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Quantifying Non-cooperative Climate Engineering

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Summary

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Keywords: Climate Engineering, Climate Governance, Free Driving, Climate Policy

JEL Classification: H41, Q54, Q58

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Quantifying non-cooperative climate engineering[*]

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December 12, 2017

Abstract

The mismatch between actions to combat climate change, which are based on voluntary national initiatives of limited effort, and the recognition of the importance of global warming is growing. Climate engineering via solar radiation management has been proposed as a possible complement to traditional climate policies. However, climate engineering entails specific risks, including its governance. Free driving, the possibility of unilateral climate engineering to the detriment of other nations, has been recently proposed as a potentially powerful additional externality to the traditional free riding one (Weitzman, 2015). This paper provides the first quantitative evaluation of the risks of free driving. Our results indicate that in a strategic setting there is significant over-provision (by almost an order of magnitude) of climate engineering above what is socially optimal, resulting in a sub-optimal global climate. Regions with high climate change impacts, most notably India and developing Asia, deploy climate engineering at the expenses of other regions.

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Motivation

The slow progress in climate change abatement policies aimed at reducing greenhouse gas emissions is in stark contrast with the estimated impacts of a warmer world. On the one hand, international climate policy has produced little in terms of emission reductions. The Paris climate agreement has been rightly considered an important step forward, due its wide coverage. But the treaty falls short of delivering the emissions cuts needed to stabilize global climate at low temperatures (UNEP, 2010; Rogelj et al., 2015; Aldy et al., 2016). Most importantly, the bottom up architecture is based on voluntary, nationally determined contributions which are inefficient and remain hostage of the political variability, making the agreement particularly fragile. This is in stark contrast with the increased long term ambition in terms of limiting global mean temperature increase, which has been set by the agreement to well below 2°C, and in the direction of 1.5°C. Among other things, one of the reason for the tight target is the increased recognition of the high impacts of climate

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change on economic and ecological systems. Recent estimates suggest significantly higher impacts (Burke et al., 2015), and emphasize non linear damages and tipping points (Lenton et al., 2008).

The observed discrepancy between what should be done and what is actually observed should not come as a particular surprise. Economists and political scientists has since long warned about the difficulty of establishing a climate agreement which is both effective and stable (Carraro and Siniscalco, 1993; Barrett, 1994). The main issue undermining the policy solution is the very essence of global warming, namely that it is a global externality and that we lack the institutions required to govern it. This gap in action has fueled the discussion about alternative policy options in order to cope with the impacts from climate change. Among these, climate engineering (CE) refers to the deliberate and large-scale intervention in the Earth's climatic system with the aim of reducing global warming. One prominent climate engineering option, Solar Radiation Management (SRM)[1], which counteracts the temperature increase by managing incoming solar radiation, has become increasingly debated in recent years, see Bickel and Agrawal (2011),Gramstad and Tjøtta (2010), Goes et al. (2011), Moreno-Cruz and Keith (2013), and Heutel et al. (2016).

Although the potential of SRM to substitute or complement mitigation measures has been mostly assessed in the global context, its impacts on the strategic incentives in the context of climate negotiations are particularly relevant, as originally suggested by Schelling Schelling (1996). Climate engineering raises specific governance issues(Victor et al., 2009).The important strategic feature of climate engineering has been discussed in the fields of science, economics, law, and politics. VirgoeVirgoe (2008) discusses several potential governance schemes to deal with the unilateral and non-cooperative incentives that can arise from SRM. Overall, the strategic nature and regional heterogeneity provide strategic incentives for the use of SRM.[2] Therefore, the possibility of unilateral implementation needs to be considered (Rabitz, 2016).

Among the various governance issues, one argument has been recently put forward (Weitzman, 2015): namely, that climate engineering is so relatively cheap (Barrett, 2008) that it might be deployed unilaterally by one country to the detriment of others, due to side its effects or asymmetric impacts. Weitzman has dubbed this new form of strategic interaction as 'free driving'. The familiar free riding externality which is at the basis of the climate change dilemma is thus extended to the case of climate engineering: if free riding leads to under-provision of emission reduction, free driving would lead to an over provision of climate engineering above what would be the global social optimum. The challenges in governing both externalities would be enormous, since they both suffer from the same lack of supra-national institutions. New governance architectures can of course be envisaged and designed (Weitzman, 2015), but the current reality is that of nation states acting in their own interest.

Given its relevance for climate policy, an assessment and comparison of this double externality is warranted. This paper aims at providing a first evaluation of the risk of free driving, vis-à-vis that of free riding. In order to do so, we first lay out a conceptual framework for thinking about climate engineering under non-cooperative and cooperative cases. Then, we use a calibrated energy-climate-economy model to numerically quantify the free driving effect and to perform sensitivity analysis.

A game-theoretic framework

Given the strategic implications of climate engineering, it is useful to lay out a simple game theoretic model to help framing the problem, before moving to the calibrated numerical analysis. Several dynamic games

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[1] For simplicity, we will use CE and SRM interchangeably throughout the paper.

[2] Indeed, Rayner et al. (2013) suggested the so-called "Oxford principles" as a first guidance for governance and research on CE by countries including its regulation as public good as first principle.

have been proposed in the literature. Ricke et. al.Ricke et al. (2013) provide a numerical assessment of coalition formation in a two-stage game of coalition formation. Millard-BallMillard-Ball (2012) considers the formation of a climate agreement about mitigation, with individual decision to implement CE. He shows that a credible threat of unilateral geoengineering may strengthen global abatement and climate cooperation. UrpelainenUrpelainen (2012) considers a simple two period deterministic model, showing that the availability for CE in the future increases mitigation effort at present. Moreno-CruzMoreno-Cruz (2015) also studies the dynamic nature of the SRM-Mitigation trade-off in a sequential two-stage game, and finds that highly asymmetric impacts are an important driver of potential over-provision of CE. Manoussi and XepapadeasManoussi and Xepapadeas (2015) study a differential game between two heterogeneous countries, also finding countries with higher benefits/lower costs will engage more in using CE. Goeschl et. al.Goeschl et al. (2013) analyze long-term inter generational trade-offs due to the possibility of CE, while Quaas et. al.Quaas et al. (2017) consider the dynamics including the strategic decision on whether or not to engage in research on SRM in the first place. Moreno-Cruz and SmuldersMoreno-Cruz and Smulders (2017) also develop optimal and strategic CE facing impacts from temperature increase and carbon concentrations (using a more complex carbon cycle) in an one-stage game, which is the most related to our approach.

Here, we follow BarretBarrett (2008) and Weitzman Weitzman (2015) and propose a static game-theoretic model of optimal abatement and SRM policies. The strategy set is$\{a_i, s_i\}$ -abatement a_i and climate engineering s_i indexed by region $i = 1..N$. We use a standard cost-benefit analysis approach, whereby each country minimizes total costs from deployment of abatement and CE technologies, as well as impacts from global warming and CE deployment.

For modeling the global climate, we use the carbon budget approach (Urpelainen, 2012; Matthews et al., 2009) and express the global mean temperature change ΔT as a linear function of both total cumulative emissions and SRM. Cumulative emissions are the sum of projected Business as usual (BAU) emissions without any climate policy (e_j^{bau}) in region j over all regions N. SRM directly lowers global temperature, proportionally to the global SRM deployment. We denote by γ the transient climate response (Matthews et al., 2009) , that is the change in mean temperature due to cumulative carbon emissions, and by λ the effectiveness of SRM to reduce temperature, so that global mean temperature increase is given by:[3]

$$\Delta T = \gamma \sum_{j=1}^{N} (e_j^{bau} - a_j) - \lambda \sum_{j=1}^{N} s_j$$

Each country i solves the problem of minimizing the total costs (TC_i) from abatement, SRM deployment, climate change impacts and SRM impacts given by:

$$TC_i = C_{Ai}(a_i) + C_{Si}(s_i) + D_{Ti}(\gamma \sum_{j=1}^{N} (e_j^{bau} - a_j) - \lambda \sum_{j=1}^{N} s_j) + D_{Si}(\sum_{j=1}^{N} s_j)$$

We can derive the first order conditions under both the Nash equilibrium and global optimum, as shown in the Appendix for the case of a fully quadratic specification of costs and impacts. We focus on the symmetric case of identical countries to show the differences between cooperative and non-cooperative solutions. More general cases are discussed in the Appendix. Naming marginal damages from global temperature increase

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[3] Back of the envelope calculations suggest for λ a value of $1.5 \frac{TtC}{MtS}$. This is based on a radiative forcing from SRM of $-1.75 \frac{W/m^2}{MtS}$ (Gramstad and Tjøtta, 2010), a typical value for radiative forcing from carbon emissions of $0.8 \frac{K}{W/m^2}$, and global warming effect from cumulative emissions of $1.5 \frac{K}{GtC}$ (Matthews et al., 2009) and computed as $\frac{1.75 \frac{W/m^2}{MtS}}{1.5 \frac{K}{TtC} / 0.8 \frac{K}{W/m^2}}$.

τ, mitigation costs α, impacts from SRM θ and SRM implementation costs σ, we find for each country the optimal level of SRM under cooperation is

$$s_{sym}^{coop} = \frac{1/N}{\lambda + \frac{\gamma}{\lambda}\left(\frac{N^2\theta+\sigma}{\alpha} + \frac{N^2\theta+\sigma}{\gamma\tau N^2}\right)} \left(\gamma \sum_{j=1}^{N} e_j^{bau}\right) \tag{1}$$

while in the non-cooperative Nash equilibrium it is given by

$$s_{sym}^{strategic} = \frac{1/N}{\lambda + \frac{\gamma}{\lambda}\left(\frac{N\theta+\sigma}{\alpha} + \frac{N\theta+\sigma}{\gamma\tau N}\right)} \left(\gamma \sum_{j=1}^{N} e_j^{bau}\right). \tag{2}$$

SRM deployment is driven by the efficacy to compensate global warming ($\frac{\gamma}{\lambda}$) and four terms comparing costs and benefits -two of which depend on N. For $N = 1$, SRM deployment is the same under the strategic and cooperative cases, and as expected there is no free driving. When $N > 1$, two effects drive a wedge between the cooperative and strategic solution: the first term in the parenthesis in the denominator of (1) and (2) represents the "free-driving effect" depending on the costs from SRM (implementation costsσ and impacts θ) compared to mitigation costs (α). This term differs between cooperative and strategic solutions: in the cooperative case, the impact of SRM in all regions are taken into account hence the factor N^2 instead of N. This leads to a wedge in SRM deployment between strategic and cooperative cases, which grows in N . The second term in the parenthesis basically compares both externalities, climate and SRM, and is of second order compared to the first effect: since the climate externality scales in N both for climate impacts and SRM impacts, here N cancels in the numerator and denominator, while only private SRM costs (σ) do not scale in N. Thus, if N increases, the second term leads to higher SRM in the cooperative compared to the strategic solution. Note however that this effect is linear in the marginal cost of SRM σ. That is, for comparably small implementation costs compared to it potential impacts, i.e., $\sigma \ll \theta$, this effect becomes negligible and the free riding due to the first term effect dominates. Indeed, as discussed in the introduction, the concept of free driving assumes that climate engineering costs are low, as it is believed to be case, see Barrett (2008).

Figure (1) provides a graphical illustration of the free driving effect, measured by the ratio of SRM in the strategic case over what socially optimal. Results are based on a calibration to given stylized facts (see the Appendix for details) under different specification and for increasing number of countries. The picture shows that when the costs of climate engineering are zero or sufficiently low, free driving grows almost linearly in the number of regions, especially for $N > 5$. When climate engineering has no adverse impacts ($\theta = 0$), there is no free driving simply because SRM is fully deployed in both cooperative and strategic solutions.

Numerical quantification

The previous section has indicated that free driving grows in the number of countries. In order to quantitatively estimate the free driving effect, we need to move to a more realistic model. We employ a calibrated energy-economy-climate model which optimizes investments in both climate engineering and mitigation in a setting with strategic interactions among nations and no cooperation, and compare it to a benchmark case with full cooperation, representing the world social optimum. The gap between these two climate architecture allows us to estimate free driving and free riding simultaneously. We use the game theoretic integrated assessment model WITCH (Bosetti et al., 2009; Emmerling et al., 2016), a numerical model which has been

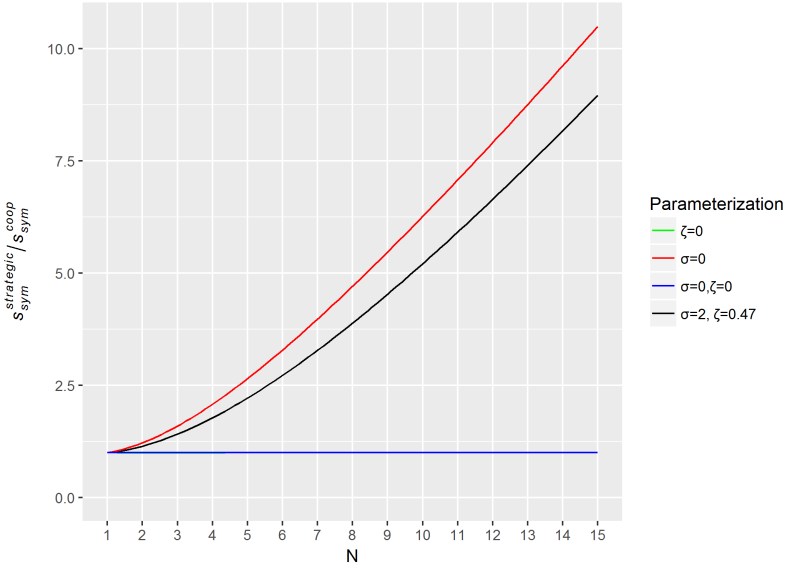

Figure 1: Free driving effect (ratio of SRM deployment in strategic over cooperative) as a function of the number of countries N.

extensively used to evaluate climate mitigation policies. The model integrates the energy sector into a dynamic optimal growth economic model, and runs for the whole century at five year time steps. WITCH divides the world into 13 regions, and can represent both the non-cooperative Nash and the cooperative Pareto solutions (see the Appendix for more details). Similarly to the analytical model, we use a cost benefit framework in which the cost of acting on climate change -either via mitigation or climate engineering- is weighted against the benefits of lowering global temperature. Climate change impacts are a quadratic function of global temperature, with regionally differentiated and calibrated impacts Bosello and De Cian (2014).

We expand the standard version of the model to include an SRM module, which accounts for operational costs, effectiveness in compensating temperature as well as social and environmental impacts of climate engineering. See the Appendix for the module description and calibration. The first two issues are relatively well understood in the literature, and we use a linear cost function and proportional compensation of radiative forcing to SRM. As for the external costs of SRM -which include possible damage to the ozone layer, side effects of the implementation itself, as well as region-specific impacts such as increased droughts and other eco-system impacts (Russell et al., 2012), these are currently unknown and profoundly uncertain. We assume them to be global, and follow Goes et al. (2011), who suggest economic impacts of a fixed percentage of consumption for a given amount of SRM. We provide boundary analysis via sensitivity scenarios. In addition, in order to capture a specific consequence of SRM regarding the potential impact from abrupt warming or cooling, which is not covered by standard damage functions, we assume a damage term coming from temperature variation (as opposed to level) and calibrated on Lempert et al. (2000). We further assume that SRM will be available from mid century onward, since SRM still needs to be further researched before being deployed at scale.

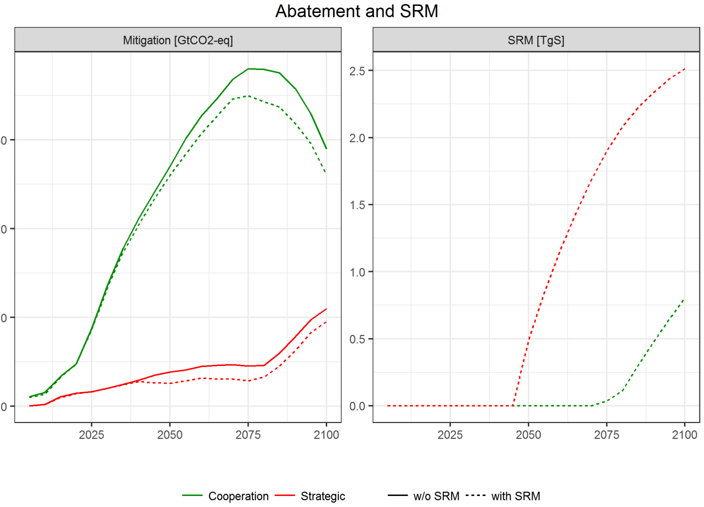

Figure 2: Cumulative mitigation (all greenhouse gases, 2010-2100) and SRM deployment for the cooperative and strategic scenarios, with and without SRM.

Global free driving

The calibrated energy-climate model allows estimating free driving. To do so, we implement a two-by-two scenario design with cooperation and strategic interaction as one dimension, and availability of SRM as the other. This yields 4 scenarios, in addition to a counterfactual business as usual without climate change and SRM. Figure 2 provides the main global results in terms of cumulative emission mitigation (left panel) and SRM deployment (right panel). The left panel highlights a major decline in emission reduction when moving from a cooperative setting to a non-cooperative one. This is the familiar issue of free riding, which limits the incentives to reduce CO2 emissions when countries do not cooperate for the public good but rather act in their own interest. Cumulatively over the century, free riding reduces mitigation by 85.4 and 82.9 for the cases with and without SRM respectively. When climate engineering is available (dashed lines), we notice a reduction in mitigation, both in the case of cooperation and in the strategic non-cooperative one. That is, we have evidence of SRM crowding out mitigation effort. This moral hazard effect has been often described as one of the main rationale for banning SRM from the set of climate strategies (McLaren, 2016). Although our estimates indicate some substitution , quantitatively the mitigation crowd out is small compared to the free riding effect (6.9% for the cooperative case, and 21.2% for the strategic case). The right panel reports deployment of SRM in the scenarios where this is available. The chart provides evidence of significant free driving: cumulatively over the second half of the century, SRM is over-provided by a factor of 8 in the strategic case ($19.1 TgS$) with the respect to the socially desirable level ($2.4 TgS$). The almost one order of magnitude free riding effect confirms the quasi linear predictions of the analytical model presented in the previous section. Overall, the SRM over-provision appears to be of a similar magnitude than the under-provision of GHG mitigation: that is, free riding and free driving are externalities of similar size.

Figure 3 shows the implications for global temperature increase.[4] Without SRM, end of century temperature would increase by 2.8°C with cooperation and by 3.5°C without cooperation. That is, free riding -by

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[4] In the appendix in Figure 12 we show the CO2 concentration.

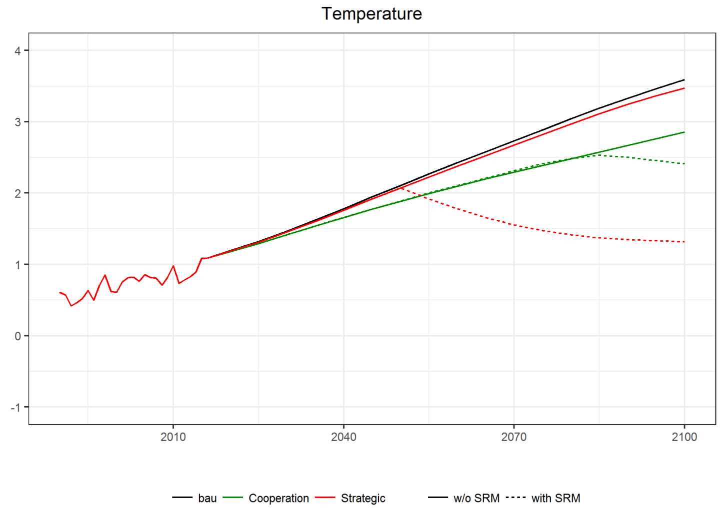

Figure 3: Global temperature over the 21st century (compared to preindustrial levels) across scenarios.

weakening mitigation efforts- increases end of century temperature by about 0.7°C, bringing it very close to the BAU case of no climate damages. Availability of SRM allows to decrease temperature moderately under cooperation (from 2.8°C to 2.4°C), but dramatically under non cooperation (from 3.5°C to 1.1°C). It is worth noticing how globally sub-optimal this outcome is. In a world governed by supra-national institutions which maximize global welfare by internalizing the impacts of SRM, SRM will be used to lower temperature only late in the century and moderately, by less than 0.5°C. In a world characterized by national interests and no coordination, SRM would be used excessively (2.4°C of cooling) and from the onset (year 2050).

Since deploying SRM generates global external costs, the over-provision of SRM documented in the previous chart can negatively influence global welfare, outweighing the benefits of reduced global warming. This is indeed what we show to be the case in Figure 4. Policy costs[5] are higher in the strategic scenarios, and increase when SRM is made available. On the contrary, cooperation lowers policy costs, and these are not affected by whether SRM is there or not. The global economic losses from free-riding (2.8%-0.6%=2.2%) further increase in the case of free driving (3.2%-0.6%=2.6%).

Decomposing the difference in policy costs between the runs with and without SRM over time, the lower panel of Figure 4 shows that climate engineering external costs outweigh the benefits of lower temperature throughout all the century. The gap between benefit of lower temperature and external damages of climate engineering are much bigger for the strategic scenarios, which we as we have seen is characterized by a much larger deployment of SRM. The other costs components appear to have only second order effects.

Regional distribution of climate engineering

So far we have looked at the global picture. Let's now turn to the disaggregated regional results coming from the integrated model, which divides the world into 13 macro-economic regions. Figure 5 reports the regional distribution of SRM deployment. The cooperative scenario shows a low level of SRM–as documented before. Moreover, given that we don't consider equity weights between regions and the implementation costs of SRM

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[5]

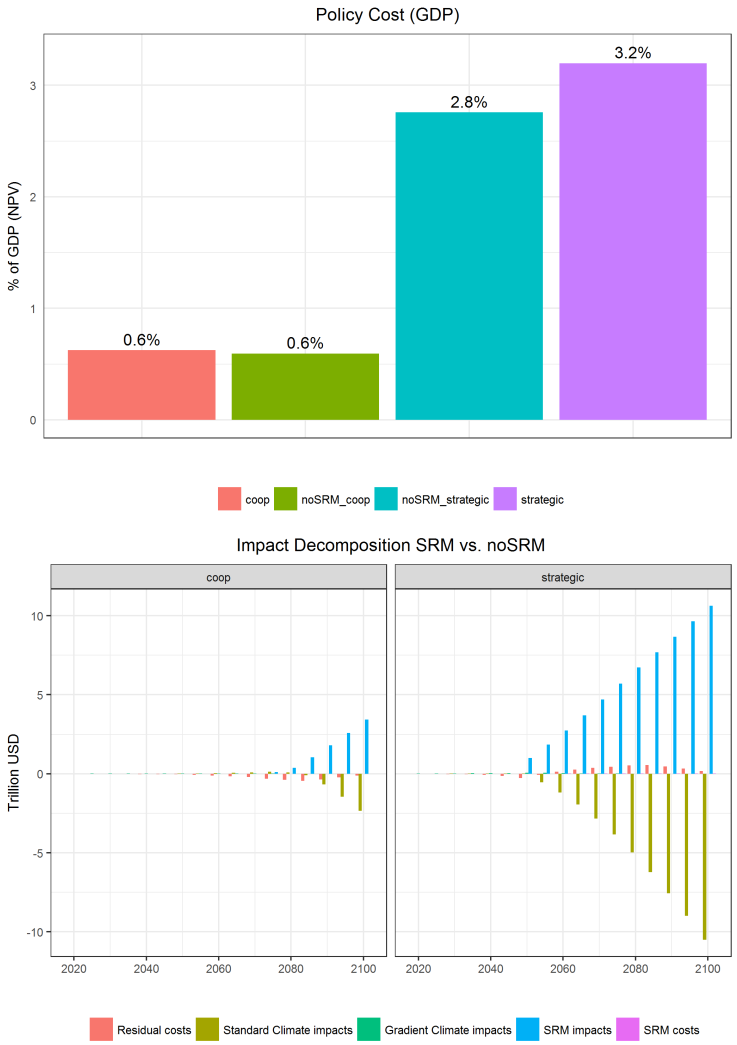

Figure 4: Global welfare impacts of climate engineering. Upper panel: policy costs computed as GDP losses over the BAU, aggregated over time as net present value (NPV) using a 3% discount rate.Lower panel: policy costs difference between "with SRM" and "w/o SRM" scenarios decomposed by source and over time.

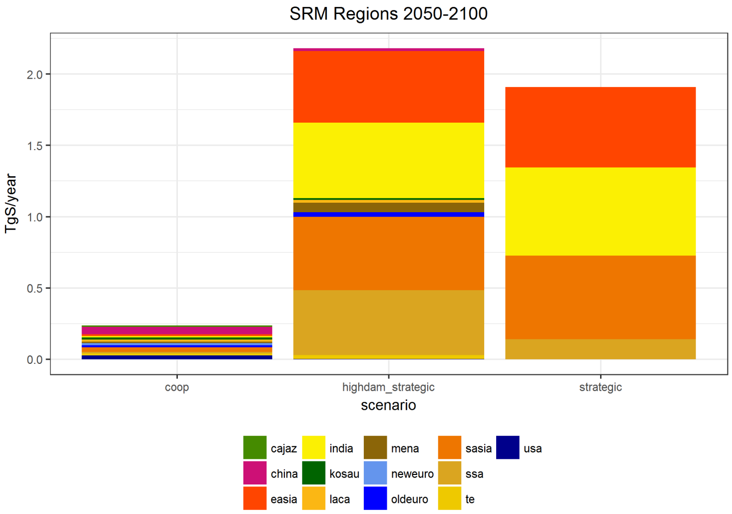

Figure 5: Regional distribution of SRM. Cumulative (2050-2100) SRM deployment across regions for the cooperative case (left bar), and the strategic cases with normal and high climate impacts (right and central bars). For the definition of the regions, see Figure 8 in the Appendix.

are linear (see Appendix 6), the distribution between regions does not matter and the results presented here prescribe an even split among regions. The most interesting results come from the non-cooperative cases, which will be the focus of the regional analysis from here onward. Finding a unique solution to this problem is not a trivial task, since multiple equilibria exist. In Appendix we discuss the approximation algorithm which we use.

Results in Figure 5 indicate that SRM would be deployed in few regions, namely ’South (sasia)’ and ’South-East Asia (seasia)’, ’India’ and ’Sub-Saharan Africa (ssa)’, and to a minor extent in ’Middle East and North Africa (mena)’. Results are confirmed when assuming that only one country at a time can deploy SRM (see Figure 10 in the Appendix). The total SRM and its regional distribution appear to be relatively similar when assuming higher climate change impacts, shown in the same chart. We also performed sensitivity analysis with respect to the damages of SRM, which are highly uncertain -see Figure 11 in the Appendix. Total SRM scales approximately linearly with the external impacts of SRM, in the expected direction of lower impacts leading to more SRM. For low SRM damages, some additional tropical region -such as ’Latin and Central America (laca)’- deploy it. Across all specifications, South Asian economies always deploy SRM. Overall, SRM deployment is not very sensitive to its impacts: the upper and lower boundaries considered differ from the central case by roughly $1 - 2$ TgS/year, compared to the central estimate of 2 TgS/year.

The rationale for the regional distribution of SRM is shown in Figure 6. Developing Asia and Africa show the highest climate benefits, in terms of reduced impacts from climate change. Indeed, these are the regions which would suffer the most from climate change according to our climate impact function9.Abstracting from the side effects of climate engineering, the global climate benefits of lowering temperature would be substantial, from an expected economic loss in 2100 of around 14 trillion USD without SRM, down to 3 trillion with SRM. Of these almost 11 trillion USD in reduced climate impacts, 7.5 trillion USD would accrue to the regions deploying SRM in Asia and Africa. Still, these countries would experience more than half of the total residual climate damages. Moreover, lowering global temperature via SRM comes at the cost of high impacts from SRM, shown in Figure 6 as a blue line.

To further delve into the strategic aspects of SRM, we evaluate which regions are gaining or losing

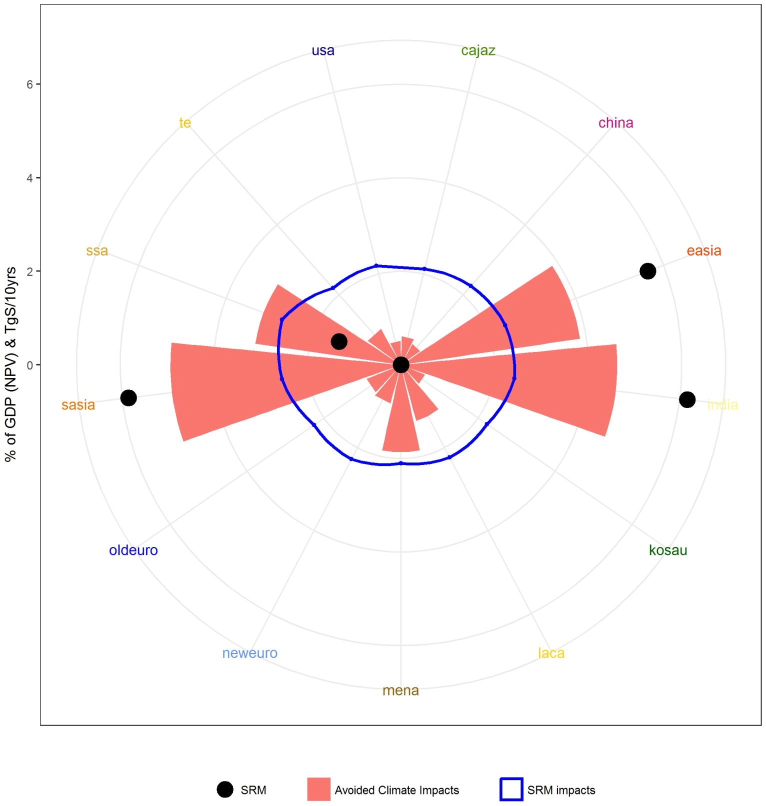

Figure 6: Avoided climate impacts due to SRM and SRM impacts (in % of GDP NPV, 3% discount rate), as well as SRM deployment (TgS per decade), for the strategic scenarios.

from its availability. Figure 7 plots welfare and consumption losses both with and without SRM for the 13 regions. The diagonal line separates regions winning from SRM (above) from those loosing (below). The chart indicates that the countries which do deploy SRM -in Asia and Africa- gain from doing so, at the expenses of all other regions. However, total welfare (lower panel) is not significantly affected, and the regions supporting SRM remain among the poorest in the world, both because of general economic factors as well due to the higher impacts of climate change in these countries.

Conclusion

The analytical and numerical modeling exercises described in this paper document a significant risk of climate engineering via free driving. When accounting for national strategic incentives, we find almost an order of magnitude of over-provision of climate engineering above what socially optimal. Free driving on climate engineering appears to be as significant as free riding on emission reductions. The regional results highlight that the countries with higher expected impacts from climate change -India, South and Southeast Asia, and to a lesser extent Africa- would be the ones deploying climate engineering at the expenses of the rest of the World. Despite it, these poor countries would still host the majority of climate change impacts. These results bear important repercussions for international climate policy. Climate engineering has been often described as a possible solution in case climate negotiations over mitigation fail. Indeed, its cost effectiveness in reducing global temperature and the ability to do so in rapid time is unparalleled. However, it is vital that climate engineering is discussed and negotiated within the few existing supra-national institutions and possibly jointly with mitigation measures. In such a setting, our model has shown that climate engineering could provide a valuable complement to emission mitigation, lowering global temperature by 0.4°C. On the other hand, failure to collectively manage climate engineering would results in free driving. This would lead to too much SRM, and to a total welfare loss as the benefits from a less hot planet would be more than offset by the damages inflicted by SRM deployment.

The underlying analysis is greatly simplified, especially for what concerns countries retaliatory measures and political influence. For example, counteracting measures against SRM aimed at undoing the temperature masking could be deployed, triggering an SRM war with unclear consequences. Although our results appear to be robust to sensitivity analysis, more work needs to quantify the interplay between climate change and SRM impacts. The latter are especially not well understood, and will require further research before they can be robustly evaluated. But the governance challenges raised by climate engineering are enormous, and should be guiding research and policy alike.

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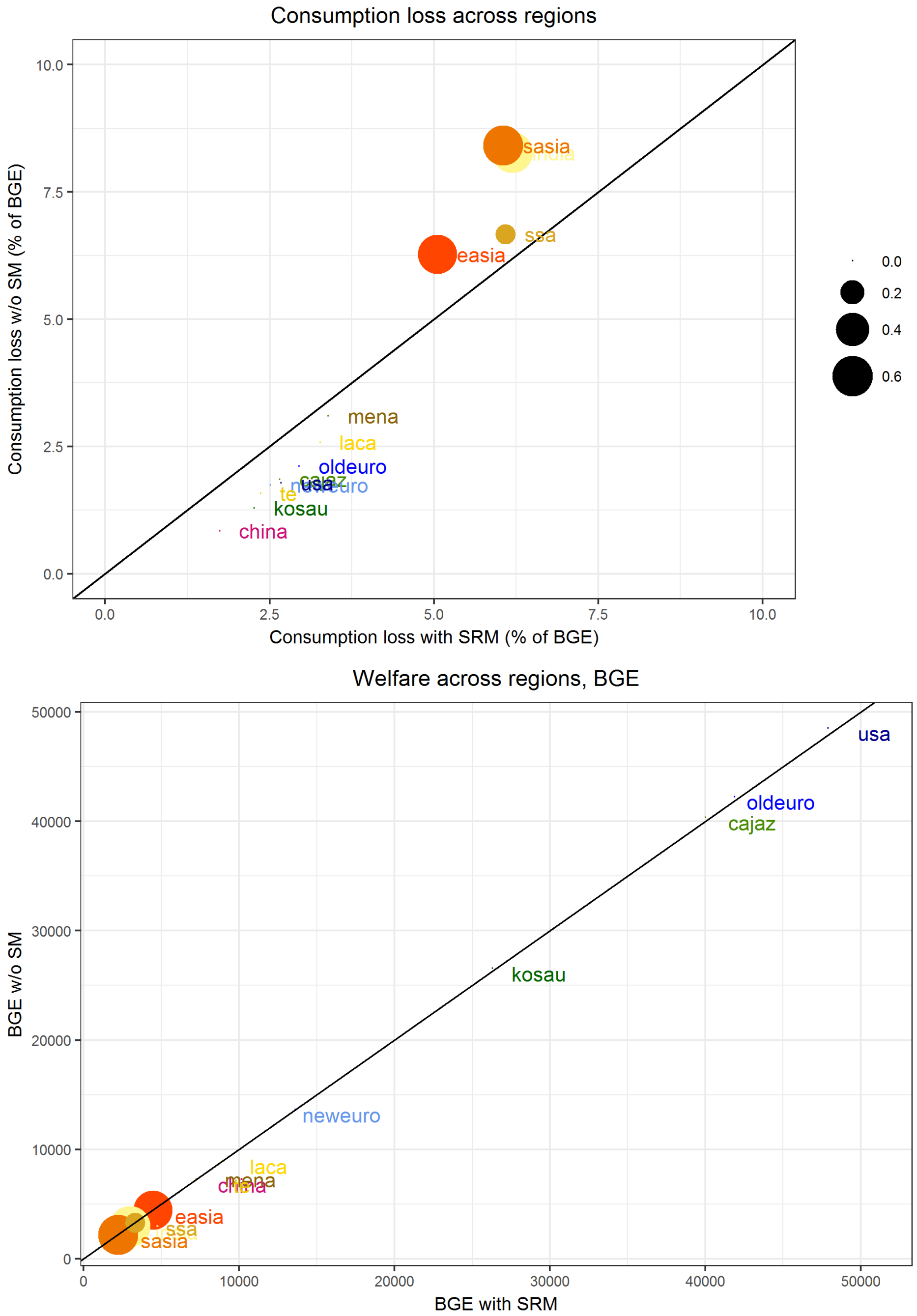

Figure 7: Consumption losses (NPV, 3% discount rate, upper panel) and welfare (Balanced Growth Equivalents, lower panel) with and without SRM across regions for the strategic scenarios. The size of the circles is proportional to the average SRM deployment.

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Supplementary Information

Appendix A: Game-theoretic framework

As shown in the manuscript, each country i solves the program of minimizing the total costs TC_i given by abatement costs, SRM costs, and impacts from global warming and SRM:

$$TC_i = C_{Ai}(a_i) + C_{Si}(s_i) + D_{Ti}(\gamma \sum_{j=1}^{N}(e_j^{bau} - a_j) - \lambda \sum_{j=1}^{N} s_j) + D_{Si}(\sum_{j=1}^{N} s_j).$$

We can derive the first order conditions under both the Nash equilibrium and global optimum. In the case of the strategic Nash equilibrium, where the program consists in $min_{s_i,a_i} TC_i$, we have the following $2N$ conditions:

$$\begin{aligned} C'_{Ai}(a_i) &= D'_{Ti}(\gamma \sum_{j=1}^{N}(e_j^{bau} - a_j) - \lambda \sum_{j=1}^{N} s_j) \\ C'_{Si}(s_i) + D'_{Si}(\sum_{j=1}^{N} s_j) &= \lambda D'_{Ti}(\gamma \sum_{j=1}^{N}(e_j^{bau} - a_j) - \lambda \sum_{j=1}^{N} s_j) \end{aligned}$$

Each regions equalizes private marginal costs and benefits of abatement. For SRM, marginal total costs (private implementation costs and private damages from implementation) are equalized with the marginal benefits of reducing global warming, which depends on SRM climate effectiveness parameter λ.

In the global cooperative settings, the optimization program consists in $min_{\{s_i,a_i\}} \sum_{i=1}^{N} TC_i$. In this case, the standard Samuelson rule is obtained whereby marginal costs are equalized to total social marginal benefits, namely:

$$\begin{aligned} C'_{Ak}(a_k) &= \sum_{i=1}^{N} D'_{Ti}(\gamma \sum_{j=1}^{N}(e_j^{bau} - a_j) - \lambda \sum_{j=1}^{N} s_j) \\ C'_{Sk}(s_k) + \sum_{i=1}^{N} D'_{Si}(\sum_{j=1}^{N} s_j) &= \lambda \sum_{i=1}^{N} D'_{Ti}(\gamma \sum_{j=1}^{N}(e_j^{bau} - a_j) - \lambda \sum_{j=1}^{N} s_j) \end{aligned}$$

To compare both solutions, we consider a fully quadratic specification: $C_{Ai}(a_i) = \frac{1}{2}\alpha a_i^2$ for abatement costs, $C_{Si}(s_i) = \frac{1}{2}\sigma s_i^2$ for implementation costs of SRM. We assume cost functions to be identical across regions both to simplify notation, and since we focus on asymmetries on impacts or damages, where the largest sources of regional variation exist. Impacts are represented by heterogeneous quadratic functions of global mean temperature T. $D_{Ti}(T) = \frac{1}{2}\tau_i \left(\gamma \sum_{j=1}^{N}(e_j^{bau} - a_j) - \lambda \sum_{j=1}^{N} s_j\right)^2$ for climate change impacts, and $D_{Si}(S) = \frac{1}{2}\theta_i \left(\sum_{j=1}^{N} s_j\right)^2$ for SRM impacts.

Let's first look at the cooperative solution, focusing on the optimal level of SRM. Straightforward solutions of the two sets of first-order conditions lead to[6]

$$s_i^{coop} = \frac{1/N}{\lambda + \left[\frac{\left(\sigma + N\sum_{j=1}^{N}\theta_j\right)\left(a + N\gamma\sum_{j=1}^{N}\tau_j\right)}{\lambda\alpha N\sum_{j=1}^{N}\tau_j}\right]}\left(\gamma\sum_{j=1}^{N}e_j^{bau}\right) \tag{3}$$

where the term in square brackets measures the reduction in SRM due to costs and impacts from SRM implementation. In the most optimistic case of a completely free and harmless SRM technology ($\sigma = 0$ and $\theta_i = 0 \forall i$), this term equals zero and SRM will be used to exactly offset the temperature increase caused by baseline emissions $\left(s_i^{coop} = \frac{1}{N}\frac{\gamma}{\lambda}\left(\sum_{j=1}^{N}e_j^{bau}\right)\right)$. Optimal SRM deployment is reduced due its implementation cost σ, impacts in all countries θ_j, and the balance between benefits $\sum_{j=1}^{N}\tau_j$ and costs α from abatement. For instance, for zero abatement costs ($\alpha = 0$), optimal SRM equals zero as full abatement of baseline emissions is optimal. In the symmetric case ($\forall i : \theta_i = \theta, \tau_i = \tau$), SRM is the same across regions and the solution simplifies to

$$s_{sym}^{coop} = \frac{1/N}{\lambda + \frac{(\sigma + N^2\theta)(\alpha + N^2\gamma\tau)}{\lambda\alpha\tau N^2}}\left(\gamma\sum_{j=1}^{N}e_j^{bau}\right) \tag{4}$$

Let's now look at the solution of strategic climate policy. We can solve for each country its optimal level of abatement and SRM given the behavior of the others in terms of abatement a_i and SRM $s_{j\neq i}$. Combining both first-order conditions for one country, we find the optimal SRM level in the Nash solution equals to:

$$\begin{aligned} s_i^{strategic}\left(s_{j\neq i}, a_{j\neq i}\right) \quad &= \quad \frac{1}{\lambda + \frac{(\sigma+\theta_i)(\alpha+\gamma\tau_i)}{\lambda\alpha\tau_i}} \\ &\left(\gamma\sum_{j=1}^{N}e_j^{bau} \quad -\gamma\sum_{j=1}^{N}a_{j\neq i} \quad -\left(\lambda + \frac{\theta_i(\alpha+\gamma\tau_i)}{\lambda\alpha\tau_i}\right)\sum_{j=1}^{N}s_{j\neq i}\right) \end{aligned} \tag{5}$$

which yields the reaction function of country i in terms of climate engineering. From this result, it can already be seen that SRM across countries is a strategic substitutes since the reaction function decreases the amount of SRM implemented by the other countries $\sum_{j=1}^{N}s_{j\neq i}$. Moreover, it is also decreasing in the amount of abatement of the other players, implying the abatement and SRM are also strategic substitutes. For the asymmetric case, the equilibrium solution $\left\{\left(s_i^{strategic}, a_i^{strategic}\right)\right\}_{i=1..N}$ can be only computed numerically considering the distribution of impacts from climate change and SRM implementation. As Barrett (2008) already noted, the number of Nash equilibria is actually very large in this game. As before, we can simplify the solution in the case of symmetric players.Using the reaction functions for SRM and abatement of all players and solving for their intersection jointly, the symmetric (interior) Nash Equilibrium can be computed as

$$s_{sym}^{strategic} = \frac{1/N}{\lambda + \frac{(\sigma + N\theta)(\alpha + N\gamma\tau)}{\lambda\alpha\tau N}}\left(\gamma\sum_{j=1}^{N}e_j^{bau}\right) \tag{6}$$

Without SRM costs and impacts, SRM will be deployed to fully undo the temperature increase: $s_{sym}^{strategic} = \frac{\gamma}{\lambda}\left(\sum_{j=1}^{N}e_j^{bau}\right)$. Costs and impacts from SRM lower its deployment. Now, also abatement costs and climate impacts reduce SRM due to the interaction between both strategies.

Since we are interested in the free driving effect, it is worth comparing the SRM deployment in the

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[6] For SRM implementation, we theoretically need to add the non-negativity constraints thus the less or equal sign in the solutions.

strategic case vis à vis with the cooperative one. For the symmetric case, we can re-write both solutions (as in the main text) as

$$s_{sym}^{strategic} = \frac{1/N}{\lambda + \frac{\gamma}{\lambda}\left(\frac{N\theta+\sigma}{\alpha} + \frac{N\theta+\sigma}{\gamma\tau N}\right)} \left(\gamma \sum_{j=1}^{N} e_j^{bau}\right) \tag{7}$$

$$s_{sym}^{coop} = \frac{1/N}{\lambda + \frac{\gamma}{\lambda}\left(\frac{N^2\theta+\sigma}{\alpha} + \frac{N^2\theta+\sigma}{\gamma\tau N^2}\right)} \left(\gamma \sum_{j=1}^{N} e_j^{bau}\right) \tag{8}$$

Barrett (2008).

Figure (1) shows the free driving effect measured by the excess SRM over what socially optimal, based on a calibration of this simple model showing the ratio between strategic and cooperative SRM under different specification and for increasing number of countries. We calibrate the model to broadly represent some common projections about the 21st century: we assume base-line emissions of 6000 GtCO2, a transient climate response of 1.5°C/TtC (Matthews et al., 2009), and effectiveness of SRM of -1.4°C/TgS based on a radiative forcing effect of $-1.75\frac{W}{m^2TgS}$ (Gramstad and Tjøtta, 2010) and a climate sensitivity value of $0.8\frac{^\circ\mathrm{C}}{W/m^2}$. We choose cost and damage parameters to represent some stylized facts, such as low cost of climate engineering compared to abatement, and global temperatures values which are in line with the projections of IAMs. In particular, the free parameters are set so that SRM costs are about 3-4 orders of magnitude lower than abatement costs, and the cooperative solution results in a degree of global temperature increase of 2.4 degrees compared with a value of 3.1 degrees for the non-cooperative case. The resulting values which are used as central specifications for (1) are $\sigma = 2$, $a = 0.0007 \cdot 10^{-4}$, θ=0.47, and $\tau = 37.5$. Of course, this is just an exemplifying specification with the aim to mimic the main orders of magnitude.

Appendix B: The numerical climate-energy-economy model

In this section we describe the implementation in the integrated assessment model (IAM) WITCH (Bosetti et al., 2009; Emmerling et al., 2016) to assess the quantitative magnitude of the effect of climate engineering on the optimal abatement path and a series of key variables of climate mitigation effort WITCH has been used extensively in the literature of scenarios evaluating international climate policies, for example as a major contributor to scenarios reviewed by the IPCC in its fifth assessment report (https://tntcat.iiasa.ac.at/AR5DB). WITCH is a global model with 13 macro-regions. It is a long-term dynamic model based on a Ramsey optimal growth economic engine, and a hard linked energy system which provides a compact but exhaustive representation of the main abatement options both in the energy and non-energy sectors. The model is solved numerically in GAMS/CONOPT. A description of the model equations can be found on the model website at http://doc.witchmodel.org. In what follow we describe the key modules for this paper, namely the climate impacts, the SRM and the solution algorithm.In terms of regional aggregation, the model regions are depicted in Figure 8.

Climate Impacts

The standard damage function approach used in most IAMs including WITCH consists in a calibrated damage function, based on global temperature increase. Impacts from climate change include economic impacts

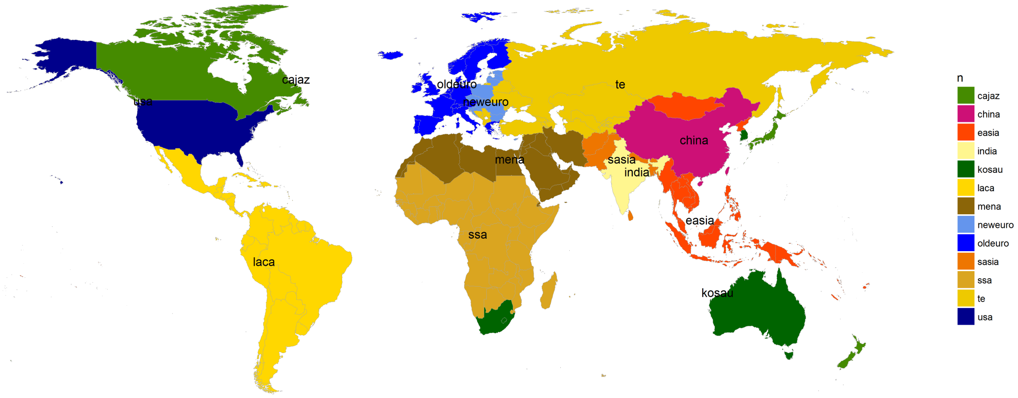

Figure 8: WITCH model regions

of climate change due to sea-level rise, increased energy demand, and agricultural productivity impacts. Moreover, non-market damages including ecosystem losses, non-market health impacts, and catastrophic damages are taken into account. The estimated regional impacts are computed with a damage function depending on global mean temperature T as

$$\Omega^{T}_{rt}(T) = a_{1r} + a_{2r}T + a_{3r}T^{a_{4r}} \tag{9}$$

where $\{a_{1r}, a_{2r}, a_{3r}, a_{4r}\}$ are calibrated region-specific coefficients, see Table 1 for the exact calibration values. For the curvature, a quadratic function is used across regions, following e.g., Nordhaus (2014). Recently, alternative specifications of climate impacts where temperature affects the rate of growth of the economy have been proposed (Burke et al., 2015; Dell et al., 2012). In this paper we use the standard climate impact formulation which is in line with the traditional body of evidence as reviewed by the IPCC. However, given the uncertainties characterizing climate change damages we perform a robustness analysis on the exponent of temperature, a_{4r}. In the standard specification this is set equal to $a_{4r} = 2$, in line with the quadratic specification of the DICE modelNordhaus (2014). We perform a sensitivity analysis in the "high damage" scenario, where the damage function is steeper with an exponent of $a_{4r} = 2.8$, resulting in global impacts from global warming (without adaptation) at 2.5°Cwarming by 2100 of 5.3% of GDP compared to 3.1% of GDP in the baseline assumption.

The calibration is based on estimated impacts at the calibration of 2.5°Cwarming described in Bosello and De Cian (2014). Figure 9 shows the impacts in per cent of GDP at the calibration point of 2.5°C across the model regions. Impacts from climate as well as other damages (see below) are summed to a total impact factor which is time and regional dependent: $\Omega_{rt} = \Omega^{T}_{tn}(T) + \Omega^{SRM}_{tn} + \Omega^{\Delta T}_{tn}$. This is applied multiplicatively to consumption, thus reducing the level of well-being.

$$C_{net,rt} = \frac{C_{gross,rt}}{1 + \Omega_{rt}} \tag{10}$$

That is, we can write the relative impacts as percentage of consumption RD_{rt} defined as $RD_{rt} = \frac{C_{rt} - \frac{C_{rt}}{1+\Omega_{rt}}}{C_{rt}}$ simplified as $(1 - \frac{1}{\Omega_{rt}})$, which for small values of Ω_{rt} is approximately equivalent to $RD_{rt} \approx \Omega_{rtrt}$.[7]

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[7] This follows from the approximation that $\frac{1}{1+x} \approx 1 - x$ for x close to zero.

region	a_{1r}	a_{2r}	a_{3r}	a_{4r}
usa	0.0075	0.0015	0.0008	2 or 2.8
oldeuro	0.0094	-0.0008	0.0019	2 or 2.8
neweuro	0	0.0052	0.0008	2 or 2.8
kosau	0.0053	-0.0008	0.0014	2 or 2.8
cajaz	0.0078	0.0017	0.0009	2 or 2.8
te	0.0025	0.0004	0.0018	2 or 2.8
mena	0	0.0043	0.0026	2 or 2.8
ssa	0	0.0102	0.0034	2 or 2.8
sasia	-0.0002	0.0028	0.0095	2 or 2.8
china	0.0041	-0.0024	0.0018	2 or 2.8
easia	0	0.0033	0.0081	2 or 2.8
laca	0	0.0069	0.001	2 or 2.8
india	-0.0002	0.0042	0.0096	2 or 2.8

Table 1: Standard Climate Damages Parametrization in WITCH

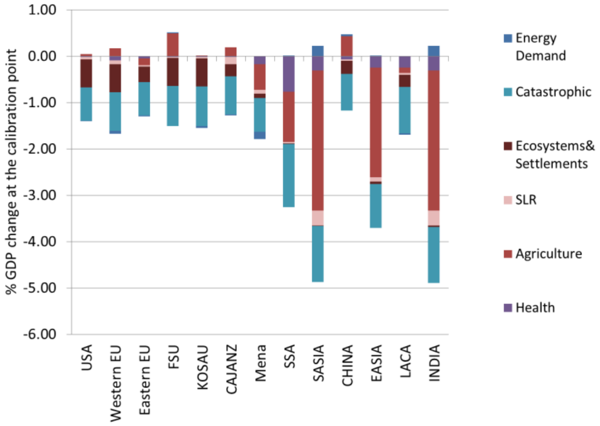

Figure 9: Standard Climate Damages in WITCH for a 2.5°Cglobal mean temperature increase. Source: Bosello and De Cian (2014).

SRM has a unique characteristics among climate strategies in that it allows affecting global temperature change in a direct and rapid way. In order to capture the potential impacts from abrupt warming or cooling, which are not covered by standard damage functions, we add a damage component on temperature change $\Delta T_t = T_t - T_{t-1}$, based on Lempert et al. (2000). The authors estimate a quartic function leading to a one percent consumption loss for a five-year warming (or cooling) of $0.35°C$:

$$\Omega_{tn}^{\Delta T} = 0.01 \times \left(\frac{\Delta T_t}{0.35}\right)^4 \tag{11}$$

SRM Module

We model climate engineering as an option to reduce solar radiation through stratospheric aerosols. Specifically, we model million tons of sulfur (teragrams or TgS) injected into the stratosphere at the global scale to lead to a negative radiative forcing of $-1.75\frac{W}{m^2 TgS}$. This is a best guess estimate of Gramstad and Tjøtta (2010), based on the range from -0.5 (Crutzen, 2006) to -2.5 (Rasch et al., 2008a). We assume a stratospheric residence time of two years, in line with the actual figure of a few years (Rasch et al., 2008b). Finally, we assume a linear cost function at a cost of 10 billion $\$$/TgS within the range considered in the literature, between 5 (Crutzen, 2006) and 25 billion (Robock et al., 2009) USD per TgS.

The second important characteristics of SRM regard its side effects. SRM technologies bring about substantial risks and potential side-effects such as ozone depletion, side effects of the implementation itself (Robock et al., 2009; Tilmes et al., 2008), as well as region-specific impacts such as increased droughts (Haywood et al., 2013). Moreover, SRM does not reduce the amount of carbon in the atmosphere. Therefore, damages from increased CO_2 concentration such as ocean acidification are not mitigated, and, moreover, a climate engineering policy cannot be suddenly discontinued as an abrupt temperature change would likely occur (Brovkin et al., 2008; Irvine et al., 2012). These and other potential side-effects of CE are important to take into consideration, see Robock (2008) and Klepper and Rickels (2014) for a recent overview. There is very little evidence of the magnitude and distribution of SRM impacts (Moreno-Cruz and Keith, 2013) For our standard specification, we follow Goes et al. (2011), who suggest economic impacts of a fixed percentage of consumption for an amount of SRM leading to offsetting a doubling of radiative forcing from CO_2 emissions. That is, the economic damages from SRM implementation equal to:

$$\Omega_t^{SRM} = \theta \times \frac{1.75\frac{W/m^2}{TgS}}{3.5} \times \left(\sum_n SRM_{tn}\right)^\alpha \tag{12}$$

where θ measures the percentage loss of consumption due to SRM. As their base value, the authors use a linear impact function ($\alpha = 1$), and use $\theta = 0.03$ leading to three percent consumption loss for SRM leading to $-3.5W/m^2$ forcing. As a sensitivity analysis, we also consider the range the authors consider, namely from zero up to five per cent ($\theta = 0.05$) for impacts from SRM implementation. In all cases, we assume SRM damages are global, but regionally equal.

Solution method: strategic and cooperative

At the strategic solution, each region n acts as one player maximizing its welfare. In this case, the set of players consists each of a single of the 13 macro-regions which constitute the model. For each region n and time period t, inter-temporal utility is computed as discounted sum of utility based on a utility function as

$$W(n) = \sum_t l(t,n) \frac{\left(\frac{C(t,n)}{l(t,n)}\right)^{1-\eta} - 1}{1-\eta} \beta^t.$$

Each player takes at this optimization

$$\underset{I_{EN}(t,n), ABAT(t,n), SRM(t,n)}{max} W(n)$$

the decisions of the other regions into account, which mainly consist in mitigation (through investment in different energy technologies, abatement of land-use emissions, and non-CO2 gases), and SRM deployment $\{I_{EN}(t, j \neq n), ABAT(t, j \neq n), SRM(t, j \neq n)\}$. In order to find the open-loop Nash equilibrium, we employ an iterative algorithm in which each regions optimizes independently, and global values such as temperature are computed after each iteration. This algorithm has been shown to be robust to initial specifications, see (Bosetti et al., 2009; Emmerling et al., 2016).

Since SRM affects global variables such as temperature, and since it creates a global externality of its own, its inclusion in the model makes obtaining a numerical solution for the equilibrium in the strategic case significantly more complicated. In particular, for high deployment of SRM, temperatures can become negative, violating some of the climate module equations. Moreover, as Barrett (2008) noted, many Nash equilibria can exist in the strategic SRM-abatement setting.

In order to find the candidate solution for the strategic setting, we used an approximation method based on two steps. First, we run the model only allowing unilateral SRM of one region at a time, that is, solving the allocations given $\{I_{EN}(t, j \neq n), ABAT(t, j \neq n), SRM(t, j \neq n) = 0\}$. The results from the unilateral SRM runs are reported in the next section, and we use them as boundary conditions for the strategic equilibrium results. In particular, we restrict SRM in each region by a maximum percentage of their unilaterally chosen level of SRM (at each point in time) such that the climate module was still able to calculate global mean temperature based on all radiative forcing. We subsequently checked that all SRM implementations across time and regions actually fell strictly within the provided boundaries, to ensure an interior solution was found. We experimented with different percentage limitations, and set them to be between 15% and 30 for the different SRM impact specifications.

In the cooperative solution on the other hand, the grand coalition of all regions maximizes a sum of the welfare of the member regions W^{coop}. While there are several welfare concepts admissible to aggregate welfare across coalition members, we consider an equal marginal utility of consumption resembling the Negishi solution to avoid re-distributional concerns entering the optimal climate policy question. That is, welfare in this case is computed as

$$W^{coop} = \sum_t \left(\sum_n l(t,n)\right) \frac{\left(\frac{\sum_n C(t,n)}{\sum_n l(t,n)}\right)^{1-\eta} - 1}{1-\eta} \beta^t$$

using the same intertemporal fluctuation aversion of $\eta = 1.5$ as in the Nash case. This solution is a spacial case of a disentangled Utilitarian solution, disregarding account inequality across regions, see Emmerling et al. (2016) or more details.

Appendix C: Sensitivity Analysis

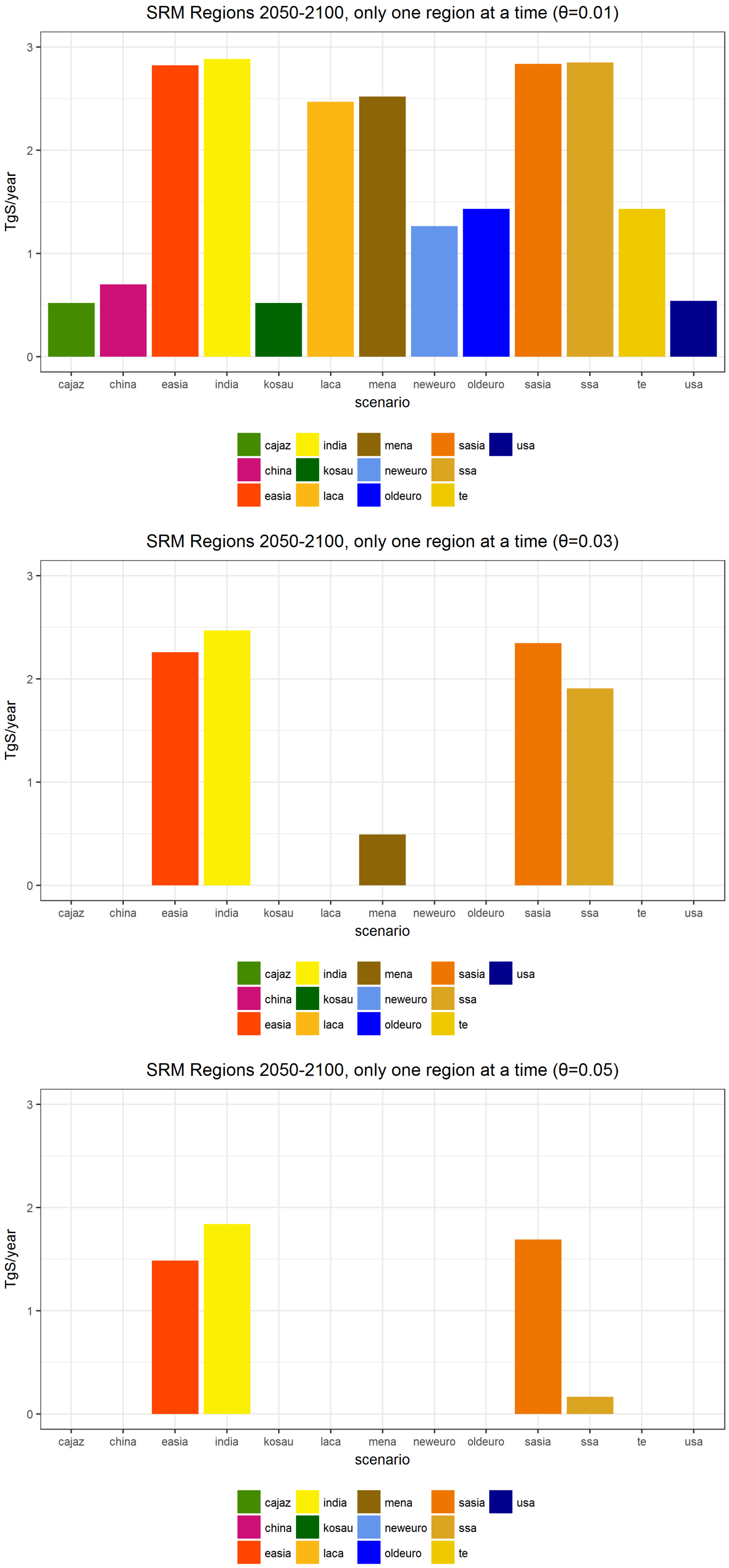

Figure 10: Unilateral SRM implementation (average per year SRM over the period 2050-2100) for different SRM impact specifications ($\theta = 0.01; 0.03; 0.05$).

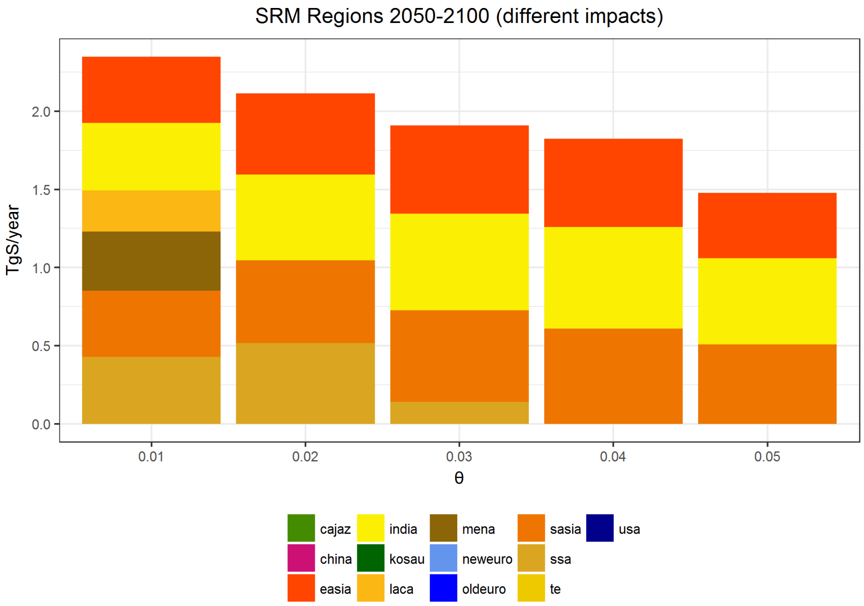

Figure 11: SRM implementation in the strategic case for different damages from SRM. The central bar shows the reference case of $\theta = 3\%$.

Appendix D: Additional Figures

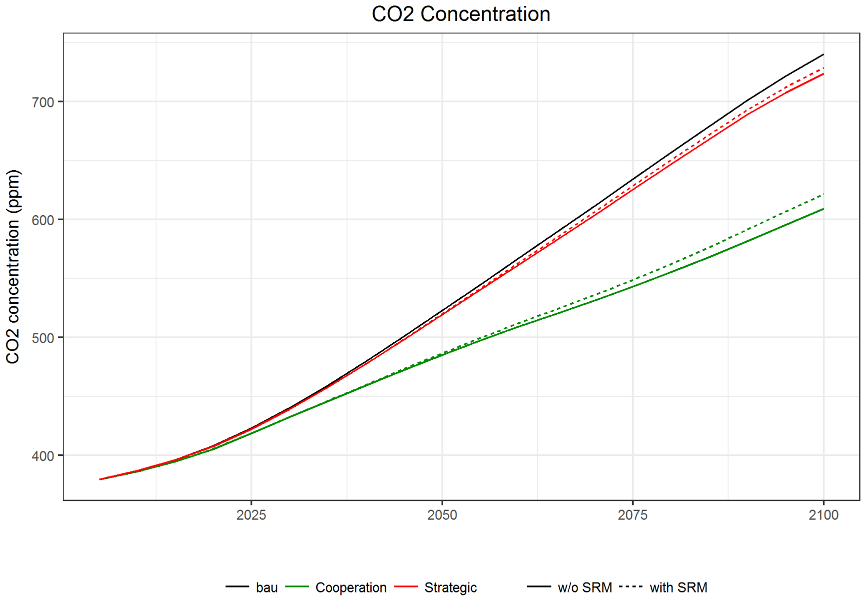

Figure 12: Global atmospheric CO2 concentration over the 21st century across scenarios.

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