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Wilfried Rickels, Martin F. Quaas, Kate Ricke, Johannes Quaas, Juan Moreno-Cruz, Sjak Smulders

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ABSTRACT

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Engineering the climate via Solar Radiation Management (SRM) is increasingly considered as a component of future climate policies. We study the strategic incentives for countries to choose the level of SRM at different times in the future, accounting for the regionally uneven effect of SRM on climate variables, heterogeneous preferences of countries for the state of the global climate, and climate change adjusted GDP growth rates. We find that even though some countries would have significant gains from realizing their individually preferred level of SRM, the economic incentives for many countries are not sufficient to consider unilateral SRM implementation to be beneficial. In contrast, several countries have strong incentives to join coalitions to prevent that too much SRM is applied. The likely scenario is that a coalition will set a level of SRM close to the global efficient level.

Keywords: Climate Engineering, Solar Radiation Management, Governance, Climate Change Winners and Loser, Free-Driving Externality, Coalition Games with Externalities.

JEL classification: Q54

Wilfried Rickels
Kiel Institute for the World Economy
Kiellinie 66
24105 Kiel, Germany
Email:
wilfried.rickels@ifw-kiel.de

Martin Quaas
Department of Economics
Kiel University
Wilhelm-Seelig Platz 1
24118 Kiel, Germany

Kate Ricke
School of Global Policy & Strategy
UC San Diego
9500 Gilman Dr. #0519
La Jolla , CA 92093-0519, USA

Johannes Quaas
Institute for Meteorology
University of Leipzig
Stephanstr. 3
04103 Leipzig, Germany

Juan Moreno-Cruz
School of Environment, Enterprise, and Development
University of Waterloo
200 University Avenue West
Waterloo, Ontario N2L 3G1, Canada

Sjak Smulders
Tilburg School of Economics and Management
Tilburg University
Warandelaan 2
5037 AB Tilburg, Netherlands

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Wilfried Rickels[a,*], Martin Quaas[a,b], Kate Ricke[c], Johannes Quaas[d], Juan Moreno-Cruz[e], Sjak Smulders[f]

*Corresponding author: wilfried.rickels@ifw-kiel.de

[a] Kiel Institute for the World Economy, 24105 Kiel, Germany.
[b] Kiel University, 24118 Kiel, Germany.
[c] UC San Diego, La Jolla , CA 92093-0519, USA.
[d] University of Leipzig, 04103 Leipzig, Germany.
[e] University of Waterloo, Ontario N2L3G1, Canada.
[f] Tilburg University, 5037 AB Tilburg, Netherlands.

Abstract

Engineering the climate via Solar Radiation Management (SRM) is increasingly considered as a component of future climate policies. We study the strategic incentives for countries to choose the level of SRM at different times in the future, accounting for the regionally uneven effect of SRM on climate variables, heterogeneous preferences of countries for the state of the global climate, and climate change adjusted GDP growth rates. We find that even though some countries would have significant gains from realizing their individually preferred level of SRM, the economic incentives for many countries are not sufficient to consider unilateral SRM implementation to be beneficial. In contrast, several countries have strong incentives to join coalitions to prevent that too much SRM is applied. The likely scenario is that a coalition will set a level of SRM close to the global efficient level.

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1 Introduction

Engineering the climate via Solar Radiation Management (SRM) has received increasing attention as a potential scenario for future climate change mitigation. Yet, the incentives to implement SRM are widely different from the strategic incentives to abate greenhouse gas emissions or to adapt to the impacts of climate change (Heutel et al. 2016). While emission abatement requires decades of cooperation to significantly change the global mean temperature trajectory, some Solar Radiation Management (SRM) technologies like stratospheric aerosol injection (SAI) have prospects of altering the global mean temperature at rather low operational cost and in the time-scale of a year (Lenton and Vaughan 2009). This high leverage of SRM is a double-edged sword in the climate change governance context: while SRM appears to reduce the cooperation problem for climate change mitigation to a coordination problem about the level of SRM deployment, the coordination problem might be hard to solve, as some countries may have a strong incentive to unilaterally deploy SRM, potentially leading to overprovision of SRM (Schelling 1996, Barrett 2008, 2014, Harding and Moreno-Cruz, 2016, Weitzman, 2015). Accordingly, the fundamental governance question is how much SRM should be applied by whom and when (Barrett 2008, 2014).

Two issues amplify the challenges for governance and coordination of SRM. First, SRM allows only for an imperfect compensation of greenhouse gas induced global climate change. It changes climate variables like temperature and precipitation in a regionally uneven way, differently from the effects of climate change (Allen and Ingram 2002, Trenberth and Dai 2007, Ricke et al. 2010, Ricke et al. 2012). For example, fully offsetting the increase in global mean temperature would result in less global mean precipitation and fully offsetting the annual-mean temperature increase in the Arctic would result in overcooling the tropic regions (and overcooling the Arctic in summer). Second, climate change affects countries very differently. While many countries will face damages from climate change, some countries may even benefit. Thus, countries have different "preferences" for the state of the global climate. Empirical results suggest that economic variables such as GDP, growth, and productivity might be maximized at some "optimal" climate (temperature) (Nordhaus 2006; Park and Heal 2014; Burke et al. 2015b; Burke et al. 2018). The state of the global climate that leads to the optimal regional climate for one country will be very different than the climate state best suitable for another country. This translates into very different preferences on possible SRM strategies (Heyen et al. 2015, Heutel et al. 2016, Quaas et al. 2016). Moreno-Cruz et al. (2012) and Ricke et al. (2013) address the first issue—heterogeneous effects of SRM on regional climate variables—in their quantitative assessment of the decision on global coordinated SRM deployment, but do not address the second issue, as they assume that all countries consider their today's climate conditions to be optimal (Heyen et al. 2015).

Here, we study the strategic incentives for countries in the decision about global SRM deployment and potential outcomes of decision-making on SRM, for different points in time in the future. We account for both issues, the regionally uneven changes in temperature and precipitation from SRM deployment and the different preferences of countries for the state of the global climate. Our analysis combines data on the influence of SRM on grid-cell temperature and precipitation derived from earth system models simulations (Ricke et al.

2012), data on the influence of temperature and precipitation on grid-cell GDP from the G-Econ database (Nordhaus 2006), and data on climate change adjusted GDP growth rates from Burke et al. (2015a). Our resulting dataset allows us to obtain insights i) about the global optimal level of SRM deployment under future climate and GDP growth scenarios, ii) strategic incentives of individual countries, and iii) potential gains from participating in (global or sub-global) agreements.

Currently rather cold regions and countries (e.g., Russia, Canada) are expected to benefit from (some) climate change because of, for example, improved resource access, transportation routes, or agricultural conditions (e.g., Heyen et al. 2015). Within the climate-econometric literature, an increasing number of studies quantifies the impacts of changing climate variables on aggregated economic variables like (labor) productivity (Graff Zivin and Neidell 2014, Park and Heal 2014, Zhang et al. 2018), income (Dell et al. 2009, Deryugina and Hsiang 2014), economic output (Nordhaus 2006, Hsiang et al. 2017), or economic growth (Dell et al. 2012, Burke et al. 2015b, Burke et al. 2018). A robust finding across these studies is that the relation between economic activity and temperature is captured by an inverted U-shaped function, suggesting that, in economic terms, some "optimal" climate exists (Nordhaus 2006, Burke et al. 2015b, Burke et al. 2018). Climate change shifts the countries' distribution along the optimal temperature curve to the right and therefore "cold" countries closer to, and "hot" countries further away from, the optimum. SRM would shift countries to the left; "cold" countries farther away from, and "hot" countries closer to, the optimum climate. Accordingly, countries have very different incentives regarding the amount of SRM.

Our work contributes to the literature that considers challenges to the governance of SRM. Moreno-Cruz et al. (2012), in a first quantitative assessment on how much SRM should be deployed, suggest there is a Pareto-improving level of SRM. They assume that all countries face climate damages as temperature or precipitation deviates from a common baseline. In their assessment, deviations from present climate to warmer or cooler conditions would equally cause climate damages. By assumption there are no climate change winners and thus, there is an amount of SRM that reduces climate damages for all countries, albeit in different proportions. In contrast to Moreno-Cruz et al. (2012), our analysis is based on empirically estimated, optimal climate conditions that deviate from the present conditions for most countries around the globe. Ricke et al. (2013) extends the framework of Moreno-Cruz et al. (2012) by investigating the level of SRM that would be optimal for different coalitions of countries. They consider coalitions that represent at least 50 percent of global population or GDP. They find that coalitions are better off with an exclusive treaty compared to an open membership treaty because that allows the members to decide on a level of SRM deployment more in line with their individual preferences. However, like in Moreno-Cruz et al. (2012), damage functions are again specified as quadratic normalized temperature and precipitation deviations from today's conditions, the variation in the country-individual optimal level of SRM is low and the gains from exclusivity are small.

Considering coalitions of countries that agree on a common level of SRM deployment, a more fundamental question is how to enforce participation (Barrett 2014). The low operational costs of SRM provide incentives for unilateral deployment (Barrett 2008; Moreno-Cruz 2015; Weitzman, 2015). In consequence, without any mechanisms to enforce participation, the pure Nash equilibrium suggests that the country with the preference for the coolest climate aims for engineering the climate outside any agreement (Barrett 2014). Taking this view, the actual governance challenge associated with SRM deployment can therefore also be characterized as a free-driver problem, in stark contrast to the free-rider problem with climate change mitigation (Weitzman 2015). Considering the existence of an "optimal climate" with respect to economic activity, several countries might even have an incentive to "overcool" the global climate in order to bring their individual regional climate closer to the optimal climate. Accordingly, not only climate change winners but also other countries would be confronted with overprovision of SRM deployment, resulting in a free-driver externality (Moreno-Cruz 2015, Weitzman 2015).

Theoretically, the opportunity of unilateral SRM deployment can work as leverage in favor of greenhouse emissions mitigation because the threat of SRM provides incentives for climate change winners to increase their abatement efforts (Moreno-Cruz 2015). Millard-Ball (2012) discusses such a threat as the "Tuvalu Syndrome", arguing that it would be the best response of desperate islands nations to commit themselves to unilateral SRM deployment such that the best response of other countries is to collectively reduce emissions. However, according to our analysis (excluding catastrophic or extinction events), the economic incentives for many countries and in particular small island states are not sufficient to consider unilateral SRM implementation to be beneficial and therefore to represent a credible threat. Still, there remains a small group of countries for which holds that a much higher level of SRM deployment than the globally efficient level would be beneficially and which also could afford this higher level unilaterally.

However, following the international logic of multilateralism, Horton (2011) argues that with the various channels of retaliation in combination with the rules of international law it is rather unlikely that SRM measures would be applied unilaterally against international opposition. In the same vein, Parson and Ernst (2013) argue that only a very small number of states would be capable of upholding SRM in terms of financial, technological, logistical, and military strength against international opposition, implying at the same time that countries outside any coalition can be expected to be capable of imposing externalities on coalition members. In our analysis, only a level of SRM deployment close to the level chosen by the grand coalition would generate a total net gain in global GDP, allowing therefore to potentially compensating SRM losers. Presuming that only a level of SRM deployment which provides global net benefit appears likely to be implementable, the grand coalition appears to be a robust guess for the solution of a SRM coalition game.

The paper is structured as follows. Section 2 introduces the decision framework for global SRM deployment and explains the calibration for the quantitative illustration (Sections 2.1 to 2.3). Section 3 presents our results, discussing first the global efficient level of SRM deployment as the reference state for the country incentives (Section 3.1), the individual country incentives (Section 3.2), and participation gains and coalition implications (Section 3.3). Section 4 discusses the limitations of our approach and Section 5 concludes.

2 Methods

Countries choose the global level of SRM deployment, R. Grid cell temperature, T_j, and precipitation, P_j, depend on R and the (multidimensional) state of non-SRM anthropogenic forcing, S, (both measured in W/m^2). The state of non-SRM anthropogenic forcing is determined by the prevailing greenhouse gas (GHG) forcing and tropospheric aerosol forcing (saer). Changing GHG forcing to a significant extent requires at least decadal global coordinated emission abatement and even with carbon dioxide removal significant changes cannot be expected in less than a decade (Lenton and Vaughan 2009; Klepper and Rickels 2014). Consequently, we assume that S is exogenously given through time, $\bar{S}_t$, and the only decision variable for countries that allows a rapid change in temperature and precipitation is R. We assume that country i's GDP at some year t is influenced by temperature T_j and precipitation P_j in grid cells either fully or partly located in country i, $j \in J^i$. SRM deployment generates cost, $C(R) = cR$, where $c>0$ is constant marginal cost of SRM.

The globally efficient level of SRM deployment is the one that maximizes world GDP. Thus, country i's GDP "weights" its preferences for the globally efficient level of R. The future global distribution of GDP (and therefore weights) is not necessarily equivalent to the current distribution. To account for this, we include exogenously given country-specific GDP growth rates, $g_i(t)$, which are corrected for the degree of climate change experienced until year t, $\bar{S}_t$. More specifically, country i's GDP in year t is calculated as:

(1) $$GDP(R, \bar{S}_t, t, Z_i) = g_i(t, \bar{S}_t) * \sum_{j=1}^{N} GCP(T_j(R, \bar{S}_t), P_j(R, \bar{S}_t), X_j, A_{ij}, Z_i) \text{ for } j \in J^i,$$

where GCP is gross cell product, X_j summarizes parameters describing cell-fixed geographic control variables, A_{ij} specifies the area size of grid cell j in country i, and Z_i specifices country-fixed effects. The HadCM3L general circulation model is applied to estimate $T_j(R, S)$ and $P_j(R, S)$ (Section 2.1). The G-Econ data is used to estimate $GCP(T_j, P_j, X_j, A_{ij}, Z_i)$ (Section 2.2, denoted for notational convenience as $GCP(T_j, P_j)$) (Nordhaus 2006). The analysis of Burke et al. (2015b) is used to obtain the estimates of the growth rates, $g_i(t, S_t)$ (Section 2.3). We restrict our analysis of SRM deployment to the case where the state of the climate $\bar{S}_t$ follows representative concentration pathways (RCP) 8.5 where emissions are assumed to increase throughout the 21st century and accordingly the climate change adjusted GDP growth rates from the corresponding shared socioeconomic pathway (SSP5) (Riahi et al. 2007 and Burke et al. 2015b, respectively).

The globally efficient level of SRM in year t is obtained by maximizing aggregated GDP of all N countries, taking into account the cost of SRM:

(2) $\max_R \sum_{i=1}^{N} GDP(R, \bar{S}_t, t, Z_i) - C(R).$

Accordingly, our decision framework is a sequence of static optimization decisions. Each time step is treated independently of each other. Our optimization is clearly not dynamic, but static in that we ask what is the optimal amount of SRM deployed under different background climate and economic conditions. Those climate and economic conditions are the result of our scenarios for $T_j(R, \bar{S}_t)$ and $P_j(R, \bar{S}_t)$, $GCP(T_j, P_j)$, and $g_i(\bar{S}_t, t)$.

Furthermore, we impose the constraint $R \geq 0$, i.e. we do not study the possibility of (solar) radiation management deployment to *increase* global temperatures, as such means of counter climate engineering are expected to face considerable practical obstacles (Parker et al. 2018). Estimates for the marginal operational cost of global SRM, $c(R)$, are obtained from a recent study by Moriyama et al. (2017). They review and estimate the cost for stratospheric aerosol injection (SAI) which is probably the most likely example to be considered in case of global SRM deployment. Furthermore, the most likely injection method is expected to be achieved by aircrafts and Moriyama et al. (2017) estimate the cost to be USD 45 billion/year/W/m^2 or USD 5 billion/year/W/m^2, using either existing aircrafts (F-15) or newly designed aircrafts, respectively.

2.1 Estimates $T_j(R, S)$ and $P_j(R, S)$

We estimated grid cell changes in temperature and precipitation as function of SRM and the state of the climate by using the HadCM3L general circulation model as detailed in Ricke et al. (2012). To estimate the influence of S and R, we relied on a standard emissions scenario (SRES A1B) to represent future trajectories for GHG concentrations and tropospheric aerosol emissions, and considered multiple trajectories for stratospheric SRM. The changes were computed against a 2005 observational baseline (to be in line with the temperature and precipitation data in Nordhaus 2006). The analysis uses then six decades of output from three SRM scenarios. Each scenario is represented by the decadal mean values from three initial condition ensemble members. Simulation output was regridded to a 1 degree resolution to correspond with the G-Econ dataset. We fitted a linear model to predict changes in temperature and precipitation as a function of greenhouse gas forcing (in W/m2), tropospheric aerosol forcing (in W/m2), and solar radiation management (in units of stratospheric aerosol optical depth*1000) at each grid cell. As radiative forcing we consider total anthropogenic forcing (relative to a pre-industrial baseline). We obtained estimates for 20577 grid cells. For all grid cells the deployment of SRM reduces grid cell temperature, $\partial T_j / \partial R < 0$, albeit with different magnitude. In 14646 grid cells SRM reduces precipitation ($\partial P_j / \partial R < 0$), whereas in the remaining grid cell it increases precipitation ($\partial P_j / \partial R > 0$).

2.2 Estimates for $GCP(T_j, P_j)$

We estimated changes in GCP as function of grid cell temperature and precipitation with a cross-section estimation, using long-term average grid-cell temperature and precipitation as explanatory variables. The data, including also other geographic control variables like the distance to the coast or elevation, are obtained from the G-Econ database (Nordhaus 2006). The 1-degree latitude by 1-degree longitude grid cells are assigned to countries proportionally to the area of the country in the grid-cell, yielding a total number of 16082 GCP observations. Burke et al. (2015b) find strong evidence for the assumption of a global non-linear functional relationship function by also i) estimating subsamples of their dataset, ii) testing whether countries individual marginal response are non-tangent to the slope of the global function, and iii) by including interaction terms for temperature with average temperature and income. Accordingly, following Nordhaus (2006) we estimated

(3)

$$\ln\left(GCP_{ij}\right) = a_o + a_1 T_j + a_2 {T_j}^2 + a_3 P_j + a_4 {P_j}^2 + c_i + \sum_{k=5}^{7} a_k G_{kij} + \sum_{k=8}^{13} a_k D_{kj} + \epsilon_{ij}$$

where GCP_{ij} is gross cell product in 2005 USD (at market exchange rates), c_i captures country fixed effects, G_k are two geographic variables (accounting for elevation and area of the grid cell in country i), D_k are six dummy variables (accounting for being in the high latitudes, for different distances to the coast (three dummy variables), and accounting for extreme rich cells (two dummy variables)), and ϵ_{ij} is the error term. We estimated equation (3) by weighted least squares where we obtained the weighting series obtained from a forecast based on a regression of the squared residuals of the non-weighted estimation on precipitation. We relied on Newey-West-based determination for the coefficient covariance matrix. Like Nordhaus (2006) or Burke et al. (2015b) our results suggest an optimal temperature and precipitation level (i.e. a_1 and $a_3 > 0$ while a_2 and $a_4 < 0$). Our estimation suggests an optimal temperature level of 14.35°C which is well in the confidence interval of study by Burke et al. (2018) on optimal temperature levels for GDP growth (9.7 to 16.8°C). They find a median estimate of 13.1°C which in turn implies that our slightly higher estimate for the optimal temperature results in a rather conservative estimate for future SRM deployment. Appendix A1 shows the complete set of results from the regression.

For our calculations of gains or potential payments as part of the global SRM decision, we require information about GDP in levels, not in logarithms like in (3). In addition to a simple retransformation, we obtained retransformations by including Duan (1983) smearing estimate at the complete sample size and the country level, and a retransformation with a perfect correction factor obtained from comparing aggregated estimated GDP against aggregated observed GDP at the country level. The results presented in Section 3 below rely on the perfect correction.

2.3 Estimates for $g_i(\bar{S}, t)$

We obtained estimates for climate adjusted growth rates from Burke et al. (2015b) where the underlying climate change scenario corresponds to RCP8.5. They estimate the nonlinear effect of temperature on GDP per capita growth, using 6584 country-year observations between the years 1960-2010 (i.e., accounting for country-fixed and time-fixed effects). The country-specific per capita growth rates were translated into country-specific GDP growth rates by using the population growth projections from the SPP database corresponding to SSP5. These growth rates were then used to adjust the country-specific forecasted GDP level through time, making the assumption that all grid cells in a country growth at the same rate.

3 Results

We first derive efficient SRM as a function of the coefficients and income levels in a simplified version of model (1)-(2) to show that the efficient level of SRM associated with the model (1)-(2) can be represented as a GDP-weighted average of the gap between actual and GDP-maximizing temperature. Abstracting from within-country (cell-level) heterogeneity, abstracting from precipitation effects, and assuming that no SRM is applied up to time *t*, we derive from equations (1)-(2) the following expression for country *i*'s GDP at time *t*:

(3) $$lnGDP_i(t) = \bar{F}_i(t) - \varphi(T_i(t) - T^*)^2$$

where parameter $\varphi = -a_2 > 0$ represents sensitivity of GDP to local temperature and parameter $T^* = a_1/(-2a_2)$ is GDP-maximizing temperature. The term $\bar{F}_i(t)$ collects all other country-specific terms, which include the effects of temperature in the past (up to time *t*) as explained in Section 2 above. Following the estimation for $T_j(R, S)$ as described in Section 2.1, we write local (country-specific) temperature at time *t* as:

(4) $$T_i(t) = \bar{T}_i + \sigma_i S(t) - \theta_i R(t),$$

where local temperature responds to non-SRM anthropogenic forcing, S, and SRM, R, in a country-specific way, as captured by parameters σ_i and θ_i, respectively, and where $\bar{T}_i$ collects all other country-specific determinants of temperature. The effect of SRM on country GDP is now given by:

(5) $$\frac{dGDP_i}{dR} = \theta_i \cdot GDP_i \cdot 2\varphi \cdot (\bar{T}_i + \sigma_i S - \theta_i R - T^*).$$

The expression measures the private marginal benefits of global SRM—and accordingly also the private marginal benefits to join a coalition of countries that organizes SRM. The incentives are large, first, if effective market size $\theta_i GDP_i$ is large and, second, if local temperature greatly exceeds optimal temperature (without the constraint $R \geq 0$ the second aspect would generalize to large incentives if local temperature greatly differs from optimum temperature).

By summing this expression over countries *i*, equating the sum to marginal cost *c*, and solving for *R*, we find that the level of SRM that maximizes aggregate GDP of a group (coalition) of countries *I* is characterized by:[1]

(6) $$R^I(t) = \sum_{i \in I} \left(\frac{\theta_i GDP_i(t)}{\sum_{j \in I} (\theta_j)^2 GDP_j(t)} \right) (\sigma_i S(t) + \bar{T}_i - T^*) - \frac{c}{\sum_{j \in I} (\theta_j)^2 GDP_j(t)}.$$

[1] The expression is not a closed form-solution since the RHS contains GDP which depends on R. Nevertheless, the expression allows for straightforward comparative statics since the GDP-dependent weights add up to unity.

The second term is the marginal cost of SRM corrected for the effect of SRM on aggregate GDP. Most action comes from the first term, representing marginal benefits. In the first term, the second factor is i's deviation from optimal temperature in the absence of SRM, or "temperature gap" for short. Obviously, if this gap would be zero for all countries, there would be no incentive for SRM.

By replacing T^* with $\bar{T}_i$ in (6), you obtain again the problem addressed by Moreno-Cruz et al. 2012) and Ricke et al. (2013) (and by setting $c = 0$ as they neglect operational cost for SRM application). With *perfect* SRM (i.e., $\sigma_i = \theta_i$), the efficient level of SRM would simply offset greenhouse gas forcing ($S = R$) in their problem.

Here, with an optimal temperature, T^*, and asymmetric countries, even with perfect SRM, SRM could not optimize temperature everywhere because of geographical heterogeneity (captured in $\bar{T}_i$). In general, the efficient level of SRM responds to the weighted average of temperature gaps across the countries, where the relative weights (the term in long brackets) are governed by the relative local sensitivity of temperature to SRM (θ_i) and relative GDP. Since the variation in GDP is much stronger than the variation in local temperature sensitivity to SRM application, the temperature gaps of high-income locations mainly drive the efficient SRM level.

Accordingly, equation (6) reveals the effects on SRM of a later implementation time t or a change in coalition I. First, postponing the SRM decision to a later point in time, when S is higher, affects efficient SRM both through the temperature gap and the weights. Due to a higher S, temperature is higher in all locations, which for given weights increases the demand for SRM: warm countries prefer more cooling and cool countries prefer less warming. However, the weights also shift towards fast-growing countries that suffer less from climate change. Since these countries are relatively cold (below optimal temperature), efficient SRM becomes lower. Second, when a country newly joins the coalition, efficient SRM moves in the direction that the joining country prefers since the coalition starts weighting the GDP effect of the joining country: more SRM if a warm country joins, as measured by the temperature gap $\bar{T}_i + \sigma_i S - \theta_i R - T^*$, and less SRM if a cold country joins.

The results here are only indicative. The full analysis cannot ignore the effects of SRM through local precipitation, which are similar to effects through local temperature but add to the total effect and might go in opposite directions. We now turn to the full estimated model.

3.1 Globally Efficient SRM Deployment

Figure 1 summarizes the globally efficient level of SRM, i.e. the solutions to the static decisions problem (2) at different points in time, for an operational cost estimate for SRM deployment of USD 45 billion/year/W/m^2. The grey dots in Figure 1 show the radiative forcing from GHG from RCP8.5 between 2020 and 2100. The red dots show the efficient levels of SRM that would be chosen if SRM were to start in that given year. Note that the efficient levels of SRM should not be confused with an optimal time-path of SRM deployment. Each dot shows the efficient level of deployment given that previously no SRM has been applied.

Figure 1 shows that the largest amount of SRM would be applied if the decision to start SRM was taken in the year 2050. Postponing the decision about SRM deployment further into the future would result in lower levels of SRM. From the year 2080, the global optimal level of SRM would be zero. Even though the number of climate change loosing countries increases towards the end of the century for RCP8.5, climate change slows down GDP growth rates for climate change losers (Burke et al. 2015b). Accordingly, the relative weight of the already warm countries decreases while it increases for the cold countries, implying that in aggregated terms it is efficient to apply less SRM.

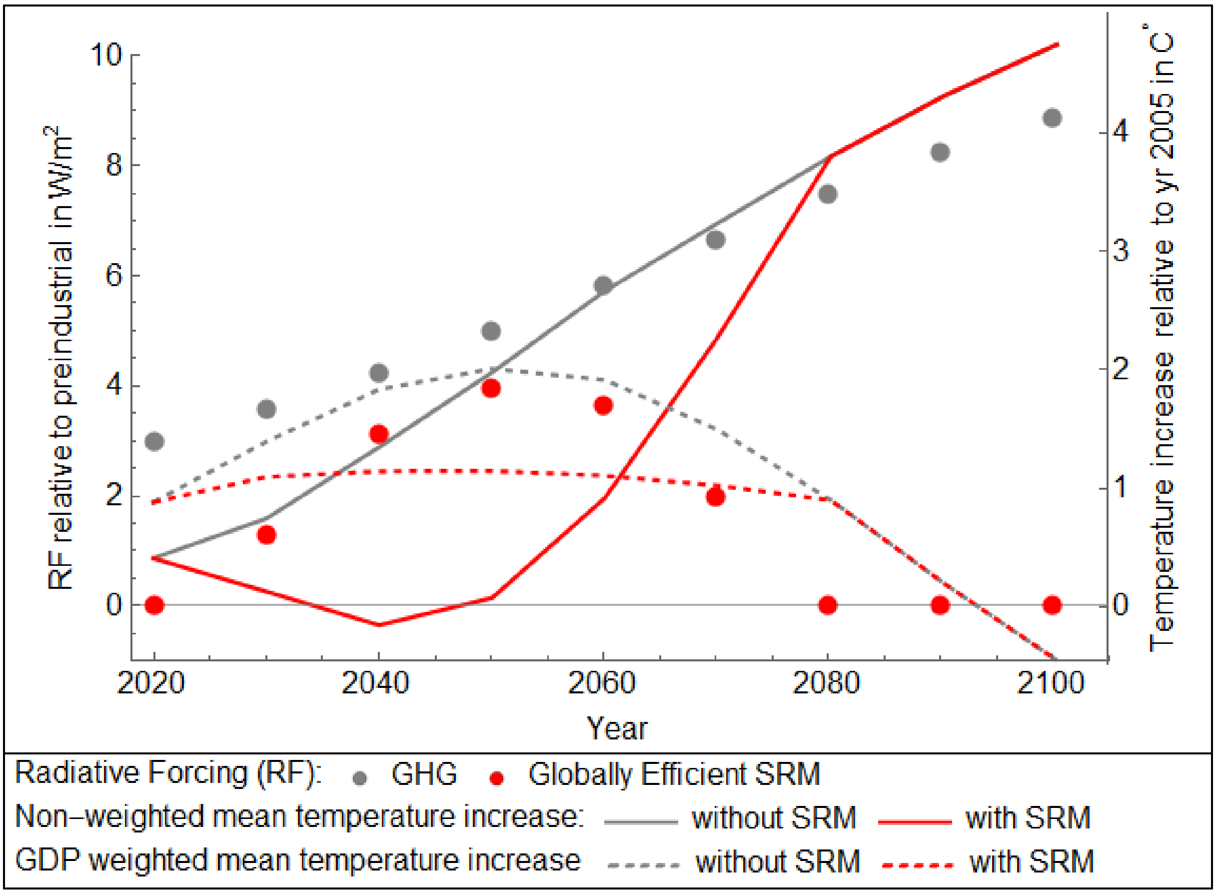

Figure 1: Global Optimal SRM Deployment at Different Points in Time. *Each red dot displays the solution to the static optimization problem of determining the efficient amount of SRM, given the degree of climate change experienced so far (which corresponds to RCP8.5). The solid and dashed lines show average mean temperature change and GDP weighted mean temperature change of the grid cells included in the analysis. The grey and red lines show temperature change without and with SRM deployment, respectively.*

To provide further intuition for the influence of climate change adjusted growth rates, Figure 1 also displays average global temperature and average GDP weighted global temperature, with and without SRM deployment. The calculation of both temperature values is restricted to the grid cells included in our analysis and therefore the simple average differs from the global mean temperature increase associated with RCP8.5 (which includes for example also ocean grid cells). Figure 1 shows that the simple average temperature without SRM deployment is steeply increasing towards the end of the century. The GDP-weighted average temperature shows an only modest increase towards the mid of the century and a decrease afterwards, because of the above explained influence of climate change on GDP growth. SRM deployment stabilizes GDP-weighted average temperature at levels found for the year 2020.

The general finding is robust against the type of retransformation from log to linear (i.e. is also present in the simple retransformation without correction and the retransformation applying smearing estimates for the complete sample size and for each country, see Figure A2.1 in Appendix A2) and it is also robust with respect to the cost estimate for SRM deployment (Figure A2.2 in Appendix A2 shows the level of SRM deployment in 2050 for different levels of GHG forcing and three different SRM cost scenarios, showing only a very small difference). If we use growth rates from SSP5 without adjusting them for climate change, we would observe an extreme overcooling towards the end of the century i.e., SRM deployment larger than GHG forcing. Then, the convergence assumption underlying the SSP growth rates implies that currently already warm but still developing countries have a higher relative weight in a future aggregated GDP which in turn would result in a higher efficient level of SRM deployment.

3.2 Individual Country Incentives for SRM deployment

Figure 2 shows the country-specific incentives to undertake SRM in the year 2050 and 2060 (left and right panel, respectively). In both panels, the axes show the marginal change in GDP as function of SRM: the x-axis at the point of *no SRM* deployment and the y-axes at the point of *globally efficient SRM* deployment (as derived in Figure 1). Accordingly, the x-axes address the question whether country i has an incentive to start SRM deployment at all and the y-axes address the question whether country i has an incentive to further increase SRM deployment beyond the globally efficient level. The size of the bubble shows the absolute change in GDP between the situation of *no SRM* and *globally efficient SRM* deployment, the color code indicates whether GDP increases (orange) or decreases (purple). In addition, Figure 2 shows on both axes the marginal cost for SRM deployment, corresponding to injecting aerosols into the stratosphere using existing airplanes (USD 45 billion/year/W/m^2). Considering a deployment of SRM in the year 2050 or 2060 one could expect that newly designed aircrafts are used for the spreading of aerosols, thus allowing for a lower marginal cost. However, the cost estimates presented in Moriyama et al. (2017) and similar assessments usually assume global coordinated deployment which implies relatively low marginal costs, as for example the best located airports could be used. Turning to the question of individual countries incentives for potentially unilateral SRM deployment, the assumptions underlying the cost estimates with respect to processing, infrastructure, or monitoring are likely on the optimistic side and we consider therefore the displayed marginal cost to be a rather low estimate for the operational cost to be faced in case of unilateral deployment.

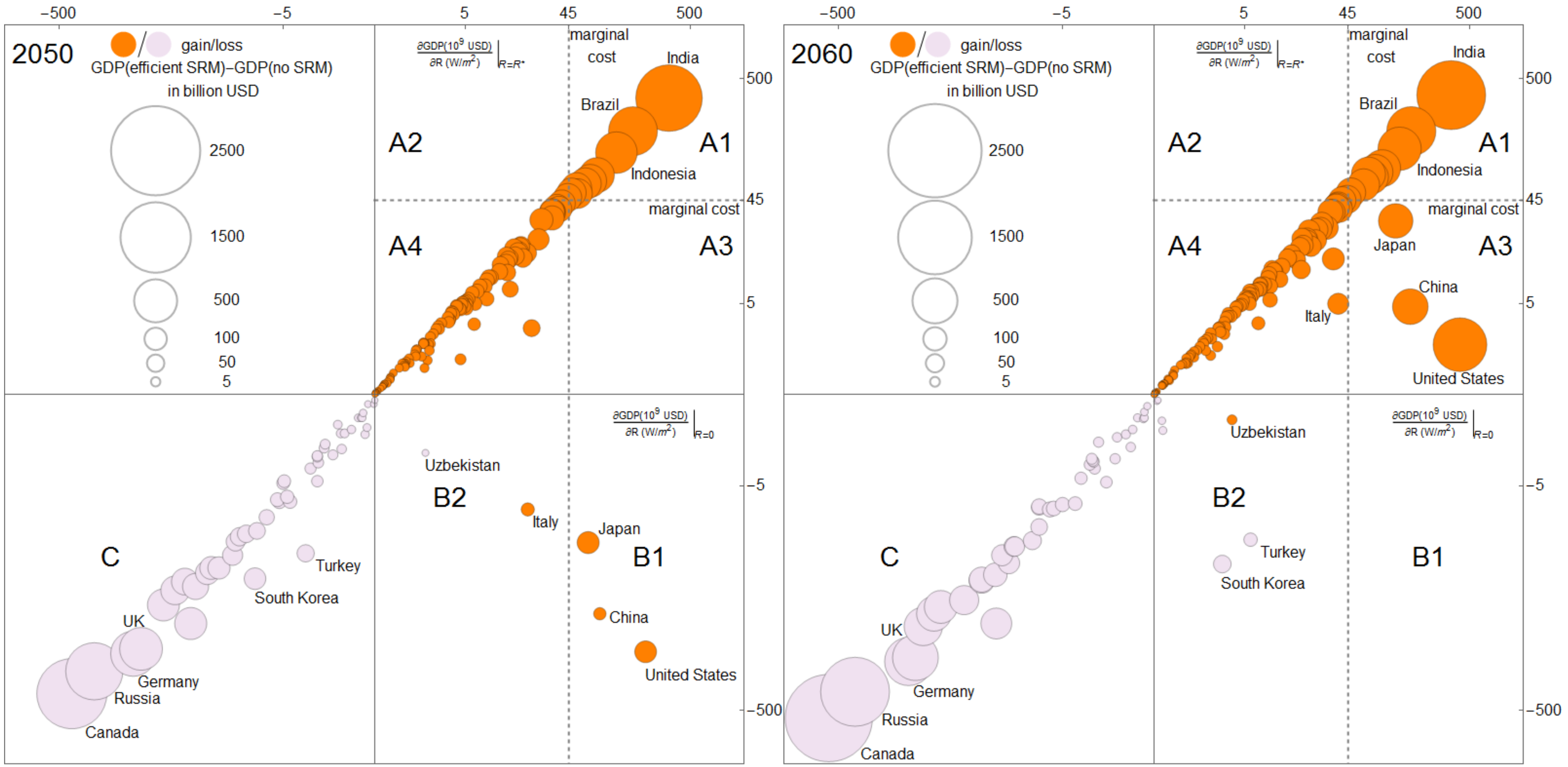

__Figure 2: Individual Country Incentives.__ The figure shows the marginal change in GDP at no SRM (R=0, x-axes) and at globally efficient SRM deployment (R=R, y-axes) in the year 2050 and 2060 (left and right panel respectively). The size of the bubble shows the absolute change in GDP and color code reveals whether a country gains (orange) or loses (purple) from SRM deployment.*

Figure 2 shows that country's individual incentives are more nuanced than just simply distinguishing between climate change losers and winners. Climate change losers are expected to gain from SRM deployment and are situated on the positive domain of the x-axes. However, not all of them would afford SRM deployment unilaterally and not all of them would still gain from SRM deployment at the globally efficient level. For that reason, we distinguish between six groups of countries in the positive domain of the x-axes, 4 groups in the positive domain of the y-axes (A1, A2, A3, and A4) and two groups in the negative domain of the y-axes (B1 and B2).

There is only a small group of countries (A1, 9 countries in the years 2050 and 2060) where the marginal gain in GDP exceeds the marginal cost of SRM at both points (*no SRM* and *globally efficient SRM*). These countries would have an incentive to deploy SRM unilaterally, because they would gain by increasing SRM application beyond the optimal level. The majority of climate change losing countries would rather free-ride (A4, 116 and 117 countries in 2050 and 2060, respectively). These countries also gain at both points of SRM deployment but their marginal gains fall short of the marginal costs of SRM deployment. According to these results, the "Tuvalu Syndrome" as introduced by the Millard-Ball (2012) cannot be considered as credible threat.

There are two further groups of countries with positive gains at both levels of SRM deployment. For the countries in the area A2 (in both years, 2050 and 2060, only one country) the gains exceed the marginal cost of SRM deployment only at the *globally efficient SRM* level which can be explained by the non-concavity of our functional form for grid-cell influence of temperature and precipitation on GDP (in levels). The interpretation is that these countries would benefit sufficiently from the implementation of the efficient level so that their marginal benefit of SRM would even exceed the marginal cost of SRM deployment. A particularly interesting group is represented by countries in area A3 (three countries in 2060, none in 2050). These countries have an incentive for unilateral SRM deployment in case *no SRM* is realized. However, if the *globally efficient SRM* is already in place, their incentives to further increase SRM deployment is not sufficient given the marginal cost, which means that the level of SRM deployment is already close to the country individual optimal level (if no SRM cost are in place).

The countries in the B area can still be considered as climate change losers as they would gain from SRM deployment. Yet, at the *globally efficient SRM* level, it is already overdone from their perspective. The countries in the B1 area (four and one country in 2050 and 2060, respectively) still gain from SRM deployment in absolute terms. This is not true for countries in the B2 area (two countries in 2050 and six in 2060). Even though these countries are (moderate) climate change losers and would benefit from reducing global temperatures, the *globally efficient SRM* level implies that they lose in absolute terms from SRM deployment. The remaining countries in area C are the climate change winning countries (47 and 42 countries in 2050 and 2060, respectively) which lose from SRM deployment, no matter how much (if we would allow for counter climate engineering, i.e. $R < 0$, we would also need to distinguish between different groups among the C-countries.

The comparison between 2050 and 2060 reveals that the distribution of countries in the different areas is not stable. Between the two points in time, two effects are at play. First, in 2060 the state of the climate, $\bar{S}_{2060}$, represents a stronger degree of climate change than in 2050, making more countries climate change losers (for example the group of countries in the area C drops from 47 to 42 while the group of countries in the area B2 increases from two to six). Accordingly, the marginal gains from SRM deployment increase. Second, because of the influence of climate change on GDP growth rates, the *globally efficient SRM* level (the reference point for the marginal change measured along the y-axes) is lower (compare Figure 1). Countries which would have been affected from overdoing SRM in the year 2050 have either shifted from the area B2 to B1 or from B1 to A3.

Most of the shifts take place for those countries which are initially already rather close to the optimal temperature and small changes in temperature determine whether these countries remain climate change winners or turn into climate change losers. Accordingly, these kind of *swing* countries cannot be expected to have stable preferences regarding SRM deployment. On the opposite side, countries which are initially rather far away from the optimal temperature (in both directions) can be expected to display rather stable preferences regarding SRM. For example, rather hot and also sufficiently wealthy countries like India or Brazil have in both years under consideration an incentive for unilateral SRM deployment. Also, the group of "Tuvalu" countries appears to be rather stable compared across the two years. As expected, countries like Russia and Canada would have no incentive for SRM deployment in either of the two years. Information about the distribution of all countries across these different incentive areas can be found in Table A3.1 in Appendix A3.

3.3 Participation Gains and Coalition Implications

Figure 3 shows the country-specific gains from participating in a global agreement on SRM in the years 2050 and 2060 (upper and lower panel, respectively). In both panels, the x-axes show the absolute change in GDP between the situation of *globally efficient SRM* deployment and *no SRM* deployment. The information is the same as shown with the bubble sizes in Figure 2. The y-axes in both panels show the absolute change in GDP between the situation of *globally efficient SRM* deployment and *efficient* SRM deployment for the remaining $N-1$ countries if the effect of SRM on country i's GDP was ignored. If country i's preferences are not considered, the resulting efficient level of SRM deployment is even further away from what country i considers to be optimal. In general, the effect is more pronounced the extremer the country-specific preferences are. For example, if Canada stays outside the global agreement, the remaining countries would decide on a higher level of SRM compared to the situation when Canada is included. Although Canada already loses when the globally efficient SRM level is deployed, it would lose even more if the effect of SRM on their GDP was ignored. If India stays outside the global agreement, the remaining countries would decide on a lower level of SRM compared to the situation of full participation implying that India would gain less compared to the situation where their desire for cooling the planet would be accounted for. Countries located close to the origin in Figure 2 have only small participation gains as their marginal gain or loss from SRM deployment is too small to change the global optimal level significantly. Accordingly, they have low (but strictly positive) values on the y-axes in Figure 3. The overall pattern for the distribution of countries preference for *globally efficient SRM* deployment displays a U-shape.

One notable exemption is the United States of America in the year 2050. In Figure 2, the USA can be found in the area B1, implying that the marginal gain from SRM at the globally efficient level is negative. Accordingly, at the globally efficient level, SRM is already overdone from the USA perspective in the year 2050. If they drop out of the global agreement in 2050, the remaining countries would pick a considerably larger amount of SRM deployment (about 1.4 W/m^2 larger compared to full participation level including the USA). Consequently, the negative impact of overdoing on the USA's GDP would increase significantly, explaining their gains from participation. In 2060 this effect is no longer present. There is more climate change in the year 2060 compared to the year 2050, implying that the USA has moved from the area B1 to the area A3 (Figure 2) and is losing more from climate change (increasing its individual incentives for SRM deployment). At the same time, the globally efficient level of SRM deployment in 2060 under full participation is lower compared to the year 2050 because of the climate change adjusted GDP growth rates (Figure 1). These two effects combined imply that the efficient level of SRM deployment in the year 2060 is very close to the level the USA would consider optimal (in a unilateral deployment scenario).

Including country i and implementing the efficient level of SRM under full participation, R^*, instead of the optimal level of SRM for the $N-1$ countries, ${R^*}_{\setminus i}$, comes at a cost: $\sum_{k\neq i} GDP_k({R^*}_{\setminus i}) - \sum_{k\neq i} GDP_k(R^*) + C(R^*) - C(R^*_{\setminus i}) \geq 0$ which is strictly positive if $R^* \neq {R^*}_{\setminus i}$. The vertical grey bars in Figure 3 display the costs resulting from including country i's preferences into the decision about the global level of SRM deployment for the remaining $N-1$ countries. The costs correspond to the payments under a Vickrey-Clarke-Groves (VCG) mechanism (Vickrey 1961; Clarke 1971; Groves and Loeb 1975) whereby our calculation of the lump-sum charge component is based on the Vickrey specification which includes, in contrast to the Clarke specification, the full change in the operational cost (which increase or reduce the charge in case of $R^* > {R^*}_{\setminus i}$ and $R^* < {R^*}_{\setminus i}$, respectively) (Loeb 1977). A VCG mechanism motivates truthful revelation of country's preferences in dominant strategies (Green and Laffont 1977), this is important if the influence of SRM on countries' GDP is considered private information. The orange dots at the lower end of each bar indicate the net gains of country i which they realize from participating in the global agreement if they have to pay the cost they induce for the $N-1$ countries. Country i's gross gains exceed their cost (which they induce for the $N-1$ countries) if $R^* \neq {R^*}_{\setminus i}$, implying that the incentives of joining the global agreement still exist (if $R^* = {R^*}_{\setminus i}$, the gains and cost would be zero). If countries decide the global level of SRM deployment under a VCG mechanism, climate change winners (countries on the negative domain of the x-axes) would actually have incentive to collude, submitting bits such that $R^* = {R^*}_{\setminus i} = {R^*}_{\setminus j} = 0$ (e.g., country i and j collude and both of them are not pivotal). Note that collusion would be harder to coordinate in case counter climate engineering (i.e., $R < 0$) would be possible.

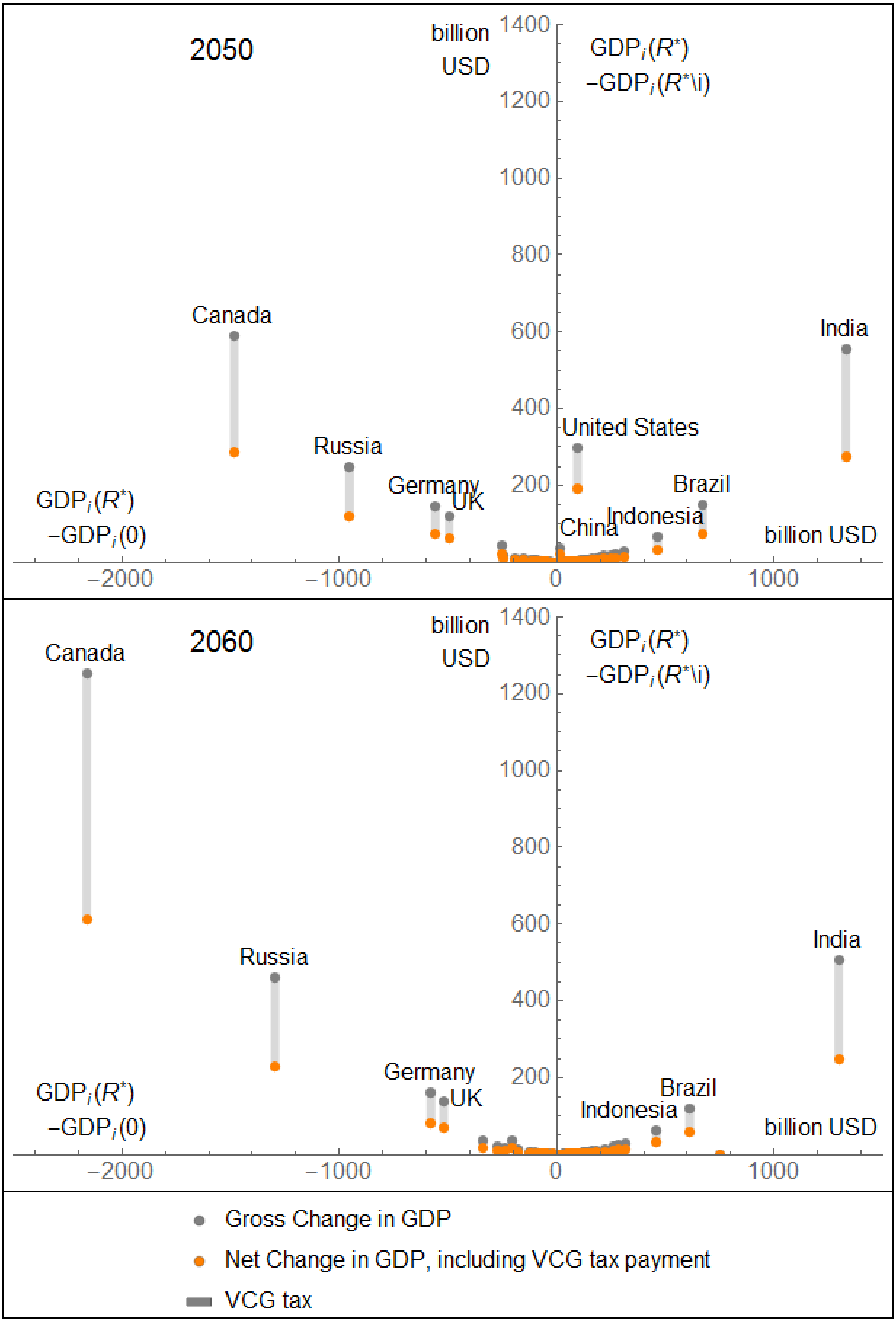

Figure 3: Participation Gains in 2050 and 2060. *The gray dots in the figure indicate the country-specific absolute change in GDP between the scenarios globally efficient SRM deployment (full*

participation) and no SRM deployment (x-axes) and globally efficient SRM deployment (full participation) and efficient SRM deployment excluding country i (y-axes). Furthermore, the figure shows the cost for the remaining N-1 countries if country i is included, which is equal to the Vickrey-Clarke-Groves (VCG) tax. The orange dots indicate the net change in GDP under the payment of the VCG tax.

The absolute changes in GDP displayed in Figure 2 and Figure 3 can be quite large for some countries. These results, however, are easy to reconcile as countries have experienced substantial growth in GDP (in nominal terms) up to the years 2050 and 2060. Still, consider Canada and India as two countries at the respective extreme positions of the country distribution. Canada is estimated to lose about 30 and 25 percent in GDP in 2050 and 2060, respectively, if the globally efficient level of SRM is implemented compared to *no SRM* deployment. India is estimated to gain about 15 percent in GDP in the years 2050 and 2060 if the globally efficient level of SRM is implemented compared to *no SRM* deployment. We discuss the limitations of these estimates in Section 4.

The individual participation gains are discussed under the assumption that all but country i are part of the agreement. However, other references agreements or coalitions are possible, including the question of how entry and exit into coalitions are organized (e.g., open membership). The literature on international environmental agreements, cooperation, and coalition formation provides so far only limited insights for the governance of SRM. The decision about the level of SRM deployment imposes a different challenge compared to problems studied in the existing literature that looks at the decision whether a country should contribute to the public good provision inside a coalition (or agreement) or whether it should stay outside of the coalition and free-ride on the public good provision of the coalition members. Some insights might be obtained from the literature on coalition (games) with externalities (Thrall and Lucas 1963). Yi (1997) examines coalition formation under the possibility of a negative and positive externality on outside coalitions, showing that under a negative externality the grand coalition is an equilibrium outcome (under open membership and other reasonable assumptions regarding the partition function) and that under a positive externality the grand coalition is not a stable outcome due to free-riding. Here, for several countries SRM deployment above a certain level, or even at all, is a public bad and they have an incentive to join the coalition to prevent that too much SRM is applied. Furthermore, the gains from free-riding are rather low. Even though the operational costs limit unilateral deployment for several small countries, they are only a minor aspect in any coalition including countries from the area A1. As mentioned above, the countries close to the origin in Figure 3 have small but positive net gains from participating (in case they would have to pay for their marginal influence on the decision of SRM deployment).

Figure 4 shows the GDP gains and losses of country groups for increasing coalition size in the year 2050 and 2060 (left and right panel, respectively). We did not model the coalition formation process, but simply assume that the SRM coalition forms from the country groups identified in Figure 2 (ranging from A1 to C), ordered by their desire for cooling the planet. Consequently, the first coalition contains only A1 countries, the second coalition also contains A2 countries (A1-A2), the third coalition also A3 countries (A1-A3) and so on until we end up with the grand coalition (A1-C). In each case, the level of SRM deployment is assumed to maximize the aggregate GDP of the coalition members.

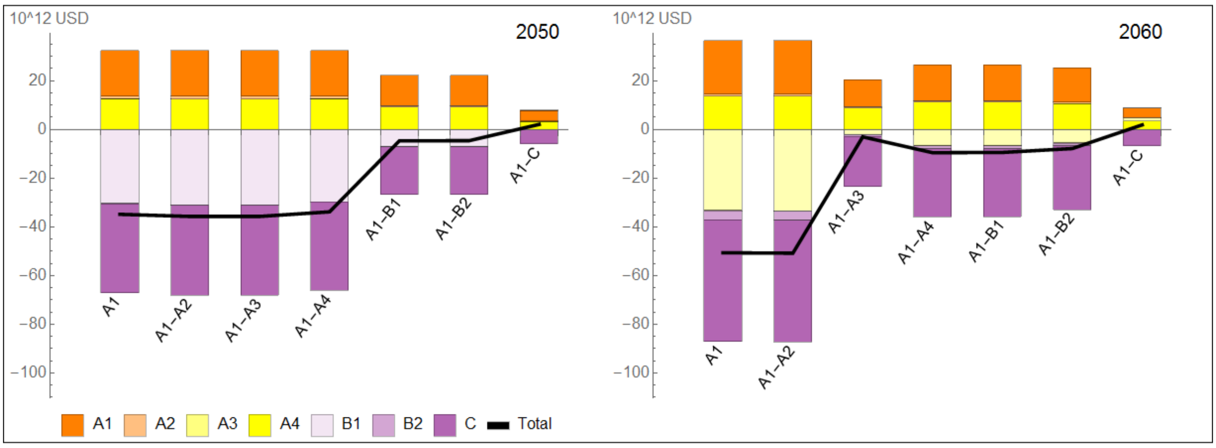

Figure 4: Coalition Gains and Losses in 2050 and 2060*. The figure displays, for coalitions of increasing size, the GDP gains and losses for the different country groups if the coalition determines the global level of SRM deployment by only taking the preferences of coalition members into account. The black line indicates the aggregated change in GDP of all countries.*

Figure 4 emphasizes incentives of A1-countries to free-drive. Their gains from exclusivity are large because they can chose a much higher level of SRM deployment on their own. However, while the rest of the A countries (in particular the A4 countries) benefit from free riding on SRM deployment, from the perspective of the rest of the world SRM is overdone. In aggregated terms, the second effect dominates (SRM is overdone) and global change in GDP is negative. This situation remains similar for coalitions of increasing size up to the grand coalition in 2050. Even though participation of the B1 countries results in a significant reduction in the chosen coalition SRM deployment, the weight of the B1 countries in the coalition is not sufficient to bring SRM deployment to a level where they gain. Accordingly, the B1 countries benefit from inviting C countries to join and thus, preventing them from losing under SRM deployment. In 2060, the pattern is slightly different because facing stronger climate change and lower global optimal SRM deployment, most of the B1 countries from 2050 are now described as A3 countries. Accordingly, when the coalition size increases to include these three group of countries, A1, A2, and A3, we observe already a significant reduction in global SRM deployment. Including now the A4 countries in the coalition, SRM deployment increases again slightly. Accordingly, here the A4 countries have no incentive to free-ride. In both points in time, only the grand coalition generates a total net gain in global GDP, being therefore capable to compensate the losers.

While the grand coalition guarantees that SRM is only implemented if it results in global net benefits, it must not necessary be the only equilibrium in a potential SRM coalition formation game. For example, in 2060 a coalition consisting of the A and C countries, only taking into account the preferences of coalition members, would decide on a level of SRM deployment which is very close to the globally efficient level. However, assuming that the A4 countries would leave the coalition, the weighting of preferences for and against SRM deployment would change such that the coalition would decide on no SRM deployment. Consequently, again, there would be no incentive for the A4 countries to free-ride even though we have classified them as free-riders in Section 3.2. The A1 countries would have an incentive to keep the A4 countries in the coalition to answer the question how much SRM to do more in their favor. Accordingly, these considerations suggest that the grand coalition is the most plausible solution of a cooperative SRM coalition game with externalities.

4 Discussion

The influence of future GHG and SRM forcing on grid-cell temperature and precipitation is uncertain. Both magnitude and pattern of the projected changes vary greatly (Collins et al. 2013): (i) by scenario (the RCP8.5 scenario selected here is at the upper end of what was considered in the Intergovernmental Panel on Climate Change 5th assessment report, and so far seems the most realistic), and (ii) by model (the GCM selected here for illustration – HadCM3 – is a model with a climate sensitivity in the middle of the range simulated by various models). Still, the applied estimates for grid cell change in temperature and precipitation provide a reasonable representation of the regional variation in SRM's effectiveness to compensate GHG induced changes.

The estimation of the influence of temperature and precipitation on grid cell GDP by a cross-sectional relationship has several limitations. In particular, the relationship may capture historical process which would not be effective in future changing climate conditions (or at least not at those timescales) (Dell et al. 2014). However, the grid cell-based approach is essential to take into account the regionally imperfect compensation of greenhouse gas induced changes in temperature and precipitation induced by SRM deployment (Moreno-Cruz et al. 2012; Ricke et al. 2013). The grid cell approach can also be expected to be less vulnerable to this omitted variable bias than estimations on the country level. Furthermore, our approach is less concerned with interference than with predicting the impacts of changes in temperature and precipitation. Accordingly, our estimation strategy was to minimize the standard error of estimation. Omitted variable bias is in so far an issue as we might overestimate the influence of temperature and precipitation (in particular in the short term). Our estimated rather large changes in GDP from SRM deployment for some countries appear to be implausible—just as the immediate implementation of the *globally efficient* level of SRM. The associated rapid change in temperature and precipitation would cause (economic) cost, suggesting that *globally efficient* SRM level would be rather approached optimally by a smooth and gradually increasing deployment scenario (Keith and MacMartin 2015). These considerations indicate that the results in our static decision framework (with the cross-sectional calibration) should be interpreted rather qualitatively than quantitatively and that our framework rather serves at identifying and illustrating the driving factors for country-specific incentives. Furthermore, even though the magnitude of estimated changes can be questioned, we believe that our major results about the influence of climate change adjusted growth rates on the globally efficient level of SRM deployment, the classification of country-incentives, and the identification and discussion of coalition participation gains provides robust insights.

Nevertheless, a more comprehensive assessment requires a truly dynamic solution, accounting for the cost associated with the rate of change in climate variables and the influence of SRM on future GDP growth rate. In our static decision framework, we account for the historical influence of climate change on GDP growth (up to the point in time when the SRM decision takes places) but neglect the influence on future growth. Due to the sustained influence of climate change on growth rates, particular countries would have strong incentives for SRM deployment before the mid of the century, while other countries would have strong incentive to delay SRM application.

In addition to aiming for a truly dynamic solution, it would be interesting to study the role of further aspects in future work, which we have ignored in our analysis. First, climate variables other than temperature and precipitation may play a role, including wind speed and direction, cloudiness, or relation of diffuse to direct irradiation, all of which can affect sector-specific economic activity and are expected to react differently to SRM deployment than compared to increased GHG concentration (Tilmes et al. 2009, Huneeus et al. 2014, Proctor et al. 2018).

Second, we have restricted our analysis to changes in annual average temperature and precipitation. In terms of economic activity it can be expected that the seasonal variability of precipitation or the number of extreme hot and cold days has at least an equally strong influence than changes in average values (Lesk et al. 2016). Again, extreme values and variability are differently affected by SRM deployment than by increased GHG concentration (Curry et al. 2014; Huneeus et al. 2014).

Third, we have neglected any extreme events like storms or hurricanes and impacts with strong delay and therefore slow response time like sea-level rise. Deployment of SRM (via SAI) could reduce tropical cyclone frequency (requiring northern hemisphere injection) (Jones et al. 2017) or could reduce coastal flood risks from Atlantic hurricanes (Moore et al. 2015), creating potentially very different incentives for neighboring countries than those derived from simply accounting for changes in mean temperature and mean precipitation. And even though the deployment of SRM is expected to allow for a quick influence on temperature, slowing or even reversing sea-level rise would require a much stronger and earlier deployment than an deployment only concerned with influencing temperatures (Irvine et al. 2012).

Fourth, our approach neglects any feedbacks arising from trade and price effects. In our simply decision framework, countries like Canada and Russia would keep gaining from climate change by moving the regional temperature closer to the optimum, even though there would not be too many serious trading partners left in the rest of the world. Factoring in these effects, the overall impact of climate change on countries' GDP could very be different than the one derived from the direct climate impacts within the country (Calzadilla et al. 2013, Aaheim et al. 2015).

Fifth, we neglect indirect impacts of climate change, like for example changes in migration and increased conflicts. Heat stress and droughts are expected to increase conflict risks and therefore potentially even civil war risk (Burke et al. 2015a) and (Maystadt and Ecker 2014) and also effect directly and indirectly migration flows (Missirian and Schlenker 2017), increasing the incentives for SRM deployment by climate change loosing countries beyond those suggested from considering only direct changes in GDP.

Sixth, and finally, we neglect other impacts of SRM deployment affecting for example health or simply the well-being of people. For example, deployment of SRM is expected to slow the recovery of the ozone layer (Tilmes et al. 2009) and to reduce the occurrence of blue skies (while at the same time increasing the number of colorful sunsets) (Robock et al. 2008). Both climate change and any SRM deployment will also affect the biodiversity and various ecosystem services. Sensible regions in this respect—like for example Antarctica or the oceans—were even not part of our analysis, as there is no GDP in those grid cells. These impacts also influence how people and therefore voters assess SRM and might therefore result in very different country preference for SRM deployment than suggested by looking only at economic impacts (Merk et al. 2015).

These further aspects may have significant influence on countries incentives, such that our results should be interpreted with caution. Yet, these limitations are not necessarily bad news for the SRM governance considerations derived from our analysis. The limitations could be interpreted in such a way that the actual spread between the country-specific optimal levels of SRM deployment is not as large as suggested by our analysis. In particular economic feedbacks via trade in an increasingly globalized world make is less likely that countries only seek to achieve an optimal regional climate without considering (to some extend) the impacts of climate change on the rest of the world. Accordingly, a Pareto-improving level of SRM deployment as suggested by Moreno-Cruz et al. (2012) could actually emerge in the future even when accounting for climate change winners. The limitations could also imply the country-specific preferences for SRM deployment are much more private information than suggested by a climate-econometric approach. Mechanism like the Vickrey-Clarke-Groves mechanism to obtain information about the true preferences for SRM deployment of countries could then be an element of a global governance framework, providing also information how much the country-specific preferences cost the rest of the world.

5 Conclusion

In his seminal paper on economic diplomacy of climate engineering, Schelling (1996) identifies three major questions: i) what to do, ii) how much to do, iii) and who pays for it. According to his view, “[] primarily the issue is who pays for it? And this is an old-fashioned issue, we have dealt with it before” (p. 306).

Our analysis supports the view that the major question is instead how much (SRM) to do, as the costs of SRM are primarily induced by under- or overprovision of SRM, and not so much the direct costs of deployment. The difficulty in answering the question how much SRM to apply arises in particular from the different preferences of countries regarding the global climate. While some countries already consider today’s climate as too warm with respect to their economic output, other countries are expected to gain economically in a warmer (future) climate. We combined information from earth system modelling on the influence of global SRM on grid-cell temperature and precipitation, information on the influence of temperature and precipitation on GDP at the grid-cell level, and information on climate change adjusted GDP growth rates in a static decision framework to discuss in more detail the question how much (SRM) to do, at different future years where the climate develops along RCP8.5. Given the various uncertainties in our framework and the overall structural limitations arising from aspects not included in our framework, our results, despite being quantitative, should be interpreted with caution. Still, they provide relevant insights for the future debate on the governance challenge associated with SRM deployment.

We conclude by highlighting four key insights. First, using climate change adjusted GDP growth rates in our analysis, we find that without any near-term significant emission reductions, SRM deployment appears to be more likely by the middle of the century. Without any near-term emission reductions or mid-of-the century SRM deployment, the future distribution of economic and thus also political weight might be very different from today's distribution.

Second, the economic incentives for many countries and in particular small island states are not sufficient to make unilateral SRM deployment beneficial. The "Tuvalu Syndrome" is not likely to materialize. With respect to the decision how much SRM to do, most influential are the 'swing' states, i.e. those countries that currently face climate conditions close to optimal. For this group of countries, small changes in temperature determine whether they remain climate change winners or turn into climate change losers with significant implications for the globally efficient level of SRM deployment.

Third, there exist strong incentives for countries to join a coalition in order to have their preferences included in the decision about the globally efficient level of SRM deployment. Countries which consider SRM deployment above a certain level or even at all as a public bad have an incentive to join the coalition to prevent that too much SRM is applied. Countries with a preference for strong cooling (high level of SRM deployment, e.g. India) and countries with a preference for no cooling (no SRM deployment, e.g. Canada) gain most from being part of the coalition.

Fourth, presuming that only a level of SRM deployment which provides global net benefit appears likely to be implementable, the grand coalition appears to be a robust guess for the solution of an SRM coalition game. Abstracting from the pure Nash equilibrium and expecting some degree of cooperation and coordination under the logic of multilateralism, future research on coalition games with externalities appears to provide an avenue for further insights for the SRM governance challenge.

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Appendix A1: Estimation Results for Gross Cell Product

Dependent Variable: LN_GDP_MIO

Method: Least Squares
Sample: 1 18841 IF D_ZEROGRID=0
Included observations: 16082
Weighting series: F1_NORD4
Weight type: Inverse standard deviation (EViews default scaling)
HAC standard errors & covariance (Bartlett kernel, Newey-West fixed bandwidth = 13.0000)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	4.346362	3.96E-01	10.9832	0
TEMP_MIX	0.161181	0.00851	18.93916	0
TEMP_2	-0.005613	0.000336	-16.70652	0
PREC_MIX	0.000364	0.000148	2.459015	0.0139
PREC_2	-9.41E-08	3.31E-08	-2.845702	0.0044
ALBANIA	-1.522356	0.532778	-2.857395	0.0043
ALGERIA	-3.919165	5.44E-01	-7.206704	0
ANGOLA	-4.241725	0.450766	-9.410033	0
ARGENTINA	-2.874349	0.417717	-6.881087	0
ARMENIA	-0.52075	0.510645	-1.019789	0.3078
AUSTRALIA	-4.622531	0.433754	-10.65703	0
AUSTRIA	2.107801	0.588813	3.579747	0.0003
AZERBAIJAN	-0.455688	0.419971	-1.085047	0.2779
BAHAMAS	-2.00209	0.872965	-2.293438	0.0218
BANGLADESH	0.743211	0.501205	1.482847	0.1381
BELARUS	-0.822668	0.460134	-1.787887	0.0738
BELGIUM	1.554218	0.501512	3.099063	0.0019
BELIZE	-3.016414	0.446391	-6.757339	0
BENIN	-2.202213	0.413985	-5.319543	0
BHUTAN	-1.658249	3.66E-01	-4.531999	0
BOLIVIA	-3.708994	0.513365	-7.224868	0
BOSNIA_HERZ	-1.428671	0.441508	-3.235886	0.0012
BOTSWANA	-3.936583	0.740037	-5.319445	0
BRAZIL	-3.498108	0.427504	-8.182635	0
BULGARIA	-1.527422	0.515713	-2.961766	0.0031
BURKINA_F	-2.500947	4.06E-01	-6.163052	0
BURUNDI	-1.487197	0.387024	-3.842651	0.0001
CAMBODIA	-2.937285	0.555618	-5.286523	0
CAMEROON	-2.74993	0.463506	-5.932884	0
CANADA	-2.14E+00	4.47E-01	-4.780215	0
CAPE_VERDE	-2.108048	0.385409	-5.469639	0
C_AFRICAN_R	-5.388663	0.517014	-10.42267	0
CHAD	-3.93033	0.488849	-8.039968	0
CHILE	-2.831067	0.530626	-5.335333	0
CHINA	-1.653621	0.396519	-4.170347	0
COLOMBIA	-2.50E+00	0.754013	-3.318859	0.0009
CONGO	-3.830156	0.534383	-7.167439	0
COSTA_RICA	-0.182172	0.437616	-0.416282	0.6772
COTE_IVORE	-2.217868	0.372461	-5.954634	0

CROATIA	-6.33E-01	0.593879	-1.066177	0.2864
CYPRUS	-2.206476	0.610998	-3.611264	0.0003
CZECH_R	1.27E+00	0.509305	2.494412	0.0126
DEMREP _CON	-5.185483	0.400802	-12.93777	0
DENMARK	0.859863	0.73164	1.175255	0.2399
DOM_REP	-0.129787	0.351693	-0.369035	0.7121
ECUADOR	-2.70E+00	0.701701	-3.843619	0.0001
EGYPT	-4.021013	0.893792	-4.498825	0
EL_SALVADOR	-0.223317	0.421823	-0.52941	0.5965
EQUA_GUINEA	-0.982997	0.353822	-2.778226	0.0055
ERITREA	-4.072045	0.437359	-9.310523	0
ESTONIA	-1.936719	0.724488	-2.673225	0.0075
ETHIOPIA	-3.633581	0.503077	-7.222715	0
FIJI	-2.020631	0.476026	-4.244792	0
FINLAND	-0.126305	0.644289	-0.196037	0.8446
FRANCE	1.202085	0.451286	2.663687	0.0077
GABON	-3.148913	0.422103	-7.460064	0
GEORGIA	-1.54512	0.414489	-3.727769	0.0002
GERMANY	2.357184	0.478281	4.928452	0
GHANA	-2.469971	0.372377	-6.632983	0
GREECE	-0.609367	0.50934	-1.196384	0.2316
GREENLAND	-2.668632	1.238554	-2.154635	0.0312
GUATEMALA	-1.372721	0.520002	-2.639837	0.0083
GUINEA	-2.617194	0.379305	-6.899978	0
GUINEA_BISS	-4.409179	0.388335	-11.35407	0
GUYANA	-5.188819	0.579548	-8.95322	0
HAITI	-1.518649	0.368569	-4.120396	0
HONDURAS	-2.469759	0.676862	-3.648838	0.0003
HUNGARY	0.729265	0.44156	1.651562	0.0986
ICELAND	-2.207643	0.701548	-3.146816	0.0017
INDIA	-0.491946	0.400357	-1.228769	0.2192
INDONESIA	-2.865508	0.434572	-6.593861	0
IRAN	-1.671535	0.456115	-3.664724	0.0002
IRAQ	-1.890226	0.470185	-4.020178	0.0001
IRELAND	-0.155026	0.588861	-0.263265	0.7923
ISRAEL	1.865933	0.523573	3.563844	0.0004
ITALY	1.279461	0.456235	2.80439	0.005
JAPAN	0.963082	0.528254	1.823142	0.0683
JORDAN	-1.995087	0.840365	-2.374071	0.0176
KAZAKHSTAN	-3.46185	0.435042	-7.957509	0
KENYA	-3.816216	0.76425	-4.993413	0
KUWAIT	1.341461	0.518487	2.587258	0.0097
KYRGYZTAN	-2.186351	0.427068	-5.119443	0
LAOS	-3.291211	0.458633	-7.176136	0
LATVIA	-1.503016	0.565991	-2.655545	0.0079
LESOTHO	-1.746894	0.407403	-4.287878	0
LIBERIA	-4.444875	0.407587	-10.90535	0
LIBYA	-4.029125	0.506799	-7.950147	0

LITHUANIA	-0.66974	0.519457	-1.289308	0.1973
MACEDONIA	-1.059343	0.464676	-2.279745	0.0226
MADAGASCAR	-4.531261	0.426272	-10.62999	0
MALAWI	-2.190573	0.458472	-4.777985	0
MALAYSIA	-1.282716	0.605359	-2.118933	0.0341
MALI	-4.800131	0.686186	-6.995375	0
MAURITANIA	-4.428969	0.603402	-7.339994	0
MEXICO	-1.240696	0.436797	-2.840441	0.0045
MOLDOVA	-1.097495	0.512666	-2.140759	0.0323
MONGOLIA	-4.283205	0.433547	-9.87945	0
MOROCCO	-3.210169	0.762599	-4.209511	0
MOZAMBIQUE	-4.178945	0.430474	-9.70777	0
NAMIBIA	-4.688622	0.535958	-8.748106	0
NEPAL	-1.258338	0.403034	-3.122162	0.0018
NETHERLANDS	1.778475	0.537326	3.309864	0.0009
NEW_CAL	-2.096144	0.407778	-5.140407	0
NEW_ZEA	-2.871642	0.707838	-4.056919	0
NICARAGUA	-3.629307	0.673088	-5.392025	0
NIGER	-4.804203	0.704118	-6.823008	0
NIGERIA	-1.669876	0.445725	-3.746424	0.0002
NORWAY	-0.448482	0.561035	-0.799383	0.4241
OMAN	-2.889525	1.037792	-2.784301	0.0054
PAKISTAN	-1.497188	0.6054	-2.473056	0.0134
PANAMA	-1.523433	0.640047	-2.380189	0.0173
PAPUA_NGUI	-4.149904	0.412246	-10.06657	0
PARAGUAY	-3.427656	0.877628	-3.905591	0.0001
PERU	-2.86759	0.49522	-5.790541	0
PHILIPPINES	-1.261888	0.394689	-3.197173	0.0014
POLAND	0.60744	0.517889	1.172915	0.2408
PORTUGAL	-0.271922	0.50853	-0.534722	0.5928
QATAR	-0.417353	0.659043	-0.633271	0.5266
ROMANIA	-0.567658	0.517381	-1.097176	0.2726
RUSSIA	-1.996027	0.399931	-4.99093	0
SAUDI_ARA	-1.037902	0.406428	-2.55372	0.0107
SENEGAL	-2.381783	0.421141	-5.655546	0
SERBIA_MONT	-1.738642	0.544379	-3.193809	0.0014
SIERRA_LEON	-2.729974	0.514369	-5.307424	0
SLOVAKIA	1.134938	0.479628	2.366288	0.018
SLOVENIA	0.662914	0.427251	1.551581	0.1208
SOLOMON_IS	-3.569268	0.433567	-8.232335	0
SOUTH_AFR	-2.651198	0.605156	-4.381013	0
SOUTH_KOR	0.785687	0.428125	1.835183	0.0665
SPAIN	0.408132	0.447371	0.91229	0.3616
SRI_LANKA	-0.335514	0.437174	-0.767461	0.4428
SUDAN	-4.057682	0.459575	-8.829202	0
SURINAME	-5.268049	0.539793	-9.759383	0
SWAZILAND	-1.301114	0.357951	-3.634895	0.0003
SWEDEN	-0.009696	0.508033	-0.019086	0.9848

SWITZERLAND	3.113248	0.517432	6.016725	0
SYRIA	-1.01992	0.44695	-2.281957	0.0225
TAJIKISTAN	-2.072591	0.426205	-4.862893	0
TANZANIA	-3.021563	0.375618	-8.044242	0
THAILAND	-0.75852	0.412994	-1.836638	0.0663
TOGO	-2.015156	0.391109	-5.152422	0
TUNISIA	-1.613095	0.516301	-3.124333	0.0018
TURKEY	-0.338233	0.406918	-0.831206	0.4059
TURKMEN	-3.03288	0.447217	-6.78167	0
UGANDA	-1.352627	0.373879	-3.617814	0.0003
UKRAINE	-1.665652	0.457776	-3.638574	0.0003
U_ARAB_EMI	1.22237	0.440839	2.772826	0.0056
UK	0.271528	0.821004	0.330727	0.7409
US	0.709571	0.402101	-1.764659	0.0776
URUGUAY	-2.168983	0.395988	-5.477391	0
UZBEKISTAN	-2.947781	0.939026	-3.139189	0.0017
VANUATU	-3.536107	0.379356	-9.321336	0
VENEZUELA	-3.548386	0.915722	-3.87496	0.0001
VIETNAM	-1.979482	0.449601	-4.402751	0
YEMEN	-3.77439	0.817046	-4.619554	0
ZAMBIA	-3.999902	0.417123	-9.58927	0
ZIMBABWE	-2.983198	0.410515	-7.266961	0
D_RICH	3.059812	0.393349	7.778873	0
D_SUPERRICH	1.234665	0.513476	2.404521	0.0162
D_SHORT	0.447628	0.089946	4.976644	0
D_MED	0.39494	0.094703	4.170306	0
D_LONG	0.574937	0.074014	7.7679 0	
AREA	0.000247	8.92E-06	27.72791	0
ELEV	-0.000333	4.83E-05	-6.89187	0
D_LAT	-0.421148	0.099085	-4.250363	0

<u>Weighted Statistics</u>

R-squared	0.618192	Mean dependent var	4.561244
Adjusted R-squared	0.614258	S.D. dependent var	2.66614
S.E. of regression	1.612015	Akaike info criterion	3.803053
Sum squared resid	41361.77	Schwarz criterion	3.881905
Log likelihood	-30415.35	Hannan-Quinn criter.	3.829126
F-statistic	157.1434	Durbin-Watson stat	0.637535
Prob(F-statistic)	0	Weighted mean dep.	4.560228
Wald F-statistic	83.64945	Prob(Wald F-statistic)	0

<u>Unweighted Statistics</u>

R-squared	0.629981	Mean dependent var	4.559587
Adjusted R-squared	0.626168	S.D. dependent var	2.579433
S.E. of regression	1.577111	Sum squared resid	39590.03
Durbin-Watson stat	0.622036		

Appendix A2: Sensitivity of Globally Efficient SRM Deployment

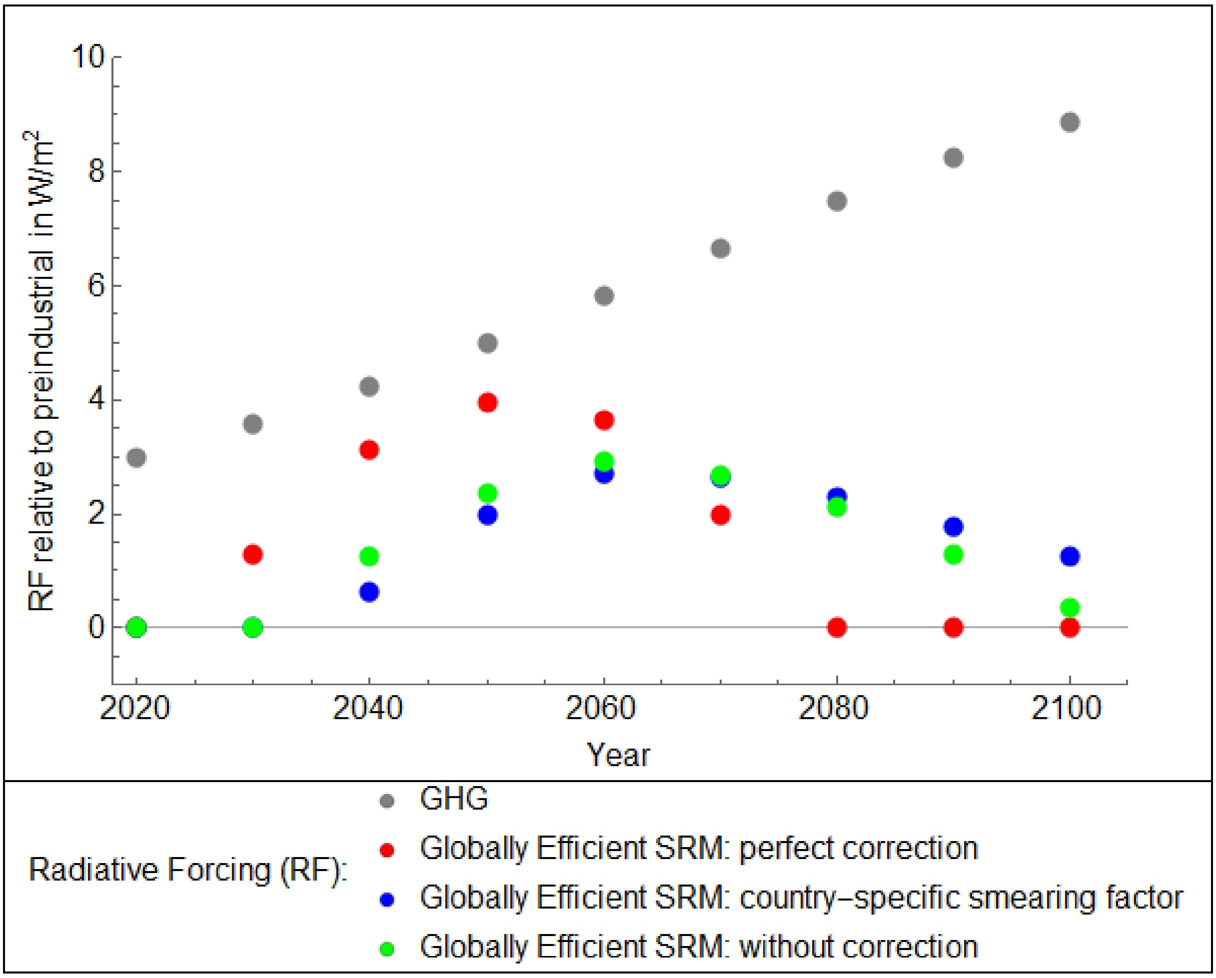

Figure A2.1 Dependence of the Globally Efficient Level of SRM Deployment from the Correction Factor at Different Points in Time. *Each red, blue, and green dot displays the solution to the static optimization problem of determining the global efficient level of SRM deployment, given the degree of climate change experienced so far (which corresponds to RCP8.5 and is shown in terms of GHG forcing by the gray dots) for the application of a perfect correction factor, of a country-specific smearing factor, and without correction factor, respectively.*

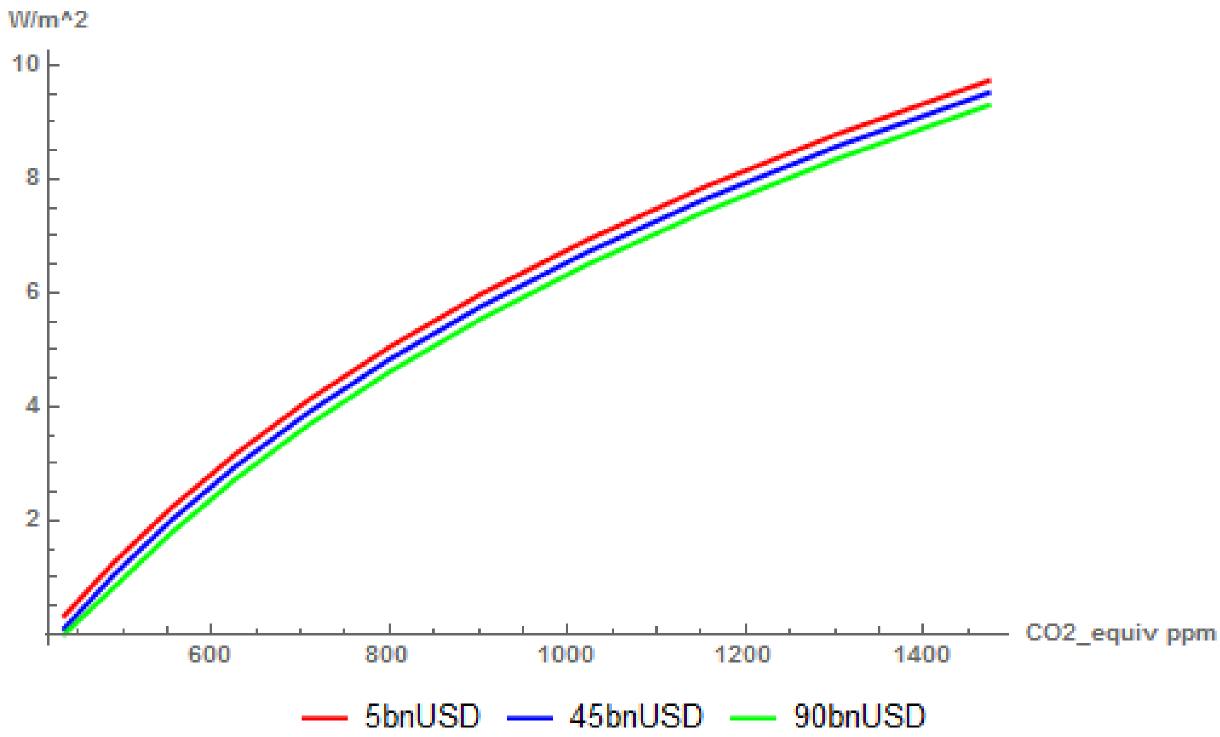

Figure A2.2 Dependence of the Globally Efficient SRM Level from the Operational Cost in 2050. *The figure shows the globally efficient level of SRM deployment (in W/m^2) in 2050 for three different cost estimates from the literature against increasing GHG concentration.*

Appendix A3: Distribution of Countries in Figure 2 in the Years 2050 and 2060

	2050	2060
A1	Australia, Brazil, Egypt, Hong Kong, India, Indonesia, Mexico, Nigeria, Saudi Arabia	Australia, Bangladesh, Brazil, Egypt, Hong Kong, India, Indonesia, Mexico, Nigeria
A2	Bangladesh	Philippines
A3		China, Japan, United States
A4	Algeria, Angola, Antigua and Barbuda, Argentina, Bahamas, Bahrain, Barbados, Belize, Benin, Bolivia, Cameroon, Botswana, Brunei, Burkina Faso, Burundi, Cambodia, Cape Verde, Central African Republic, Chad, Colombia, Comoros, Congo, Costa Rica, Cote d'Ivoire, Cyprus, Democratic Republic of Congo, Djibouti, Dominican Republic, Ecuador, El Salvador, Equatorial Guinea, Eritrea, Ethiopia, Federated State of Micronesia, Fiji, French Polynesia, Gabon, Gambia, Ghana, Greece, Grenada, Guatemala, Guinea, Guinea Bissau, Guyana, Haiti, Honduras, Iran,	Algeria, Angola, Antigua and Barbuda, Argentina, Bahamas, Bahrain, Barbados, Belize, Benin, Bolivia, Cameroon, Botswana, Brunei, Burkina Faso, Burundi, Cambodia, Cape Verde, Central African Republic, Chad, Colombia, Comoros, Congo, Costa Rica, Cote d'Ivoire, Cyprus, Democratic Republic of Congo, Djibouti, Dominican Republic, Ecuador, El Salvador, Equatorial Guinea, Eritrea, Ethiopia, Federated State of Micronesia, Fiji, French Polynesia, Gabon, Gambia, Ghana, Greece, Grenada, Guatemala, Guinea, Guinea Bissau, Guyana, Haiti, Honduras, Iran,

	Iraq, Israel, Jamaica, Jordan, Kenya, Kuwait, Laos, Lebanon, Liberia, Libya, Madagascar, Malawi, Malaysia, Mali, Malta, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Nepal, New Caledonia, Nicaragua, Niger, Oman, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Portugal, Puerto Rico, Qatar, Rwanda, Samoa, Sao Tome and Principe, Senegal, Sierra Leone, Singapore, Solomon Islands, South Africa, Spain, Sri Lanka, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Sudan, Suriname, Swaziland, Syria, Tanzania, Thailand, Togo, Tonga, Trinidad and Tobago, Tunisia, Turkmenistan, Uganda, United Arab Emirates, Uruguay, Vanuatu, Venezuela, Vietnam, West Bank and Gaza, Yemen, Zambia, Zimbabwe	Iraq, Israel, Italy, Jamaica, Jordan, Kenya, Kuwait, Laos, Lebanon, Liberia, Libya, Madagascar, Malawi, Malaysia, Mali, Malta, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Nepal, New Caledonia, Nicaragua, Niger, Oman, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Portugal, Puerto Rico, Qatar, Rwanda, Samoa, Sao Tome and Principe, Saudi Arabia, Senegal, Sierra Leone, Singapore, Solomon Islands, South Africa, Spain, Sri Lanka, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Sudan, Suriname, Swaziland, Syria, Tanzania, Thailand, Togo, Tonga, Trinidad and Tobago, Tunisia, Turkmenistan, Uganda, United Arab Emirates, Uruguay, Vanuatu, Venezuela, Vietnam, West Bank and Gaza, Yemen, Zambia, Zimbabwe
B1	China, Italy, Japan, United States	Uzbekistan
B2	Lesotho, Uzbekistan	Albania, Azerbaijan, Croatia, Lesotho, South Korea, Turkey
C	Albania, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bhutan, Bosnia&Herzegovina, Bulgaria, Canada, Chile, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greenland, Hungary, Iceland, Ireland, Kazakhstan, Kyrgyztan, Latvia, Lithuania, Luxembourg, Macedonia, Moldova, Mongolia, Netherlands, New Zealand, Norway, Poland, Romania, Russia, Serbia and Montenegro, Slovakia, Slovenia, South Korea, Sweden, Switzerland, Tajikistan, Turkey, Ukraine, United Kingdom	Armenia, Austria, Belarus, Belgium, Bhutan, Bosnia&Herzegovina, Bulgaria, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greenland, Hungary, Iceland, Ireland, Kazakhstan, Kyrgyztan, Latvia, Lithuania, Luxembourg, Macedonia, Moldova, Mongolia, Netherlands, New Zealand, Norway, Poland, Romania, Russia, Serbia and Montenegro, Slovakia, Slovenia, Sweden, Switzerland, Tajikistan, Ukraine, United Kingdom

Table A3.1: Distribution of Countries across Incentive-Areas in the year 2050 and 2060.