countries tend to see the largest benefits, reducing global economic inequality relative to the baseline. However, reduced damages and lower inequality are accompanied by higher emissions under SRM, potentially leading to additional adverse effects not captured here. These findings highlight potential trade-offs between economic benefits, reduced inequality, and increased emissions relevant for SRM governance.

Keywords: climate change, economic impacts, climate interventions, solar radiation modification

1 Introduction

Is climate interventions a potential solution to avert dangerous climate change while we reduce greenhouse gas emissions, or instead a crutch that undermines long-term mitigation efforts? As 2024 became the first year to exceed 1.5 degrees of global warming (Bevacqua et al., 2025), the need to mitigate greenhouse gas emissions is increasingly urgent. Yet achieving such reductions faces substantial challenges, such as political resistance, economic constraints, and the rapid pace at which mitigation must occur. In this context, climate interventions—particularly Solar Radiation Modification (SRM)—have been proposed as a potential complementary tool to limit dangerous warming (Crutzen, 2006; Parson and Keith, 2024; MacMartin et al., 2018), but what are its economic consequences? Here, we examine the economic implications of using SRM to limit climate change, focusing on the regional distribution of impacts across the globe and its effect on global emissions.

Climate intervention is defined as an intentional large-scale action designed to modify the Earth's climate system in order to reduce the impacts of climate change (National

Research Council et al., 2015). Two main approaches have been proposed: removing CO_2 from the atmosphere (Carbon Dioxide Removal (CDR)) or reducing the amount of incoming sunlight (SRM). Because these approaches work through fundamentally different mechanisms, they face different problems and challenges. CDR is expensive and slow but directly reverses emissions, while SRM is relatively cheap and fast but does not address elevated CO_2 concentrations and their associated impacts. Here we focus on the latter, also referred to as solar geoengineering.

With the Paris goal of limiting warming to 2 degrees and striving for 1.5 degrees, SRM is becoming increasingly relevant in the effort to limit warming. Most emission scenarios consistent with the Paris Agreement are reliant on CDR, at scales that are likely unfeasible. SRM could be a temporary measure to limit temperature increases while we develop and employ the technologies needed to sufficiently reduce emissions. However, many uncertainties remain regarding its feasibility, impacts on the Earth system, economic impacts, and consequences for mitigation efforts. Despite the challenges, SRM is becoming an increasingly relevant part of the climate policy debate and, therefore, a better understanding of its economic and distributional consequences is important.

A substantial body of literature has examined the climate response to various SRM scenarios (e.g. Govindasamy and Caldeira, 2000; Kravitz et al., 2013; Robock et al., 2013; Niemeier et al., 2013; Crook et al., 2015). Similarly, many studies have looked at the economic impacts of SRM, generally finding that it is economically attractive due to its ability to reduce climate damage at a much lower cost than mitigation (e.g., Harding and Moreno-Cruz, 2016; Heutel et al., 2018; Belaia et al., 2021; Meier and Traeger, 2023).

However, far fewer studies have looked at the regional distribution of these economic impacts. Using an 11-region framework, Aaheim et al. (2015) find that the economic impacts of SRM are likely small and depend on the chosen technique. In contrast, using a country-level framework, Harding et al. (2020) find considerable impacts and suggest that SRM could decrease economic inequality. In a setting with a small number of (large) regions, Meier and Traeger (2022) study a dynamic game in which regions make decisions about whether to implement SRM, finding that SRM reduces the social cost of carbon unevenly across regions; see also Manoussi and Xepapadeas (2017) and Manoussi et al. (2018) who study the adoption of SRM in a two-country setting. These contrasting results highlight the importance of more research on the regional distribution of the economic impacts of SRM.

Building on this literature, we present an idealised SRM experiment using the newly developed NorESM2–DIAM modelling framework (Bjordal, Smith Jr., Cornec and Storelvmo, 2026) to study the effects of SRM at a high degree of geographic resolution.

Rather than simulating aerosol injection or other physical mechanisms, we reduce incoming solar radiation directly by 1%. The model employs a two-way coupling between an Earth System Model (ESM) and an Integrated Assessment Model (IAM) with $1^\circ \times 1^\circ$ resolution. Unlike many existing studies, our framework eliminates the need for simplified representations of climate dynamics when analyzing the economic effects of SRM; instead, we leverage the state-of-the-art dynamics captured by a full Earth System Model. We use the model to investigate the spatial distribution of economic impacts from SRM and how this may affect decisions related to energy use and emissions. We find that SRM reduces inequality—consistent with the finding that unmitigated climate change increases inequality (Taconet et al., 2020; Krusell and Smith, 2022)—but also leads to higher emissions.

2 Methods

To study the effects of Solar Radiation Modification, we employ the climate-economy model NorESM2-DIAM, a dynamic coupling of the Norwegian Earth System Model version 2 (NorESM2) and the Disaggregated Integrated Assessment Model (DIAM). NorESM2 is a state-of-the-art Earth System Model that calculates the evolution of the full climate state, including an interactive carbon cycle, while DIAM calculates economic activity in all populated areas at a high degree of spatial resolution. The two components pass information back and forth at an annual time step: NorESM2 delivers annual mean regional surface air temperatures to DIAM and, in response, DIAM delivers regional CO_2 emissions to NorESM2 at a $1^\circ \times 1^\circ$ resolution. Economic productivity varies with temperature via a damage function; productivity, in turn, determines emissions, thereby creating a two-way feedback between the climate and economic activity.

In the economic model (DIAM), economic agents (consumers and firms) in each $1^\circ \times 1^\circ$ grid cell use physical capital, labor, and energy to produce output (i.e., gross domestic product, or GDP). Current wealth (i.e., output plus physical capital) is divided in every year between consumption and savings, which determines the capital stock in the next year. Agents solve dynamic optimization problems: they choose savings and energy use in every year to maximise their lifetime utility, i.e., the total benefit they gain from consumption throughout their lifetimes. To make their annual choices, agents use decision rules that depend on their current wealth and their current regional temperature. Agents' decision problems are forward-looking: agents base their decisions on forecasts of future regional productivity (which depends, in turn, on future regional temperature) and they anticipate how savings today will affect wealth in the future. Regional capital is immobile in DIAM and regional population changes exogenously. Consequently, regions interact only through the effects of their actions on the path of emissions.

An economic equilibrium in DIAM satisfies a fixed-point condition: agents' forecasts of future regional temperature align with its actual behavior as determined by agents' decisions about energy use (which, in turn, depend on their forecasts). As explained in Bjordal, Smith Jr., Cornec and Storelvmo (2026), an approximation to this fixed point is computed using a standalone version of DIAM in which regional temperatures—and agents' forecasts of them—depend only on cumulative CO_2 emissions and the elapsed time since the implementation of SRM (see below for further details on these forecasts). In a simulation of the fully-coupled model, by contrast, regional temperatures are determined by the interaction of agents' decision rules (as computed in the standalone model) with the geophysical dynamics embedded in NorESM2. Consequently, in such a simulation, regional temperatures display realistic interannual variability around agents' forecasts. See Bjordal, Smith Jr., Cornec and Storelvmo (2026) for full details on the workings of NorESM–DIAM.

As described in Bjordal, Smith Jr., Cornec and Storelvmo (2026), the initial distribution of capital across regions and the parameters in DIAM are calibrated using high-resolution data on GDP and population in 1990 from version 4.0 of the G-Econ database (Nordhaus et al., 2006), as well as data on the shares of labor and energy in GDP. The regional damage function relating productivity to temperature is calibrated to reproduce estimates of aggregate damages caused by global warming. Regional changes in population over time are calibrated using high-resolution data in the G-Econ database from 1990 to 2005, augmented by country-level population data (until 2024) and projections (from 2025 to 2100) provided by the United Nations World Population Prospects (United Nations, 2024).

We perform idealised simulations in which CO_2 is the only anthropogenic emission, and all other emissions are kept at their pre-industrial (i.e. 1850) levels. The energy system undergoes relatively rapid decarbonisation, with the share of green energy increasing from 5% in 2025 to 50% in 2065 and 90% in 2095. Actual CO_2 emissions are determined by the energy use decisions of economic agents, resulting in a realized emission scenario that lies somewhere between SSP2-4.5 and SSP3-7.0 (van Vuuren et al., 2014; Kriegler et al., 2014; Riahi et al., 2017) for the baseline without SRM.

In the SRM experiments, SRM is initiated in 2030 and implemented as a 1% reduction in incoming solar radiation at the top of the atmosphere. We do not specify the underlying technology or its feasibility. For now, we assume that the expense of SRM is shared across all economic regions, making the economic expense for individual regions negligible, and thus we omit it here.

As described above, economic agents form expectations about future temperatures to make decisions about savings and energy use. In the absence of SRM, agents' forecasts depend only on cumulative CO_2 emissions, as explained in detail in Bjordal, Smith Jr., Cornec and Storelvmo (2026). Under SRM, we add to this forecast a region-specific offset that depends on the elapsed time since the introduction of SRM:

$$a_i(1 - e^{b_i t}), \tag{1}$$

where i denotes the region, t is the number of years since SRM implementation, a_i is the asymptotic temperature offset, and b_i controls the rate at which the offset is realised. After 100 years, we assume that the temperature response has stabilised and the offset remains constant.

The parameters a_i and b_i are estimated using four NorESM2 simulations: two simulations with emissions according to SSP3-7.0 and SSP5-8.5, respectively, each run both with and without SRM initiated in 2030. In the 12 grid cells where we failed to find a fit, a_i was set to the mean of the grid cell's temperature offset in the last ten years, i.e. 2091-2100 (averaged across both SSPs), and b_i was set to the global mean of all fitted b_i coefficients (i.e. $\overline{b} = 0.089$, while $\overline{a} = 3.26$). If the grid cell's expected offset in 2030 is within ±10% of its a_i value, the final constant offset is set to a_i; otherwise (in fewer than 5% of the grid cells), the final constant offset is set to the expected offset in 2130, i.e. $= a_i(1 - e^{100 b_i})$.

We model SRM deployment as an unanticipated shock. Prior to 2030, agents form expectations assuming temperatures depend solely on CO_2 emissions. Once SRM is implemented, agents update their expectations to include both the CO_2-driven temperature change and the SRM-induced offset in equation 1. Although SRM implementation would normally be discussed in advance, SRM could plausibly be deployed rapidly or unilaterally—such as in response to a devastating extreme weather event—making this assumption reasonable under certain conditions.

3 Results

Our simulations show that the lower global temperature under SRM implementation is associated with higher CO_2 emissions (figure 1a and b) compared to the baseline without SRM. This is because a lower global temperature change means smaller damages to the global economy, and consequently higher productivity. From 2030 to 2100, cumulative emissions are 5.4% higher with SRM than without.

With SRM, the area-weighted temperature change over inhabited land decreases from around 2.5°C above pre-industrial levels in 2030 to around 1.35°C in 2100, while the baseline increases to around 4°C in 2100. Both the population-weighted and the global area-weighted temperature changes (not shown) respond similarly, decreasing from around 2°C in 2030 to 1.1°C in 2100 under SRM, while the baseline reaches

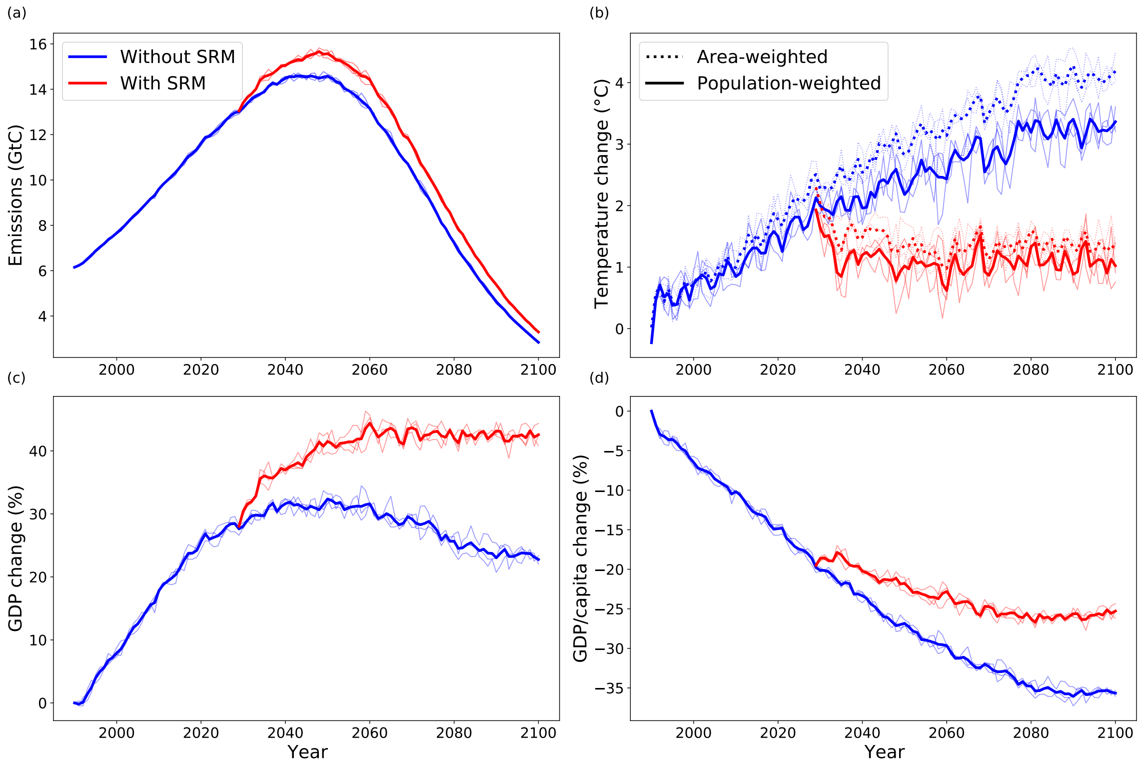

Figure 1: *Global emissions (a), mean annual 2 m air temperature change from pre-industrial (b), percentage GDP change from 1990 (c), and percentage GDP per capita change from 1990 (d) for the simulations with SRM (red) and without SRM (blue). The thick line is the ensemble mean, while the thinner lines are the three individual ensemble members. For temperature, the dotted lines display the area-weighted temperature over inhabited land while the continuous lines display the population-weighted temperature.*

roughly 3.2°C in 2100. The population-weighted temperature change is lower than the area-weighted temperature change for the same grid cells because there are more people closer to the equator than at high latitudes, i.e., more people where temperature change is slower. It is important to note that this population pattern becomes more pronounced over time, as the UN projects population to grow substantially in Africa and the Middle East while decreasing or stabilizing at high latitudes. Although population weights are not constant over time, population-weighted temperature is at the same time the most relevant for evaluating how climate change affects economic welfare (for details see Bjordal, Smith Jr., Cornec and Storelvmo, 2026).

The maps in figure 2 show the spatial distribution of temperature change from 2020-2029 to 2090-2099 with and without SRM, as well as the difference between the decadal means. Without SRM, we see the expected Arctic amplification pattern of warming, while temperature change under the SRM scenario is modest: less than 1°C in most locations. Comparing with the baseline change, the difference (SRM minus baseline) is largest in the Northern Hemisphere, with most cooling at the highest Northern latitudes.

Moving to the economic impacts of these temperature changes, figures 1c and d show the percentage change in global output (GDP) and in GDP per capita, respectively. Note that these are detrended values, from which the underlying exogenous trend growth in GDP (of 1.5% per year) is removed, so that we can isolate the effect of climate change and population changes. In the baseline scenario, GDP initially rises before declining after 2050. Under SRM, GDP increases further before stabilizing around 2060, remaining above the baseline trajectory for the remainder of the century, and ending at a level near twice as high as under the baseline scenario. The initial rise in both scenarios is driven by population growth, which peaks around 2080. The following decline in the baseline stems partly from climate damages (because of continuing global warming) and partly from changes in the spatial distribution of the population, as population shifts from colder to hotter parts of the globe. Under SRM, the economy instead stabilises as population-weighted temperatures remain relatively constant after an initial drop

GDP per capita, by contrast, declines rapidly throughout the period in the baseline scenario as population shifts to warmer regions and climate damages increase. Under SRM, GDP per capita also declines, though by a considerably smaller amount as global temperature stabilizes. Our model projects that global GDP per capita in 2020-2029 is 17% below 1990 levels. By the end of the century, this decline reaches 36% under the baseline scenario and 26% under SRM. But there is substantial spatial heterogeneity masked by these changes in global aggregates, just as there is for the changes in global temperature.

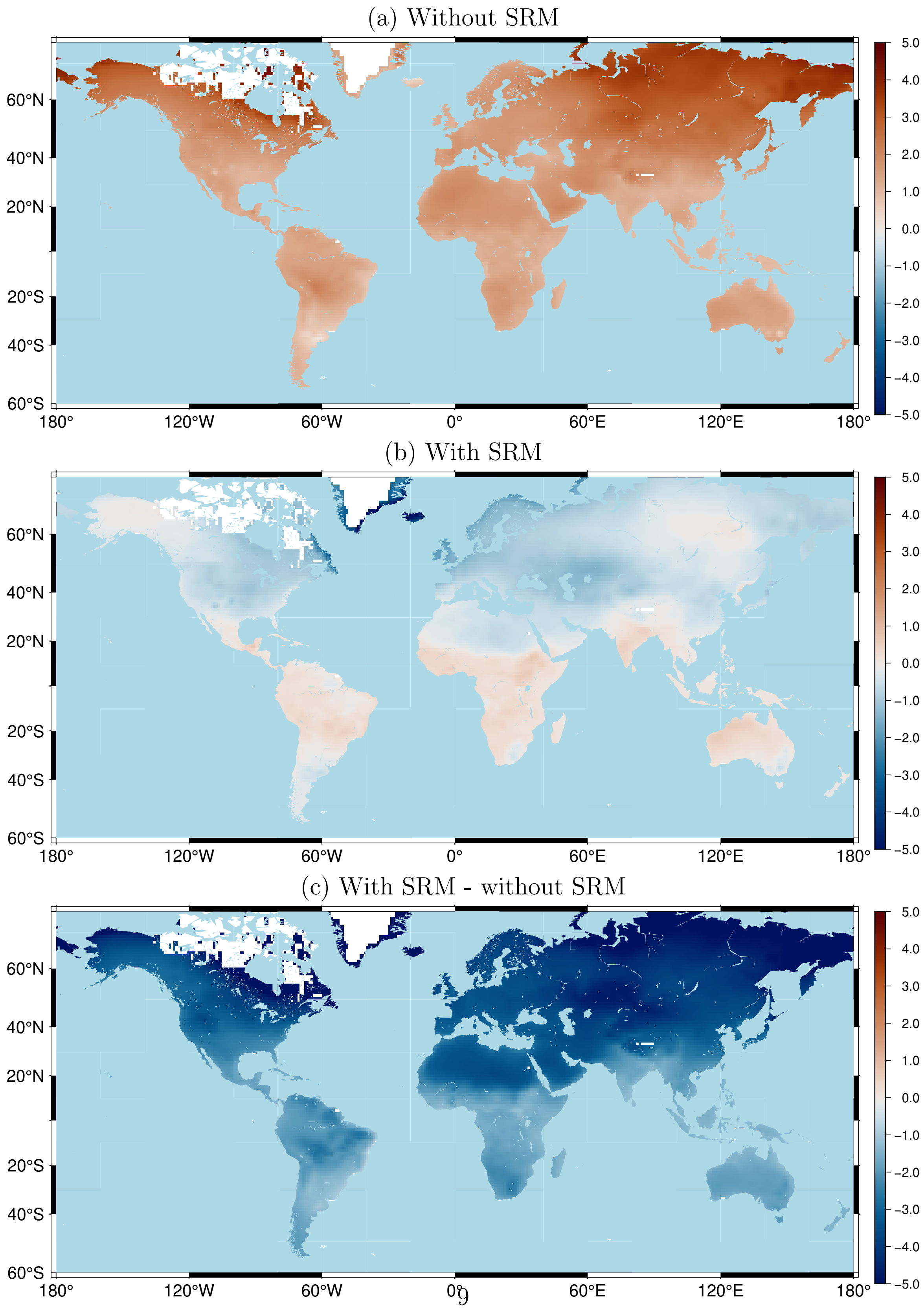

Figure 2: *Projected temperature change from 2020-2029 to 2090-2099 without SRM (a), with SRM (b) and the difference between the two (c).*

Turning to this heterogeneity, figure 3 shows the changes in regional GDP per capita from 2020-2029 to 2090-2099, corresponding to the maps showing regional temperature change. This pattern follows from the shape of the damage function relating economic productivity to regional temperature: in particular, economic productivity reaches its peak at an annual mean temperature of 12.6°C and then declines for both higher and lower temperatures following a bell-shaped curve (for details, see Krusell and Smith, 2022; Bjordal et al., 2022). Thus, regions whose temperature is lower than this optimum temperature, such as those in the high Northern latitudes, actually benefit from warming because they get closer to the optimum. Furthermore, many regions around 40-60° latitude show little effect, since these have temperatures close to the optimum, where temperature changes have the least effect on productivity (top of the bell shape). Finally, most of the Global South, where annual mean temperatures are well above 12.6°C, experience more than 10% higher GDP per capita with SRM.

These maps show the regional distribution of GDP per capita changes, but do not account for where people live. Comparing who benefits rather than where reveals a key asymmetry: although SRM produces higher GDP per capita in 59.7% of regions, these regions are home to 93.4% of the global population. Similarly, country-level changes in temperature and GDP per capita (figure 4) show that most people live in countries that experience higher GDP per capita under SRM than without it. Only a few countries see lower GDP per capita with SRM, and most of these have small and/or decreasing populations. Correspondingly, the countries with highest population growth tend to be among those that benefit the most.

We further show that it is mainly the low-income countries that benefit most from SRM implementation. Figure 5 displays the distribution of country-level end-of-century GDP per capita differences between SRM and baseline simulations, highlighting countries' initial GDP per capita and share of global GDP in 1990. The figure indicates that most high-income countries experience losses or only small benefits. Overall, these results suggest that SRM implementation reduces economic inequality.

To further investigate economic inequality, figure 6 shows the evolution of the 90th and 10th percentiles of GDP per capita, as well as their ratio with time. In 2030, we see that the 90th percentile has approximately 35 times higher GDP per capita than the 10th percentile. Without SRM this ratio increases to around 43 by the end of the century, whereas under SRM it declines slightly before going back up to the same level, indicating lower inequality relative to a world without intervention.

Both the 90th and the 10th percentiles of (detrended) GDP per capita decrease over the simulated period for both the baseline and the SRM simulation. The 90th percentile decreases from approximately $38,000 in 2030 to a minimum around the 2080s, before increasing slightly to about $30,000 by the end of the century without SRM, compared

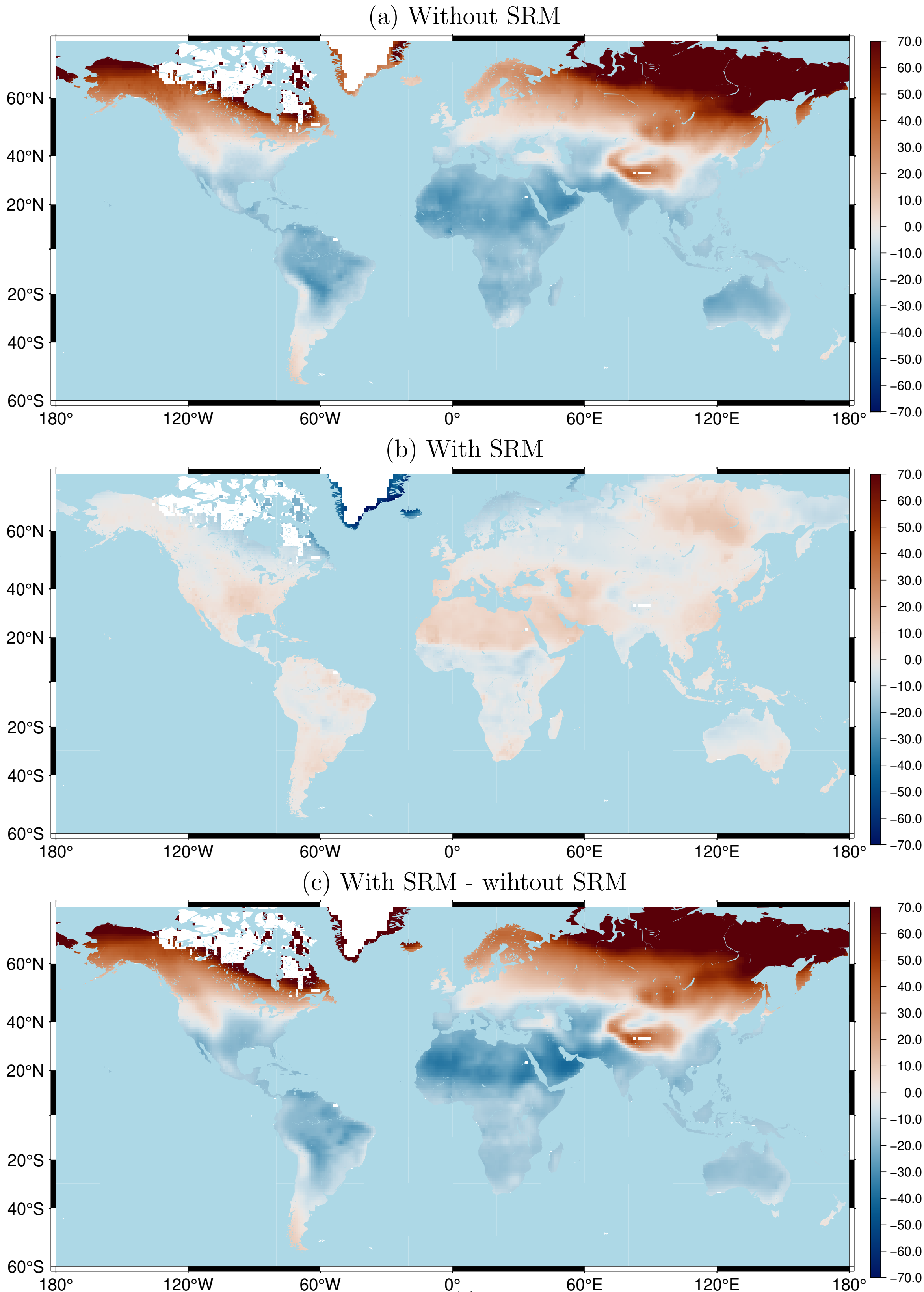

Figure 3: *Projected percentage change in GDP per capita from 2020-2029 to 2090-2099 without SRM (a), with SRM (b) and the difference between the two (c).*

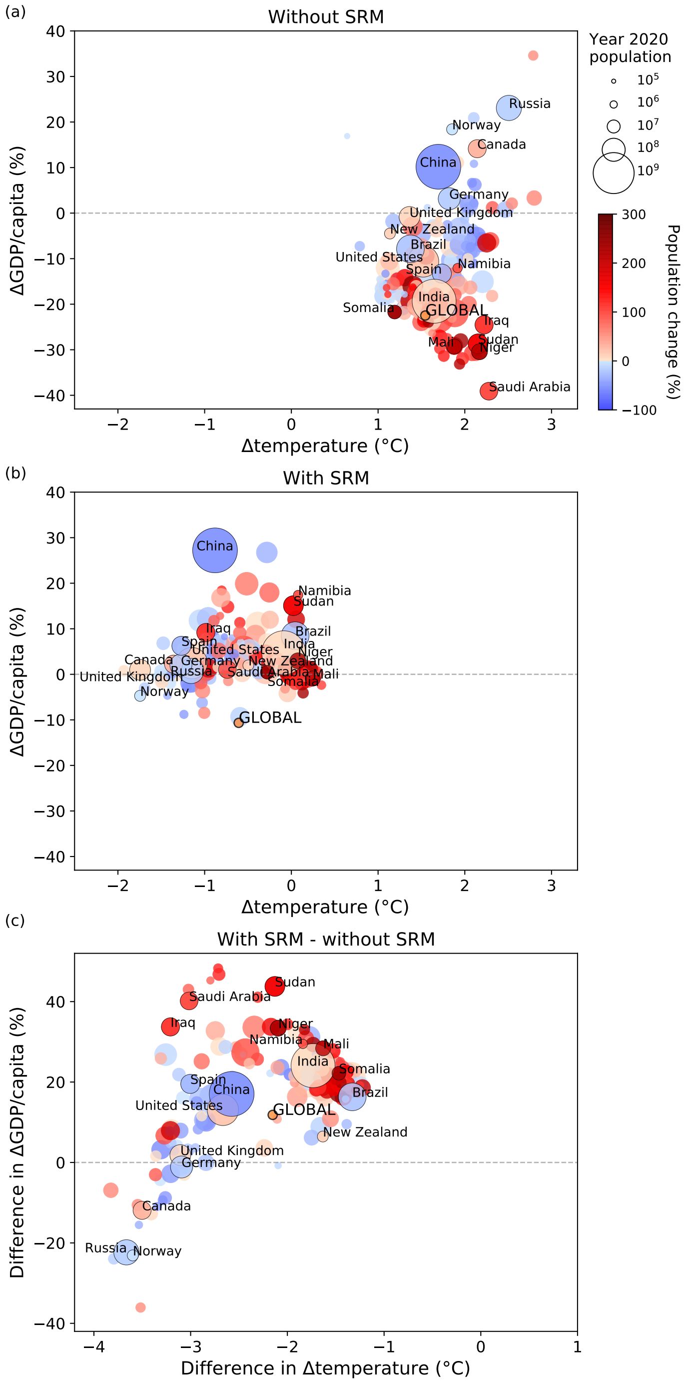

Figure 4: *Country-level temperature change and percentage change in GDP per capita at the end of the century (2090-2099) compared to the last decade before SRM (2020-2029). a) without SRM implementation, b) with SRM implementation, and c) difference between the two, i.e. difference at the end of the century between SRM implementation and the baseline without SRM. Each country has a bubble, where the size indicates the population in 2020, and the colour indicates the population-change from the last decade before SRM to the end of the century.*

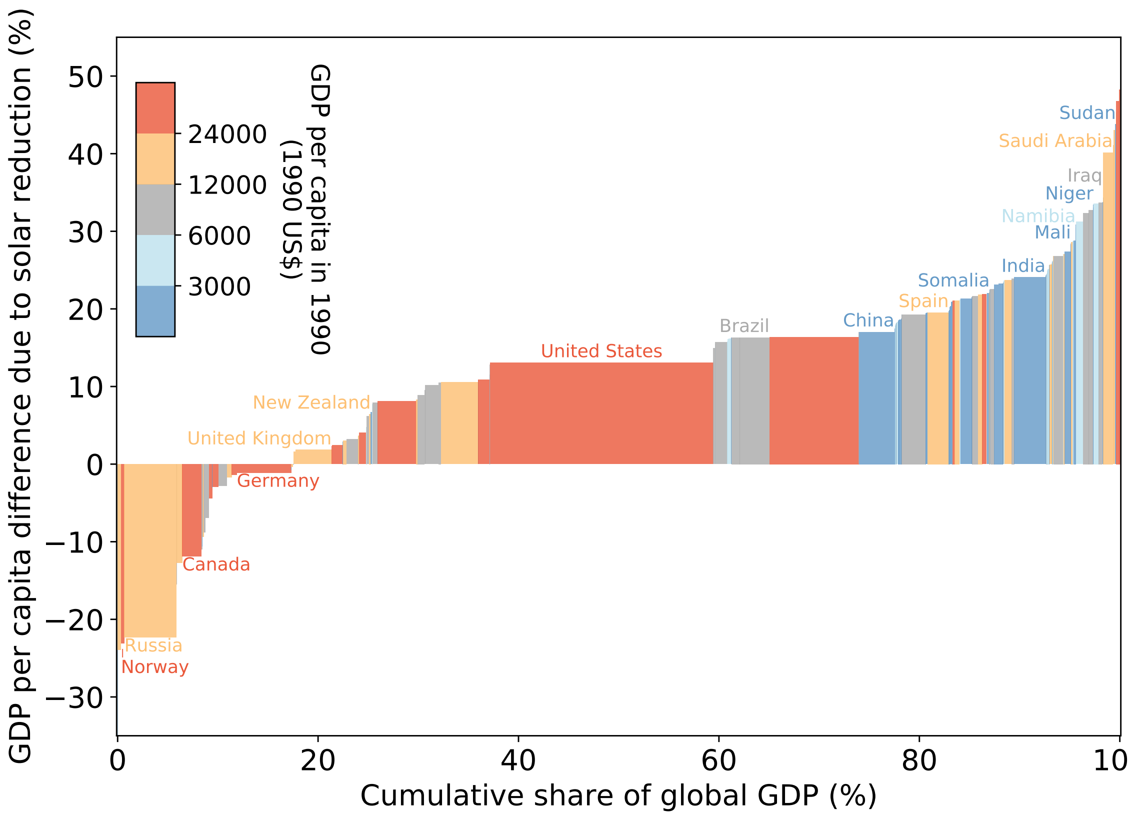

Figure 5: *Country-level percentage difference in GDP per capita change with SRM compared to baseline without SRM (same as y-axis in fig. 4c) at the end of the century (2090-2099 average). Each bar represents a country, sorted by percentage change in GDP per capita from most negative to most positive, where bar width indicates share of global GDP in 1990 and colour indicates GDP per capita in 1990.*

to roughly \$33,000 with SRM. Meanwhile, the 10th percentile decreases linearly , from approximately \$1,080 in 2030 to approximately \$750 without SRM and to \$950 with SRM by the end of the century. The rising 90:10 ratio in the baseline scenario is therefore driven by relatively larger proportional losses at the lower end of the distribution rather than higher GDP per capita at the top.

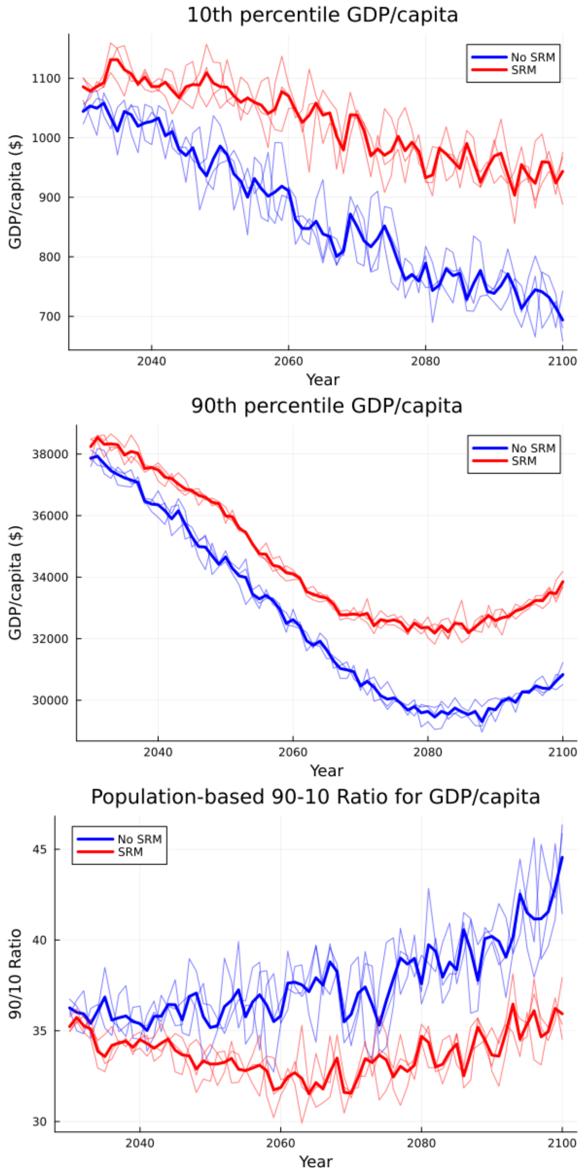

Figure 6: *10th percentile (a) and 90th percentile (b) of GDP per capita, as well as the 90-10 ratio (c). Blue is the baseline scenario and red is the SRM scenario.*

4 Discussion

Previous studies have also noted higher emissions under SRM implementation (e.g. Heutel et al., 2018; Belaia et al., 2021). SRM may also affect mitigation policies, either by providing more resources for mitigation thanks to smaller climate damages or by diminishing the sense of urgency to mitigate emissions. (Ricke and Harding, 2023). Assessing optimal mitigation strategies and how SRM influences them is beyond the scope of our study. Instead, we focus on quantifying how SRM changes economic activity and consequently emissions.

However, it is important to note that the increase in emissions that we report under SRM is specific to our experimental setup. We assume a decarbonisation where emissions will decrease relatively rapidly from mid-century regardless of whether SRM is implemented or not. The increase in emissions would therefore likely be higher in a scenario with slower decarbonisation.

It is also important to note that in our model, the economy is affected by climate only through regional annual temperatures. Impacts such as changes to the hydrological cycle, extreme events, ocean acidification, and CO_2 fertilization are only indirectly included here but could potentially be important for assessing the economic impacts of SRM and their distribution.

Our finding of reduced inequality under SRM is consistent with the work of Harding et al. (2020), which incorporates the effect of precipitation on the economy in addition to the effect of temperature. However, their framework differs substantially from ours. They rely on exogenous climate projections from climate models, meaning that no feedback between the economy and the climate system is possible, and they model climate impacts on economic growth rather than on output levels. The fact that two structurally distinct modeling approaches yield qualitatively similar implications for inequality strengthens confidence in the robustness of this finding. However, several potentially important climate-economy links are still missing from our framework, such as extreme event or precipitation changes, suggesting that further work is required to assess the full effect of SRM on economic inequality.

One of the strengths of our study is the coupled climate–economy model that we use to investigate the effects of SRM. Rather than rely on simple climate models, like most IAMs, or restrict ourselves to climate model data, we use instead NorESM2–DIAM, which has a sophisticated climate response generated by a rich Earth System Model, while also allowing for two-way interaction between the climate and the economy. Consequently, it would be feasible to allow additional climate variables beyond temperature to affect the economy, as their behavior is already captured by NorESM2. We plan to explore these avenues in future research.

Furthermore, although dimming the sun has been used extensively as an approximation of SRM and such experiments can still inform many outstanding questions related to SRM and its implications, it is not a perfect proxy for actual SRM methods, such as stratospheric aerosol injections (SAI) (Visioni et al., 2021; Irvine et al., 2016; Niemeier et al., 2013). Because NorESM2–DIAM incorporates an Earth System Model as one of its components, it would be feasible to study the effects of more realistic SRM methods like SAI, and we plan to explore this too in future research.

5 Conclusion

We find that the implementation of SRM yields an economic benefit for most countries, while at the same time reducing economic inequality. However, these economic consequences come at the cost of higher emissions. We expect that different policymakers will weigh each of these factors differently and that their views on potential future SRM implementation will also be strongly influenced by their regional perspectives. Specifically, our findings indicate that the developing countries of the Global South would generally have much greater incentive to support implementation of SRM than the developed countries of the Global North. However, it is important to note that, while we are confident that the qualitative aspects of our findings are robust, our quantitative findings come with large uncertainties and caveats. Our idealised experiment lacks several potentially important factors, such as realistic SRM deployment, additional climate-economy interactions (such as extreme events and their associated costs), and the economic effects of enhanced CO_2 levels unrelated to temperature (such as ocean acidification). These extensions are certainly feasible within our modeling framework and will represent important directions for future research to better assess the economic and environmental trade-offs associated with SRM.

Code and data availability The NorESM2 source code used in this study is archived as *release-noresm2.0.9* on Zenodo(https://doi.org/10.5281/zenodo.17865358; Seland et al., 2025). The NorESM2 restart files required to run the simulations are available on Zenodo (https://doi.org/10.5281/zenodo.17856602; Bjordal, 2025*c*), and the additional model input files not generated by our own scripts are likewise provided via Zenodo (https://doi.org/10.5281/zenodo.17865023; NorESM Climate Modeling Consortium,, 2025). Further information on installing and configuring NorESM2 can be found in The NorESM developers group, (2020).

The complete NorESM2-DIAM codebase—comprising the standalone DIAM model, coupling scripts, and input file generation scripts for the baseline simulation is archived as *release-v1.0.2* on Zenodo (https://doi.org/10.5281/zenodo.17986166; Bjordal et al., 2025). The codebase specific to this paper—comprising of scripts for input data, adjusted scripts to run SRM experiment in NorESM2-DIAM, as well as scripts for analysing and plotting the output—is archived as *release-v1.0.0* on Zenodo (https://doi.org/10.5281/zenodo.19494362; Bjordal, Cornec, van Dijk, Smith and Storelvmo, 2026).

Finally, the full output from the simulations presented here are available from the Norwegian Research Infrastructure Services (NIRD) Research Data Archive (RDA):

- Baseline 1: https://doi.org/10.11582/2025.90V981QK (Bjordal, 2025*a*) and https://doi.org/10.11582/2025.31NEY5Y8 (Bjordal, 2025*b*)
- Baseline 2: https://doi.org/10.11582/2026.8P3MR4B3 (Bjordal, 2026*a*)
- Baseline 3: https://doi.org/10.11582/2026.KIEN66G0 (Bjordal, 2026*b*)
- SRM 1: https://doi.org/10.11582/2026.NGZR041O (Bjordal, 2026*c*)
- SRM 2: https://doi.org/10.11582/2026.5LOUIGPD (Bjordal, 2026*d*)
- SRM 3: https://doi.org/10.11582/2026.Q2UMWAD7 (Bjordal, 2026*e*)

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Author contributions All authors helped design the study. JB developed the

SRM emulator and ran the fully coupled model. HC adjusted and ran the standalone version of the model. JB, ED and HC prepared and analysed the model output, and all authors helped interpret the results. AAS contributed to the economic components of the study and ensured the accuracy of their presentation in the manuscript. TS contributed to the experimental design and interpretation of the results. JB and HC prepared the figures. JB drafted the original manuscript, and all authors reviewed and approved the final version.

Conflict of interest The authors declare no competing interests.

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