

The economic cost of termination shock

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Abstract

Termination shock is widely regarded as one of the worst risk surrounding geoengineering deployment. However, a quantification of its economic impacts is lacking. Here, we use state of the art empirical impact functions and climate-economic modelling in a first attempt to estimate the costs of sudden and unplanned termination of geoengineering. We find that results are uncertain and depend on the imagined functional form through which the climate affect the economy, but we foresee potentially catastrophic consequences, with the potential of a termination event to cause a global recession and a 50% loss in total GDP.

Introduction

Given poor emission reductions and high climate impacts, the interest around SAI is increasing. Because of the short lifetime of sulfur compounds in the stratosphere, if the SAI is suddenly terminated the global climate would rebound to the level of climate change implied by greenhouse gas concentrations in a matter of years. This event, known as termination shock, is often cited as one of the main risks associated to solar geoengineering, as well as a core reason why SAI and greenhouse gas emission reductions cannot be considered substitutes. While studies exist that analyze the physical and biodiversity consequences of a termination shock even under different background conditions, no attempt has been made to calculate its economic implications. Empirical relationships between variation in economic output and local climates have been attempted at the national and subnational level. This literature consistently finds a non-linear relationship between economic growth and local climate variables, but estimates differ in the functional form, the magnitude and the distribution of impacts, and their robustness.

For example, (Burke et al., 2015) assumes that economic growth are associated with temperature *levels*, finding the existence of a concave relationship between average temperature and growth, with a uniform local temperature at around 12°C. Not only temperature but also precipitation matter for economic growth, if the same approach is explored but with subnational (Damania et al., 2019) or decile level (Palagi et al., 2022) data. A complementary stream of literature focuses on the relationship between economic growth and the yearly *variation* of temperature and precipitation, finding significant effects with subnational data (Kalkuhl and Wenz, 2020; Kotz et al., 2022). Finally, (Mérel and Gammans, 2021; Polonik et al., 2025) consider an hybrid approach, highlighting an adaptation mechanism where the deviation of yearly realization (*weather*) from long-run average of past outcomes (*climate*) effect economic production.

While these alternative approaches overall concur that global climate change significantly hinders economic growth, albeit with different implications at the regional level, they assume radically different channels through which climate change negatively affect economic growth, with very different implications over the persistency and magnitude of its impacts. For example, Burke-like specifications are insensitive to the rate of change in temperature or precipitation but the growth effect of a permanent change in climate persists forever. Specification against the interannual differences in temperature or against the long-term running mean, on the contrary, are sensitive to the rate of change and predict no long-lasting economic impacts from a stable climate, but only from transition states.

Due to slow-moving temperature effect of greenhouse gases that lead to a predictable rate of warming under current and future climate change, these differences are less relevant in “traditional” climate change analysis. However, they become first order considerations in case of a termination shock as it breaks apart the predictable relationship between rate and speed of change.

Here, we run multiple empirical impact functions in a country-level integrated assessment models augmented with a spatially explicit and dynamic emulator of SAI applied to several scenarios of termination to quantify and unveil the determinants the economic impacts of sudden SAI termination. We find that the economic impacts of termination are linearly proportional to the amount of warming masked with SAI before termination, and that in most of the scenarios tested a termination event causes a global economic recession. However, in most impact specifications tested, global output loss converges to that of the counterfactual scenario where SAI is never implemented – and terminated. We finally discuss the implications and limitations of our approach, highlighting direction for future improvements.

Model

We use the RICE50x model, a near country-level integrated assessment with multiple greenhouse gases and a realistic dynamic and regional representation of climate dynamics. The model is hard-linked with a dynamic global emulator of climate change (FAIR v1.3), a linear downscaling of global temperature change from the CMIP6 ensemble, and an emulator of multi-injection latitude stratospheric aerosol injection trained from (Visioni et al., 2023) and described in (Andreoni et al., 2025).

The previous version of the model assumed instantaneous temperature changes following the SAI injection, a defensible assumption during a smooth ramp-up or phase-down of SAI described in (Andreoni et al., 2025). However, when evaluating the effects of a termination shock a certain inertia, mainly given by the response of the oceans, must be considered (Farley et al., 2025). Therefore, we introduce a dynamical representation of global and regional SAI-driven temperature and precipitation changes. Given a certain amount of SAI injected by country n to a latitude z $SAI_{n,z,t}$, a total latitudinal injection $SAI_{z,t} = \sum_n SAI_{n,z,t}$, a global injection $SAI_t = \sum_z SAI_{z,t}$, and the matrix coefficients of the emulator $\varepsilon_{n,z,T}$, $\varepsilon_{n,z,P}$, and $\varepsilon_{n,z,T}$ for global temperature, the variation of climate variables is expressed as:

$$\begin{aligned}\Delta T_{SAI_{n,t}} &= \Delta T_{SAI_{n,t-1}} * e^{-\frac{1}{\tau_{SAI,T}}} + \sum_{z=-60}^{+60} \varepsilon_{n,z,T} * SAI_{z,t} \\ \Delta T_{SAI_t} &= \Delta T_{SAI_{t-1}} * e^{-\frac{1}{\tau_{SAI,T}}} + \sum_{z=-60}^{+60} \varepsilon_{z,T} * SAI_{z,t} \\ \Delta P_{SAI_{n,t}} &= \Delta P_{SAI_{n,t-1}} * e^{-\frac{1}{\tau_{SAI,P}}} + \sum_{z=-60}^{+60} \varepsilon_{n,z,P} * SAI_{z,t}\end{aligned}$$

In an analogous representation to the FAIR temperature-to-forcing response. $\tau_{SAI,T}$ and $\tau_{SAI,P}$ represent the thermal response timescales for SRM and are set at 4.07 years for temperature compatibly with the upper ocean timescale response in FAIR.

Impact specification

We estimate and consider four different models that empirically estimate the relationship between growth and climate. We leverage subnational data from the last release of the DOSE database (Wenz et al., 2023) from 1990 to 2023 and corresponding subnational temperature and precipitation data from (Gortan et al., 2024). All specifications control for the same country and year fixed effects as well as country-time linear and quadratic trends, and where X are the two relevant climate variables (T and P):

$$g = h(X) + f_n + f_t + f_n(t, t^2) + \varepsilon$$

In the BHM specification,

$$h_{BHM}(X) = X_t + X_t^2$$

This specification implies that an absolute maximum that maximizes economic productivity exists, common to all countries and regions. Therefore, a deviation from its current climate can be beneficial or detrimental for a country depending on whether it brings them closer or further away from the optimum climate. Furthermore, because no first order differences are considered, such a specification implies no adaptation to future climate change, as a permanent variation in its climate causes a permanent effect on the *growth* path of a country.

In the ADA specification, the channel for climate impacts is the deviation of each year's realization of the climate variable from the historical climate:

$$h_{ADA}(X) = \left(\frac{X_t - \bar{X}_w}{s(X_w)} \right)^2 + \frac{X_t - \bar{X}_w}{s(X_w)}$$

Where $\bar{X}_w = \frac{1}{w} * \sum_{t^*=t-1-w}^{t-1} X_{t^*}$ is the mean climate and $s(X_w) =$

$\sqrt{\frac{1}{w-1} \sum_{t^*=t-1-w}^{t-1} (X_{t^*} - \bar{X}_w)^2}$ is the standard deviation of the climate in the past w years. In this specification, originally developed for agricultural productivity, the mismatch between expected and realized weather produces economic impacts. Unlike BHM, it therefore assumes that each economy is adapted to their own climate, and the same absolute deviation causes larger impacts for countries with more predictable climates. Furthermore, because the deviation is expressed against the moving average of the past climate, a permanent variation in its climate causes a transitory effect on the growth path of a country, the permanence of which depends on the length of the window w .

We also consider a BHM+ADA specification where the two terms are considered jointly:

$$h_{ADA+BHM}(X) = h_{BHM}(X) + h_{ADA}(X)$$

Finally, in the LAG specification, first order differences between yearly realizations of the climate variables are considered, including several lags to estimate the time persistency of a shock. An interaction term with the average climate is also considered, to account for the fact that the same climate shock might have different effects in different climates (e.g. hot versus cold countries):

$$h_{LAG}(X) = (\overline{X_w} + 1) * \sum_{n=0}^{10} X_{t-n} - X_{t-n-1}$$

Like the *ada* specification, this formulation implies that permanent climate shocks cause transient deviations of the growth paths, but it allows us to determine (instead of assuming) the permanence of impacts by analyzing the significance of subsequent first order difference lags. Like the *bhm* specification it also considers the possibility, through the interaction term with the average climate, that the same shock causes opposite growth effects in different countries depending on their past average climate.

As we are ultimately interested in evaluating the effects of a termination shock, i.e. a sustained, high climate velocity event, it is necessary to evaluate if such an event is out of sample relative to the training dataset. While no such event existed in recent human history, temporary and local warming driven by interannual variability can provide a proxy, similarly to how interannual variability is considered a proxy to long-term global warming in climate econometrics literature. Figure 1 shows the climate velocity, calculated as the 5 year best linear fit, for each region-year pair (black density plot). The training dataset includes a large number of data points where the local rate of warming is temporarily comparable and even exceeding that of a termination shock, albeit the comparison is not immediate as the projection results are at the country-level (see Figure xx for the future scenario estimate of the country-level climate velocity during termination shock).

However, the comparison is not straightforward, first because short-term warming trends identified in the historical dataset are local while a termination shock is global, second because the climate velocity is extrapolated from interannual variability, but it is not necessarily sustained across multiple years. Therefore, we isolate warming runs where, in a region, each year is warmer than the precedent for at least 3 (dark blue) or 5 (light blue) years. While these warming runs constitute a fraction of the total dataset (around 4% for 3 years run and 0.3% for 5 year runs), it shows that sustained local sustained warming windows are present. As for the global nature of shocks, Figure 1b plots the beginning year of the warming run windows, showing that these warming runs tend to be correlated at the global level, and linked to large volcanic eruption. It should be noted, however, that not only volcanic eruption, but also environmental policy – especially reduction of SO_x tropospheric pollution in the 70s in OECD countries and early 2000s in China – might have caused significant local warming in those regions. As, unlike volcanic eruption, pollution policy is endogenous to economic output, this might confound the contribution of local termination events in the impact functions, especially those explicitly depending on the rate of warming.

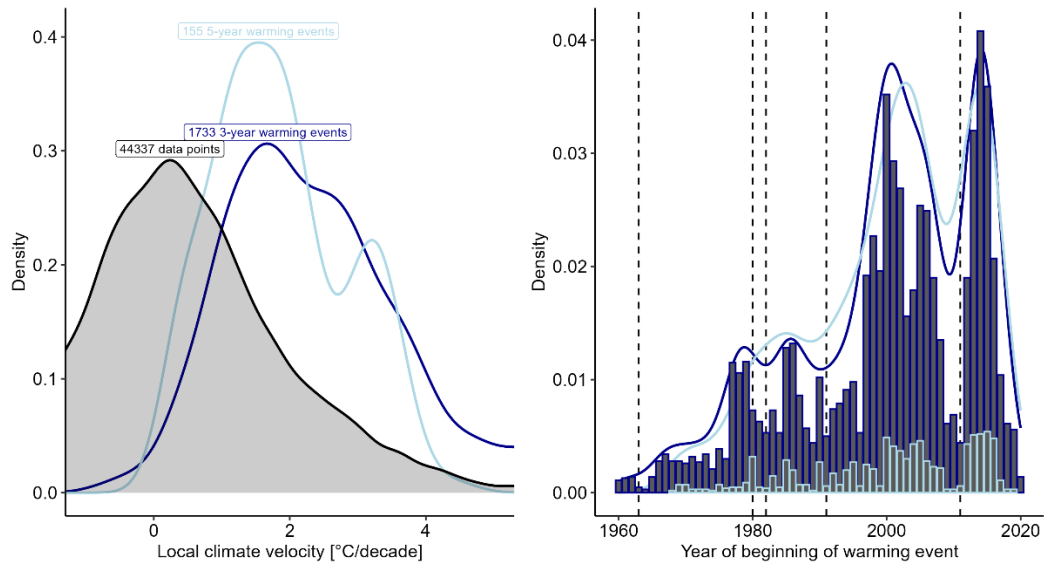


Figure 1: density plot of the climate velocity distribution in the historical climate (ERA5) dataset. Only region-year pairs where GDP data are also available are considered. The climate velocity is calculated as the best linear fit of a 5 year bubble centered around each year. Light and dark blue density plot identify the maximum climate velocity occurring over group of years where temperatures increased in the region for at least 3 (dark blue) and 5 (light blue years).

The results for the specifications using population weighted era5 subnational data and a time window of 10 years for the rolling average of past climate is shown in the table below. For ADA and LAG, we also test a 20 years moving window for the calculation of the past average climate. For all specification, we consider both annual average temperature and precipitation as relevant climatic variables, evaluated with the same functional form. However, precipitation coefficients are omitted in the table as they are never found to be statistically significant. Note that, in the BHM+ADA specification, only the quadratic deviation term is found to be statistically significant. Therefore, we only consider the three specification separately.

	ADA	BHM	BHM+ADA	LAG
dev_TM_2	-0.002*		-0.002*	
	(0.001)		(0.001)	
dev_TM	0.002		0.006	
	(0.003)		(0.012)	
TM		0.016*	0.006	

	ADA	BHM	BHM+ADA	LAG
		(0.007)	(0.018)	
TM_2		-0.001+	-0.001	
		(0.000)	(0.000)	
dTM				0.017*
				(0.007)
ldTM				0.026+
				(0.015)
l2dTM				0.028
				(0.017)
l3dTM				0.032
				(0.021)
l4dTM				0.037+
				(0.019)
l5dTM				0.039+
				(0.020)
l6dTM				0.048*
				(0.021)
l7dTM				0.036*
				(0.016)
l8dTM				0.016
				(0.014)
l9dTM				0.011
				(0.015)
l10dTM				-0.016
				(0.013)

	ADA	BHM	BHM+ADA	LAG
mean_TM × dTM				-0.001* (0.001)
mean_TM × l2dTM				-0.002* (0.001)
mean_TM × l2dTM				-0.002+ (0.001)
mean_TM × l3dTM				-0.002* (0.001)
mean_TM × l4dTM				-0.002* (0.001)
mean_TM × l5dTM				-0.003+ (0.001)
mean_TM × l6dTM				-0.004* (0.001)
mean_TM × l7dTM				-0.003** (0.001)
mean_TM × l8dTM				-0.002+ (0.001)
mean_TM × l9dTM				-0.001 (0.001)
mean_TM × l10dTM				0.000 (0.001)
Num.Obs.	42789	42789	42789	42789
R2	0.280	0.279	0.281	0.289
R2 Adj.	0.191	0.190	0.192	0.201

	ADA	BHM	BHM+ADA	LAG
R2 Within	0.002	0.001	0.003	0.014
R2 Within Adj.	0.001	0.001	0.003	0.013
AIC	-27821.8	-27795.6	-27865.4	-28300.7
BIC	12907.8	12934.1	12898.9	12775.5
RMSE	0.16	0.16	0.16	0.16
Std.Errors	by: GID_0	by: GID_0	by: GID_0	by: GID_0
FE: GID_1	X	X	X	X
FE: year	X	X	X	X

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

As in comparable literature (Burke et al., 2015), these specification are translated into impact function and implemented in the RICE50x model by recomputing the counterfactual GDP per capita given the per capita baseline growth rate $g_{n,t}$ and the estimated effect of climate variables $\Delta g_{n,t}$:

$$yd_{n,t} = yd_{n,t-1} * (1 + g_{n,t} + \Delta g_{n,t})$$

The difference in growth is given by the growth implied by future scenario climatic conditions X_j minus the growth effect of current climatic conditions $X_{j,base}$:

$$\Delta g_{n,t} = h_i \left(X_j(E_{RCP}, S) \right) - h_i(X_{j,base})$$

For all specifications h_i , we consider only terms significant at the 90% level using country-clustered p-values. A more detailed and general description of the impact functions and how they affect economic output in RICE50x can be found in (Andreoni et al., 2025; Gazzotti, 2022; Paolo Gazzotti et al., 2021).

Scenario design

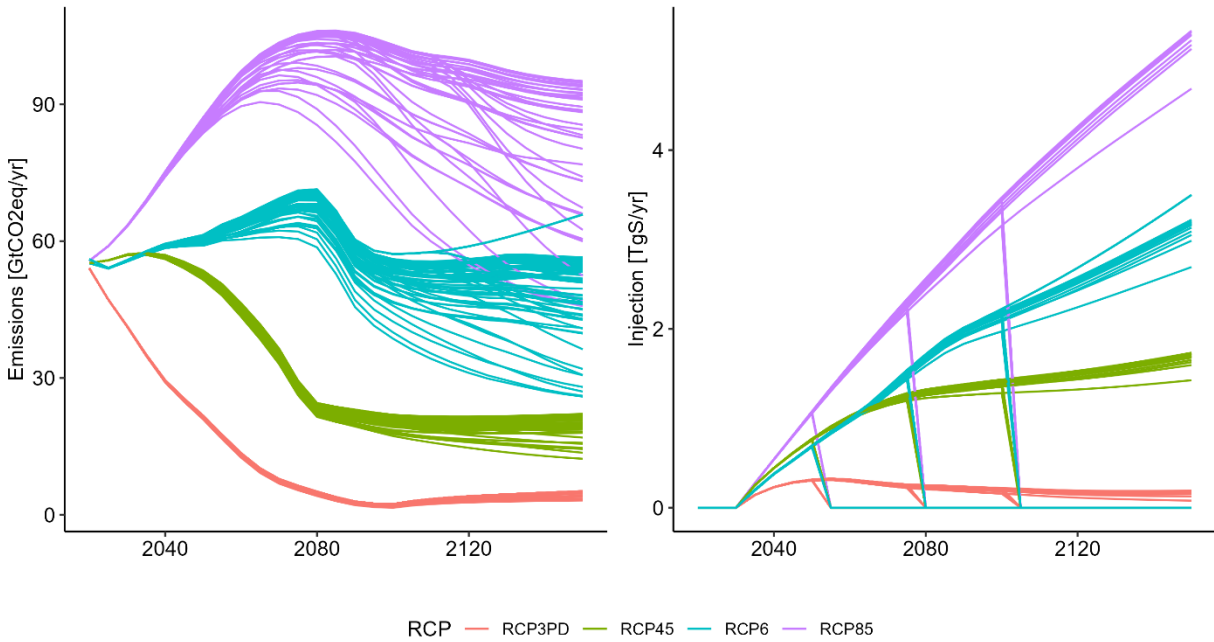


Figure 2: Emissions and SAI across scenarios and time.

To test the impacts of a termination shock, we consider a three-dimensional scenario matrix and a double counterfactual. First, we vary background socio-economic, emission and climate outcomes by using a combination of SSP-RCP data from (Gütschow et al., 2021). We consider a combination of SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP6.0 and SSP5-RCP8.5 (Figure 1, left). For each of these background emission scenarios, we consider an SAI strategy aimed at limiting global temperature increase at 1.5°C above pre-industrial levels (Figure 1, right) through symmetric tropical injection of SO₂ with an assumed efficacy of 0.5 °C of cooling per TgS injected per year, linearly declining at a rate of 1.17% per additional global TgS injected. While it should be noted that this efficacy is on the upper hand of the available estimates (Yu et al., 2026), it is uninfluential in our results as we only consider climate impacts with a pre-determined scenario design. The 1.5°C and baseline scenarios constitute the two counterfactuals of the analysis. In each SSP-RCP scenario, the SAI strategy is terminated at three different years (2050, 2075, 2100). Finally, we run each of these simulations with the three impact specifications. For each impact specifications, we consider the 33-66th percentile of the statistically significant coefficients (grouping standard errors at the country level) as well as different adaptation windows (5, 10 or 20 years).

The global climate outcomes of the scenario matrix are visualized in Figure 2. Note that the temperature and emission trajectory of the baseline scenarios is different across simulations because of the climate impact functions dampen to a different extent global economic activity and thus global emissions and temperatures. After the SAI termination event, global temperatures revert to baseline conditions after 10-20 years depending on the amount of cooling previously masked with SAI.

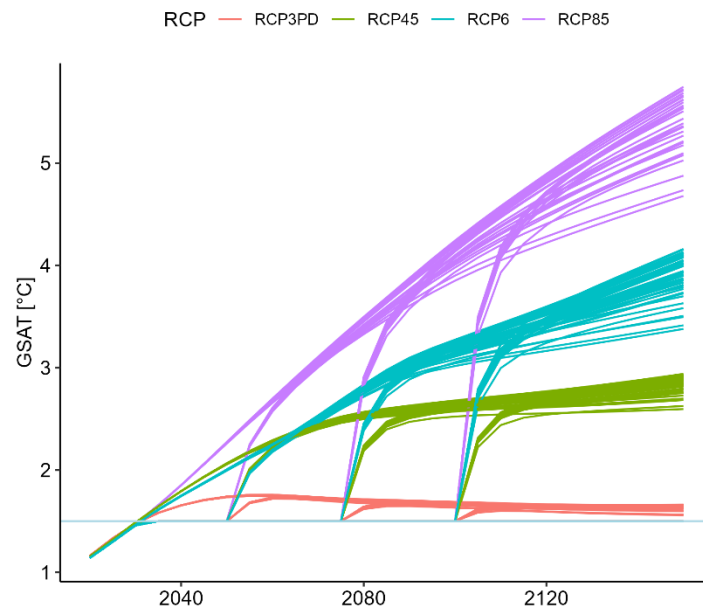


Figure 3: Global Surface Temperature increase across scenarios and time.

Figure 3 plots the maximum climate velocity, or rate of warming, for each region and scenario, compared to the climate velocity at the subnational level in the historical data used to estimate the impact functions. The climate velocity is expressed in degrees Celsius per decade and, for the historical data, it is calculated estimating the best linear fit of the 5-year average rate of warming/cooling around each region-year pair. Relative to Figure 1,

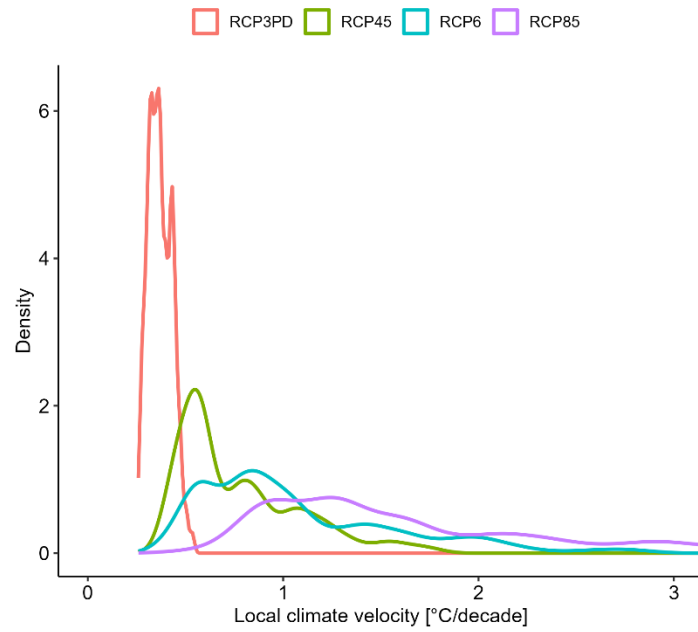


Figure 4: climate velocity (°C/decade) across termination scenarios grouped by RCP (color).

The economic impact of termination

We aim to analyze the economic impacts of an SAI termination event across background conditions, year of termination, and assumed economic impacts of climate change. Figure 3 shows the effects on GDP and GDP growth of termination events across scenarios, grouped by impact specification.

The top row shows the variation of global GDP *growth* due to a termination event. Before the termination event, most scenarios have a higher GDP growth rate as SAI stabilizes global temperature to 1.5°C. After the termination event, however, all impact specifications show a slow or reversal in growth, with losses touching 5 to 10% of global GDP per year in worst-case scenarios. Specifications where the *rate* of warming determines global impacts (ADA and LAG) foresee significantly higher losses than the BHM specification, where climate change impacts are merely determined by the level of climatic conditions.

To evaluate the risks of termination shock across scenarios with different background emissions and assumed impacts, however, growth rates are an insufficient metric. Over the long run, what matters is the GDP loss in each termination scenario, and in particular the value relative to the baseline counterfactual. The bottom of Figure 3 plots the percentage of the baseline GDP loss recovered in the termination scenario, normalized by the gains of maintaining global temperature to 1.5°C without termination ($\frac{Y_{BASE} - Y_{TERM}}{Y_{NO TERM} - Y_{BASE}}$ %), where Y_i is global GDP in a given scenario). While values above a 100% don't necessarily imply that the risks outweigh the benefit (as the likelihood of the termination event at a given time is impossible to determine but is certainly below 1) and vice versa, this metric allows to compare the risk of termination $Y_{BASE} - Y_{TERM}$ against the benefits of keeping temperature stable to 1.5°C through geoengineering $Y_{NO TERM} - Y_{BASE}$.

Unlike for growth rate, different impact specifications produce qualitatively different results for this metric. In the BHM specification scenarios (bottom left of Figure 3), global GDP loss after half a century from a termination event at most convergences to that of the respective baseline scenario, and in some cases only 50% of the impacts are recovered in this time horizon. This would imply that, at worst, global impacts after a termination shock would be equal or lower than the case where the SAI is never implemented in the first place, consistently facing unmitigated impacts from warming. This counterintuitive behavior is explained by the combination of two factors: first, the BHM impact specification does not depend on the rate of change of climate variables, but their levels. Second (and related), BHM impacts persist indefinitely as long as the level of the climate variable is different to their historical level. Because of this, the gains of avoided the warming before the termination event are large, and the loss in GDP growth due to termination are not worse

than those reached with the same level of global temperature but slower warming. In other words, BHM-like impacts at a given time are proportional to the *integral* of past warming. As a result, the benefit of decades of avoided impacts before termination outweigh the cost of the termination shock. In the LAG specification, instead, global GDP loss rebounds to or slightly above the baseline scenario in 10 to 20 years, because the specification is linearly sensitive to the rate of warming, meaning that the same amount of warming in one year or two causes the same aggregate effect. The overall effect on growth rates is higher than the other specifications because LAG foresees the higher sensitivity of GDP from climate change variations. Finally, in the ADA specification global GDP loss can reach levels well above (or below) those of the corresponding baseline scenario, depending on the intensity of the termination event. This is because this is the only specification containing a quadratic term depending on the rate of warming, meaning that larger warming rate cause proportionally higher growth impacts.

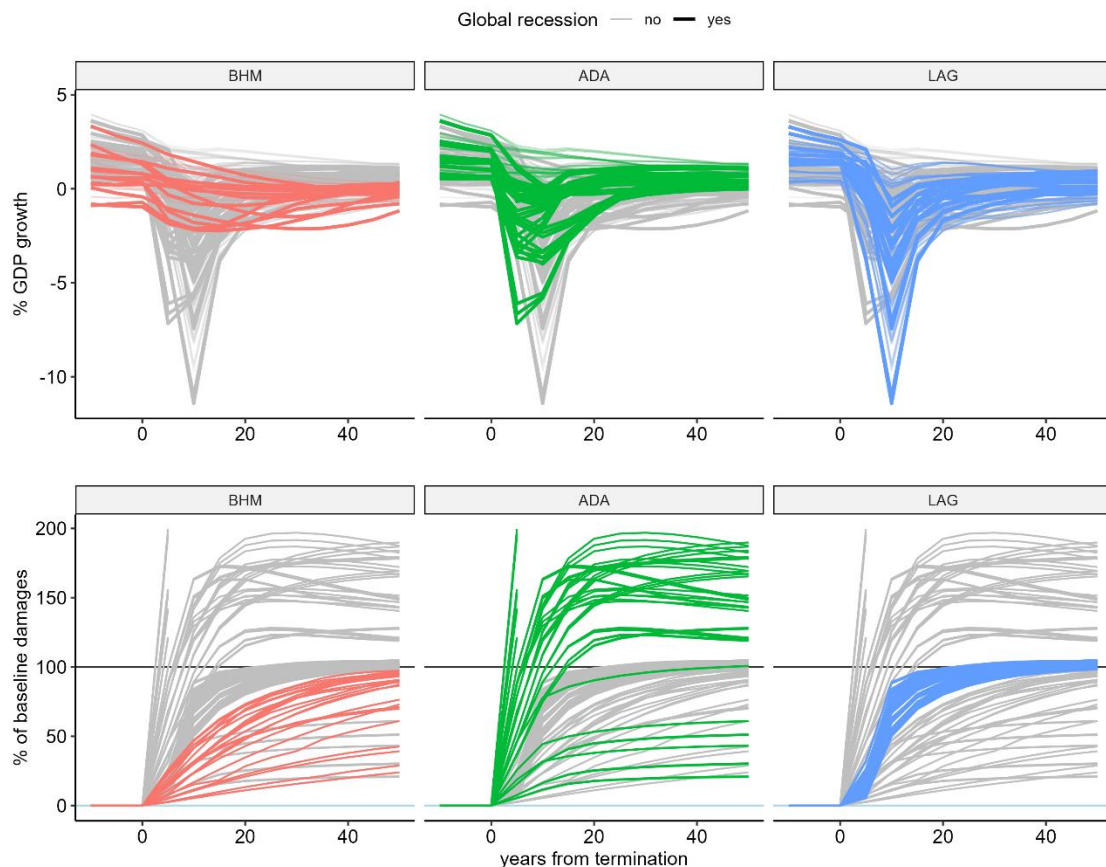


Figure 5: Economic impacts of termination shock. Top: GDP growth relative before and after the termination event. Bottom: total GDP loss before and after the termination, relative to the baseline event and normalized by the gains of maintaining 1.5°C through SAI. Expressed in % terms and capped at 200%.

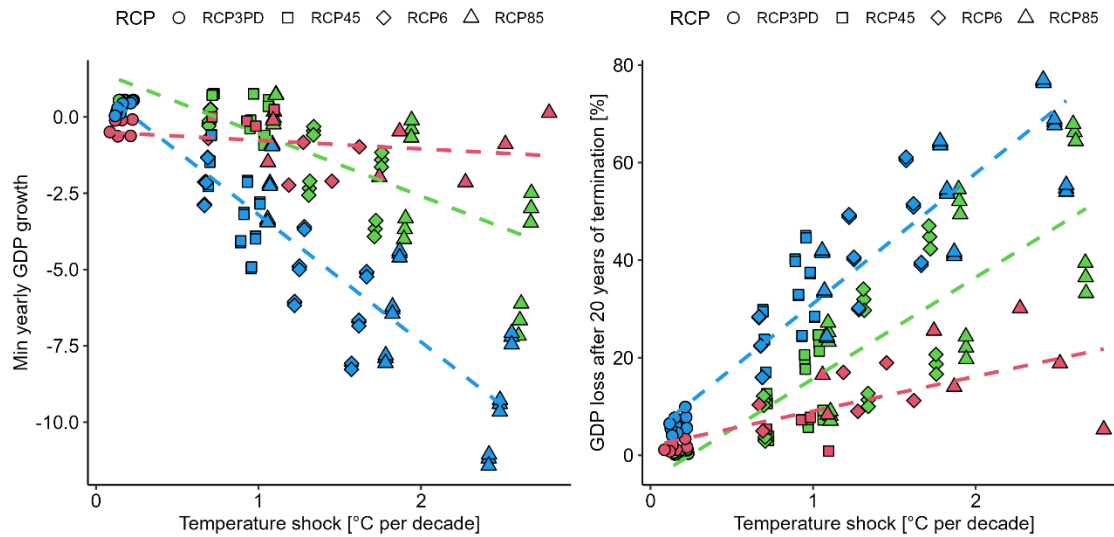


Figure 6: Determinants of termination shock. Left, minimum global GDP growth (negative values indicate global recessions) in the years following a termination shock (y axis) against the size of the temperature shock (x-axis). Right, GDP loss relative to the 1.5°C counterfactual without termination after 20 years from the termination event. Color represent different impact functions specifications, while shapes different background emissions (RCPs).

Figure 6 analyzes the determinants of GDP growth and total GDP loss. Both the dip in GDP growth (left) and GDP loss (right) after 20 years from the termination event is directly proportional to the size of the temperature shock following the termination event, with the LAG impact function showing higher impacts and higher sensitivity to the size of the shock. The BHM impact function shows lower impacts and less sensitivity of the growth rates to the size of the shock. Under scenarios with low underlying forcing, the shock is in most cases insufficient to cause a global depression but can still produce long-term economic losses of up to 10% the counterfactual GDP where SAI is never terminated.

For a global temperature shock amounting to around 1°C in a decade, compatible with an end-of-century use of SAI to keep temperatures under 1.5°C under current projections for future emissions and climate sensitivity, economic losses can amount from as low as a few percentage points to half of the counterfactual GDP, with lowest growth rates around termination ranging from positive to a 5% global recession.

Conclusions

In this paper, we showcased how empirical impact function can be used to analyze the economic impacts of a termination shock from geoengineering. We identified robust results across specifications, primarily the fact that economic impacts are directly proportional to the amount of warming masked at the moment of termination and that a termination event under a low-warming baseline (Paris consistent) causes low to moderate economic impacts. We also highlight important sources of uncertainty, including the nature of the impact function chosen to represent climate impacts. We find that impact functions based on the level of warming find lower impacts from a termination shock, while impact functions that are sensitive to the rate of warming foresee worst consequences. We also identified methodological challenges associated with the estimation of future economic consequences from termination shock.

Our results suggest potentially very large but highly uncertain impacts from termination in the event of a termination shock of around 1°C of cooling, due to the uncertainty in climate impacts across and within specifications. While these results confirm the concerns around the termination of solar geoengineering (Parker and Irvine, 2018), it should be noted that this is an event whose likelihood could be reduced by preemptive adaptation to possible shocks in the deployment platforms of geoengineering, for example through redundancy in the airports (and the number of countries that control them) or number of planes available for the deployment. However, these adaptation measure cannot shield completely from social factors that could increase the risk of termination, for example geopolitical risk and war. Further research should analyze the economic cost of less dramatic – but more likely – interruption or disruption events such as temporary changes in the deployment amount or strategy following political or technical disruptions (Farley et al., 2025).

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