Is there Room for Geoengineering in the Optimal Climate Policy Mix?

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Abstract

We investigate geoengineering as a possible substitute for adaptation and mitigation measures to address climate changes. With the help of an integrated assessment model, we disentangle between the effects of solar radiation management on atmospheric temperature levels and its side-effects on ecosystems. To address the variability of the latter we rely on a distributional analysis. Our findings are threefold. First, we show that accounting for all three policy alternatives guarantees the best results from a welfare perspective. Mitigation emerges as the first pillar to address climate change, with adaptation as an effective complement. Accounting for the serious side-effects of geoengineering on the environment shows that its use is optimal in only a few of the analyzed scenarios. Second, our results point out that a sustainable climate policy needs to target both temperature and CO_2 concentration levels. Third, we show that annual GDP losses rise considerably when sulfur dissipation side-effects diverge from estimations, even for short-term horizons. The adjustment of the policy mix after updates in information, gives primary weight to mitigation, but its slow feedback on concentrations fails to deter fast temperature increases above safe levels.
Keywords: Climate change; Climate policy mix; Adaptation; Mitigation; Geoengineering
JEL: Q43, Q48, Q54, Q58.

1 Introduction

Despite international initiatives to curb greenhouse gas (GHG) emissions, atmospheric concentrations keep increasing. In this context, alternatives (or complements) to the traditional mitigation approach are being considered. The first such strategy is adaptation: while mitigation seeks to prevent climate changes by abating GHG emissions, adaptation measures target the reduction of damages from climate change. Adaptation strategies cover a large array of sectors and options, and can be 'proactive' or 'reactive'. Despite having recently gained attention for the several advantages over mitigation (Tol,

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2005; Adger et al., 2007; Klein et al., 2007), investments in adaptation remain to this day quite limited.

Given the increasing risk of an unmanageable temperature path, some scientists are now advocating for a second alternative to mitigation, namely geoengineering solutions (for a survey, see IPCC, 2007). They correspond to deliberate modifications of the climate system in order to alleviate climate change impacts (Keith, 2000). One may distinguish between two main techniques, namely Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM). In this paper, we focus on the SRM approach that targets the reduction of incoming solar radiation by injection of stratospheric aerosols. Its premise is the ability to modify earth systems and keep temperature levels artificially low, instead of reducing GHG emissions. In case of abrupt climate changes, with potentially rare but catastrophic impacts, SRM could act as a quick and effective temperature 'backstop' (Barrett, 2008), while adaptation and mitigation measures would be too slow to deal competently with damages.

However, SRM brings along important risks, as it may produce unintended consequences and harmful side effects (Victor, 2008). Injecting particles into the upper atmosphere is expected to cause ozone depletion (Crutzen, 2006; Tilmes et al., 2008) and may also significantly alter ecosystems (Stanhill and Cohen, 2001) as well as trigger regional imbalances (e.g., in the patters of surface temperature, radiation and the water cycle (Bala et al., 2008; Niemeier et al., 2013; Kravitz et al., 2013; Schaller et al., 2013)). It would also result in less sunlight for solar power (Robock et al., 2009). Moreover, SRM achieves only an 'artificial' reduction in temperature levels. With a continued increase in atmospheric concentrations, the injection of aerosols would need to raise proportionally, and a disruption in geoengineering would lead to a significant jump in temperatures at the corresponding GHG concentration level (Brasseur and Roeckner, 2005; Lenton and Vaughan, 2009; Vaughan and Lenton, 2012) with probable dire consequences.

Given these important drawbacks, support for geoengineering measures has been weak and inconclusive until now. Geoengineering as *the* alternative solution was first discussed by Dickinson (1996), Keith (2000) and Teller et al. (2003), and the reactions that followed their work varied widely between marked enthusiasm, precautionary dismissal, and furious refusal. This triggered however the development of a new thread of literature analyzing the geoengineering option from the perspective of the physics, geo-political, and economics disciplines. In an attempt to distinguish between different geoengineering activities, Nordhaus (2001), Wigley (2006) and Shepherd (2009) select the injection of aerosol precursors into the stratosphere as the best option to increase the Earth's albedo effect. Their reasoning relies on a few key factors, such as implementation costs and effectiveness in reducing global temperatures. With little known about the consequences of geoengineering on the environment, Crutzen (2006), Wigley (2006) and Carlin (2007) assume low risks of side-effects, and recommend geoengineering as a valuable climate policy. However, the recommendation comes with a strong warning, and mitigation emerges as the safe and ethical solution, while geoengineering is portrayed in a gray zone, towards which extended additional research should be dedicated.

Recent studies focus on modeling decision-making in the context of multiple sources of risk. Moreno-Cruz and Keith (2013) account explicitly for uncertainty in climate responses to CO_2 concentration increases and risks associated with SRM. They find that even modest reductions in uncertainty through dedicated research on the side-effects of sulfur dissipation could significantly reduce total costs of climate change. Gramstad and Tjotta (2010) propose an integrated assessment model (IAM) that allows for parametric uncertainty in the impact of sulfur dissipation on radiative forcing and temperature changes. They find that SRM passes the cost-benefit test under all scenarios, but admit that other factors (such as the risk of SRM interruptions) could lead to the opting out of climate engineering projects. Using also an IAM, Goes et al. (2011) reach less optimistic conclusions regarding the benefits of SRM. By accounting for the failure to sustain the aerosol forcing and the subsequent unraveling of drastic climate changes, they show that SRM could be an economically ineffective strategy.

Despite the abundant discussions concerning SRM, the approach remains controversial. In this paper, we contribute to the debate with the Ada-BaHaMa integrated assessment model (Bahn et al., 2012), enriched to consider explicitly a SRM strategy. We disentangle between the different effects of SRM on atmospheric temperature levels and on ecosystems. While the *desired* effects of SRM on radiative forcing can be estimated with a significant degree of confidence (Crutzen, 2006), the *undesired* side-effects of sulfur dissipation on the environment represent a large and important unknown. We focus on this second uncertainty source, and model damages as a stochastic process. Therefore, our model analyzes whether SRM remains a viable strategy when its downside risks are accounted for. Our original contribution consists in presenting the optimal policy mix when various climate strategies are available (mitigation, proactive and reactive adaptation, and SRM); the optimization is achieved via a dynamic IAM, that meticulously specifies the uncertainties of SRM.

The reminder of the paper is structured as follows. Section 2 details the dynamic IAM, whose calibration is presented in Section 2.2. Sections 3 and 4 provide numerical results and analyze specific uncertainties related to SRM. Section 5 concludes on the most important policy implications.

2 The Model

2.1 Overview

In this section we briefly review the original Ada-BaHaMa model (whose equations are presented in Bahn et al., 2012) and detail only the new modeling features: the introduction of SRM as an instrument to control temperature increases, and a new reactive adaptation strategy to complement the proactive approach introduced in the original model.

2.1.1 Production dynamics

The Ada-BaHaMa model distinguishes between two types of economy: a 'carbon' economy (our present economy), where production is fossil fuel intensive, and a 'low-carbon' economy, with small GHG contributions. More precisely, production (Y) occurs in the two economies according to an extended Cobb-Douglas function in three inputs: capital (K), labor (L), and energy (measured through GHG emission level E). Capital stock in each economy evolves according to the choice of investment (I) and a standard depreciation relation. Finally, total labor (L) is divided between the two economies.

2.1.2 Climate change dynamics in presence of SRM

The stocks of GHGs evolve according to the dynamic equations of the DICE model (Nordhaus, 2008) that distinguishes between three reservoirs: (i) an atmospheric one (M_{AT}), (ii) a quickly mixing one in the upper oceans and the biosphere (M_{UP}), and (iii) a slowly mixing deep-ocean reservoir (M_{LO}) which acts as a long-term sink.

Additionally to the original Ada-BaHaMa, we include a geoengineering strategy in the form of sulfur injection in the stratosphere to increase the albedo effect (SRM). Sulfur dissipation is recognized as one of the most efficient strategies currently available (Wigley, 2006; Shepherd, 2009), and thus the most probable for implementation among the geoengineering options (Kintisch, 2010).

Sulfur injection in the upper atmosphere directly affects the relationship between the accumulation of GHGs and the temperature deviation, by reducing the radiative forcing $F(t,s)$:

$$F(t,s) = \eta log_2 \left(\frac{M_{AT}(t,s)}{M_{AT}(1750)} \right) + F_{EX}(t) - \omega G(t,s) \tag{1}$$

where η is a calibration parameter for a climate sensitivity of 3°C, F_{EX} the exogenous radiative forcing term, ω the effectiveness factor of SRM, and G the amount of sulfur injected in the stratosphere, measured in teragrams of sulfur (Tg S). The index s identifies the specific 'side-effects' scenario that describes the evolution of the damage level from the uncertain SRM strategy.

The other elements of the climatic model remain unchanged from Ada-BaHaMa and follow the DICE model to compute the earth's mean surface temperature (T_{AT}) and the average temperature of the deep oceans (T_{LO}).

2.1.3 Climate change damages and SRM side-effects

The original Ada-BaHaMa model follows the approach used in MERGE (Manne and Richels, 2005) to link climate change damages and their economic impacts. Here, we additionally account for negative externalities from sulfur injection. According to Ramanathan et al. (2001) and Brovkin et al. (2009), dissipating large amounts of sulfur in the upper atmosphere may have potentially disruptive effects on weather patterns and the water cycle. Additional damages are expected in case the sulfur particles enter the troposphere and add to the sulfur concentration in soil (Crutzen, 2006). Nevertheless, the diversity and magnitude of possible side-effects from sulfur dissipation remain large scientific unknowns, and our proposed way of modeling SRM damages is not immune to these uncertainties.

We model the magnitude of SRM negative side-effects (D_{GE}) based on: (i) the amount of sulfur used relative to the natural stock of sulfur observed in the stratosphere in 1750, and (ii) a random factor quantifying in economic terms the possible side-effects. The damages persist over time and exhibit the following dynamics:

$$D_{GE}(t+1,s) = \delta D_{GE}(t,s) + \alpha_{GE}(t+1,s)\frac{G(t+1,s)}{SG_{nat}}, \tag{2}$$

where δ (< 1) is a constant depreciation rate, SG_{nat} the natural (1750) concentration level of sulfur in the upper atmosphere, and α_{GE} a time-varying random process. Each state s describes a different and unique path taken by $\alpha_{GE}(t,s)$ between $t = 0$ and $t = T$ (the model horizon). In total, more than 32,000 different paths were used to construct the distribution of the SRM damages; see Section 2.2.

Equation 2 assumes that the different damages resulting from SRM (both the direct effects such as changes in the water cycle, and the indirect damages from higher CO_2 concentrations causing ocean acidification) depend on G in the same way. In reality the latter components may be delayed and nonlinear in G, due to long timescales of CO_2 absorption by the ocean; here, we assume that this is accounted for in the uncertainty and time-dependence of the effectiveness parameter α_{GE}.

The temperature increase (T_{AT}) entails damages that can be alleviated through adaptation (AD). Together with the side-effects from SRM, they impact the production function. We model the total economic loss factor (ELF) as follows:

$$\mathrm{ELF}(t,s) = 1 - \left(\mathrm{AD}(t,s)\left(\frac{T_{AT}(t,s) - T_d}{cat_T - T_d}\right)^2 + D_{GE}(t,s)\right), \tag{3}$$

where T_d is the temperature deviation (from pre-industrial level) at which damages start to occur, while cat_T represents the 'catastrophic' temperature level at which the entire production would be wiped out. To have a comparable basis with the current literature on IAM with adaptation, T_d and cat_T are calibrated to replicate the damage intensity in DICE; see Section 2.2.

2.1.4 Proactive and reactive adaptation

Recent IAM models (Bosello et al., 2010; Agrawala et al., 2011) include both reactive and proactive adaptation in the available policy mix. Acknowledging the increased flexibility of considering both strategies, we distinguish between reactive (flow) and proactive (stock) adaptation. We model the effectiveness of the two adaptation strategies in reducing climate change damages as follows:

$$\mathrm{AD}(t,s) = 1 - \alpha_{\mathrm{AD}_p}(t,s)\frac{K_3(t,s)}{K_{3\max}(t)} - \alpha_{\mathrm{AD}_r}(t,s)\frac{S_3(t,s)}{S_{3\max}(t)} \tag{4}$$

where α_{AD_p} (respectively, α_{AD_r}) is the maximum proactive (resp. reactive) adaptation effectiveness, K_3 (resp. S_3) the amount of proactive adaptation capital (resp. reactive adaptation spending), $K_{3\max}$ (resp. $S_{3\max}$)[1] the maximum amount of adaptation capital (resp. spending) that would ensure the optimal effectiveness of the proactive (resp. reactive) adaptation measures. Like $K_{3\max}$ in our original model, $S_{3\max}$ is modelled as an increasing function of the temperature level:

$$S_{3\max}(t) = \beta_{\mathrm{AD}_r} \left(\frac{T_{AT}(t)}{T_d} \right)^{\gamma_{\mathrm{AD}_r}} \tag{5}$$

where β_{AD_r} and γ_{AD_r} are calibration parameters; see Section 2.2.
The two options are assumed to be complementary, in that the implementation of one enhances the effectiveness of the other (similar to Agrawala et al., 2011, that use a constant elasticity of substitution function). This can be justified as follows. On the one hand, reactive adaptation requires the existence of some infrastructure; for instance, the deployment of new crops (better suited to new climatic condition) possibly requires that tests have been conducted beforehand (pro-actively) in R&D facilities. On the other hand, since investments in (proactive) adaptation are initiated much earlier than their first use, they are based on expectations and can result in inadequate solutions when damages start to occur. Reactive adaptation can marginally modify the solution to ensure maximum effectiveness. Optimal adaptation effectiveness is given by the following equations:

$$\alpha_{\mathrm{AD}_p}(t,s) = (\overline{\alpha_{\mathrm{AD}_p}} - \underline{\alpha_{\mathrm{AD}_p}}) \left(\gamma_1 \frac{K_3(t,s)}{K_{3max}(t)} + \gamma_2 \frac{S_3(t,s)}{S_{3max}(t)} \right) + \underline{\alpha_{\mathrm{AD}_p}} \tag{6}$$

$$\alpha_{\mathrm{AD}_r}(t,s) = (\overline{\alpha_{\mathrm{AD}_r}} - \underline{\alpha_{\mathrm{AD}_r}}) \left(\gamma_1 \frac{S_3(t,s)}{S_{3max}(t)} + \gamma_2 \frac{K_3(t,s)}{K_{3max}(t)} \right) + \underline{\alpha_{\mathrm{AD}_r}} \tag{7}$$

where $\underline{\alpha_{\mathrm{AD}_p}}$ and $\overline{\alpha_{\mathrm{AD}_p}}$ are the absolute minimum and maximum effectiveness values for proactive adaptation, $\underline{\alpha_{\mathrm{AD}_r}}$ and $\overline{\alpha_{\mathrm{AD}_r}}$ the corresponding values for reactive adaptation, and γ_1, γ_2 calibration parameters ($\gamma_1 > \gamma_2$, $\gamma_1 + \gamma_2 = 1$). We model adaptation effectiveness such that: (i) the absence of the other strategy does not make adaptation ineffective, but reduces its potential to a minimum intrinsic level; (ii) only maximum capital level ($K_3(t,s) = K_{3max}(t)$) and spending ($S_3(t,s) = S_{3max}(t)$) ensure maximum effectiveness; and (iii) each adaptation strategy benefits more in relative terms from efforts done in its own measures and from learning effects.

2.1.5 Welfare maximization

As with the original Ada-BaHaMa model, a social planner is assumed to maximize social welfare (W) given by the sum over T 10-year periods of a discounted utility from pro capita consumption. The maximization of welfare is done independently for each state s, corresponding to a certain evolution of SRM side-effects. Consumption comes from an optimized share of production, the remaining being used: (i) to invest in the production capital of the carbon and low-carbon economies (I_1, I_2) and in the proactive adaptation capital (I_3); (ii) to spend for reactive adaptation (S_3) and SRM measures (S_4); and

[1] We impose at all time periods $K_3(t,s) \leq K_{3\max}(t)$ and $S_3(t,s) \leq S_{3\max}(t)$.

(iii) and to pay for energy costs. The presence of damages (defined by the ELF factor) reduces the available production such that:

$$\begin{aligned}\mathrm{ELF}(t,s)Y(t,s) \quad &= \quad C(t,s)+I_1(t,s)+I_2(t,s)+I_3(t,s)+S_3(t,s)+S_4(t,s)\\ &\quad +p_{E_1}(t,s)\phi_1(t,s)E_1(t,s)+p_{E_2}(t,s)\phi_2(t,s)E_2(t,s)\end{aligned} \tag{8}$$

2.2 Calibration

The economy and climate modules are calibrated on DICE (version 2007[2], thereafter referred to as DICE2007). More precisely, we calibrate a baseline scenario – in which only the carbon economy is producing – to match as closely as possible production, concentration, and temperature trajectories of the DICE2007 baseline. Production in the low-carbon economy is more energy efficient, but also more costly, than in the carbon economy. Without distinguishing among specific technologies, we capture their different characteristics in the low-carbon economy relying on the MERGE model (Manne and Richels, 2005).

Calibration of the adaptation strategies follows the AD-DICE model (de Bruin et al., 2009), accounting for the additional reactive adaptation option and its complementarity with proactive adaptation. The calibration of $K_{3\max}$ relies on World Bank estimates (Margulis and Narain, 2009). Parameters $S_{3\max}$, β_{AD_r} and γ_{AD_r} are calibrated using similar techniques and cost estimates. However, we assume that reactive adaptation is 50% more costly than proactive adaptation to achieve its maximum potential.[3] The calibration of the effectiveness parameters α_{AD_p} and α_{AD_r} reflects stylized assumptions about the reactive-proactive relationship. First, we assume that reactive adaptation is slightly more efficient than proactive adaptation, as 'last-minute' strategies are easier to adjust to observed damages. This assumption is coherent with Agrawala et al. (2011), where reactive adaptation offsets on average 27% of gross damages and proactive adaptation only 21%. Our calibration is very close, with 25% for reactive adaptation ($\overline{\alpha_{\mathrm{AD}_r}}$) and 22% for proactive ($\overline{\alpha_{\mathrm{AD}_p}}$). Second, the maximum effectiveness of total adaptation cannot be higher than 0.5. This is coherent with Nordhaus and Boyer (2000) where total adaptation potential is 0.48 (compared to 0.47 in our calibration). And third, the difference between minimum and maximum effectiveness for the two strategies is chosen to be relatively small, which implies that proactive and reactive adaptation options are only weakly complementary, similar to Agrawala et al. (2011).

The values for the different SRM parameters are derived from Ramanathan et al. (2001), Crutzen (2006) and Shepherd (2009). Firstly, for the sulfur effectiveness (ω) we rely on Crutzen (2006) that reports (from the Mount Pinatubo natural experiment) a "*sulfate climate cooling efficiency of 0.75 W/m^2 per Tg S in the stratosphere*". Secondly, the estimations of possible externalities from stratospheric sulfur injection are very limited and uncertain to this day (2013). This lack of scientific evidence motivates us to

[2]See: http://www.econ.yale.edu/ nordhaus/DICE2007.htm.

[3]Indeed, deployment of last minute strategies should incur organizational costs much higher than under a long-planned strategy. Besides, compared to proactive adaptation, reactive adaptation should bear some of the infrastructure and deployment costs upfront, which induces large overhead.

rely on scenario analysis for SRM side-effects, where many possible paths are considered with positive probability. To calibrate the impact factor α_{GE}, we define three levels of damages: an initial level $\alpha_{GE}(t_0)$, and two threshold levels for the final period T defining a minimum ($\underline{\alpha_{GE}}$) and a maximum level ($\overline{\alpha_{GE}}$) that damages can reach. We calibrate $\alpha_{GE}(t_0)$ such that the injection of 1 Tg S per year during one decade would match the damages from a temperature increase to one-fourth of the catastrophic temperature level (cat_T). This results in a value of 0.2523 for $\alpha_{GE}(t_0)$.

The calibration of $\overline{\alpha_{GE}}$ follows the same methodology but with increased damages equivalent to $\frac{cat_T}{2}$. The resulting value for $\overline{\alpha_{GE}}$ is 1.0366. The uncertainty regarding α_{GE} is modeled using a binomial tree approach, with the following dynamics:

$$\alpha_{GE}(t) \begin{cases} \alpha_{GE}(t+1) = (1+u)\cdot\alpha_{GE}(t) & \text{, with probability} \quad p \\ \alpha_{GE}(t+1) = (1+d)\cdot\alpha_{GE}(t) & \text{, with probability} \quad (1-p) \end{cases}$$

with u the percentage increase, d the percentage decrease, and p the probability of having an up-move next period. To allow for a symmetric tree, $p = 0.5$ and $d = -u$; u is calibrated to link the initial to the maximum value of α_{GE} in a monotonically increasing path over 15 decades (until $T = 2155$): $\alpha_{GE}(t_0)\cdot(1+u)^{15} = \overline{\alpha_{GE}}$. Based on the binomial representation we obtain 32,768 ($= 2^{15}$) different but equiprobable scenarios. The stochastic and time-varying representation of the side-effects from sulfur dissipation is motivated by the view that ecosystems present dynamic and non-linear resilience to shocks and perturbations (Holling, 1973; Gunderson, 2003) such as SRM. Complex socio-ecological systems (SESs) can have a highly optimized tolerance to a certain set of disturbances (Janssen et al., 2007; Carlson and Doyle, 2002), but the same systems would suffer if the disturbances evolve or change outside of their optimized tolerance zone, causing them to move to new equilibria. The SES appear as a vulnerable and complex system subject to multiple transient evolutions (Folke, 2006) between different stability domains, some of them unfavorable (Renaud et al., 2010). Considering the number of systems that SRM impacts and the possible existence of complex feedback loops, we consider its short- and long-term disturbances to be unpredictable and to evolve in a possibly non-monotonic manner. We therefore proxy the evolution of damages on the ecosystem with a binomial tree such that at each period, the process can evolve to a weaker or stronger state.

3 The optimal policy mix

3.1 Selected scenarios for SRM side-effects

In this section, we consider only selected scenarios for the (negative) side-effects associated with the implementation of SRM: a *strong* side-effects scenario, where α_{GE} gradually increases over time until $\overline{\alpha_{GE}}$ at T; a *weak* scenario, where α_{GE} decreases monotonically over time until $\underline{\alpha_{GE}}$ at T; and a *mild* scenario, where α_{GE} evolves over time until $\overline{\underline{\alpha_{GE}}}$[4] at T. The strong and weak scenarios reflect the edges of the distribution of side-effects from SRM, where the specific paths are given by the branches of the binomial tree at the extremes. They represent the marginal cases when SRM has either almost no impact on the environment (weak), or the impacts are extremely harmful (strong). The latter case refers to the situation in which all forecasted side-effects from sulfur dissipation would be triggered (ozone depletion, unfavorable change in precipitation patterns, warming of the tropical tropopause) and the total magnitude would be amplified by the interactions between different effects. The third scenario (mild) allows only for limited effects from SRM and represents a middle case between the two extremes (when only some of the side-effects would be unleashed, or their magnitude would be benign).

In these three scenarios, all policy strategies (adaptation, SRM, and mitigation) are available. We consider two additional scenarios: a mitigation-only scenario (where adaptation and SRM are not possible), and an adaptation-mitigation scenario (where SRM is not available).

The traditional policy to address climate change is mitigation, which corresponds in our model to a transition from the carbon economy to the low-carbon one. Fig. 1 illustrates the optimal capital accumulation in the two economies.

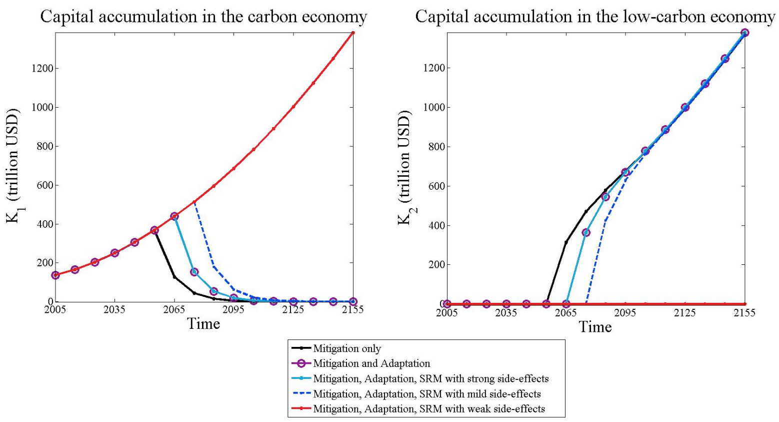

Figure 1: Capital accumulation in the two economies

When mitigation is the only climate policy available (mitigation-only scenario), there is a clear transition between the two economies: the carbon-intensive capital is rapidly phased out after 2055 and completely replaced by the low-carbon capital by the end of the century. When adaptation is also available as a policy tool (adaptation-mitigation scenario), this transition does take place, but starts one decade later. The SRM option has contrasted implications: under mild side-effects, the transition is further delayed by ten years (after 2075), whereas the transition never occurs under weak side-effects. In

[4] $\overline{\underline{\alpha_{GE}}}$ is selected among the available scenarios, such that $\overline{\underline{\alpha_{GE}}}(T) \in [\underline{\alpha_{GE}}(T), \overline{\alpha_{GE}}(T)]$, and the path results in an optimal policy mix where both mitigation and SRM are employed.

agreement with Barrett (2008), our results indicate thus that there is no incentive to curb GHG emission if SRM is available and its side-effects are benign. Conversely, notice that SRM is not used under strong side-effects, therefore the path is identical with the adaptation-mitigation scenario.

Fig. 2 reports on adaptation and SRM, the two alternatives to mitigation. When its side-effects are weak, SRM is the main instrument to address climate change. It is used after 2055 (substituting for mitigation efforts), together with adaptation (after 2065). When its side-effects are mild, SRM is only used (after 2075) as a complement to adaptation and mitigation strategies. And as already mentioned, SRM is not employed when its side-effects are strong. Concerning adaptation, we note that: (i) accumulation of proactive adaptation capital starts before spending on reactive adaptation; and (ii) proactive and reactive strategies act as complements, with their respective effectiveness increasing in the deployment of the other adaptation measure. Besides, the decreasing trend in adaptation efforts towards the end of the horizon directly reflects the lowering of temperature (see next Fig. 3) through SRM and/or mitigation efforts.

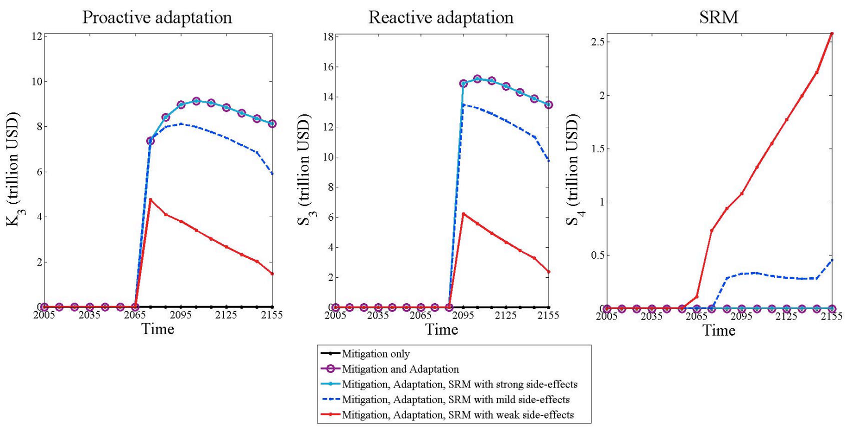

Figure 2: Capital accumulation in proactive adaptation, and decade spending with reactive adaptation and SRM

An interesting aspect is the relative dynamics of reactive adaptation and SRM. As ex-post measures, they share the advantage of rapid implementation and immediate impacts on damages. According to our results, the preference for either measure depends on the magnitude of sulfur damages: whenever side-effects remain low, SRM is clearly favored over adaptation. This result underlines the high-effectiveness low-cost features of SRM strategies, which target directly temperature and are unbounded. On the contrary, adaptation can only reduce a limited share of damages. However, when SRM damages increase, the reactive adaptation takes the lead in alleviating damages.

Fig. 3 reveals that temperature is only kept below the 2°C threshold proposed by the Copenhagen Accord (except for a brief period around 2065) when the side-effects of SRM are weak. This reduction is achieved at the expense of: (i) large spendings in

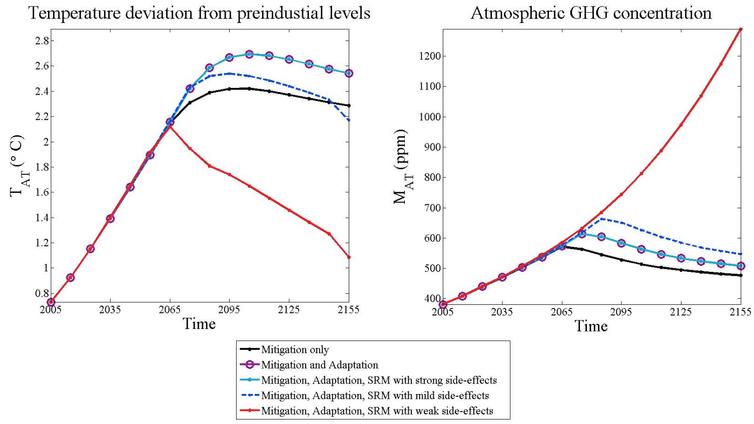

Figure 3: Atmospheric temperature and GHG concentrations

SRM[5] (see again Fig. 2); and (ii) increasing atmospheric GHG concentrations, due to an exclusive reliance on the carbon-intensive economy for production across the entire time horizon. Otherwise, concentrations start decreasing shortly after the transition to the low-carbon economy begins, followed later on by a downward trend in temperature. Note also that under mild side-effects, the use of some SRM allows temperature to move closer to the 2°C threshold towards the mid twenty-first century.

Constraining the optimization to a maximum increase in temperature of 2°C, leads to an anticipation in time of mitigation and/or SRM implementation. For the strong side-effects case, investments in mitigation are advanced by three decades; in case of low side-effects, SRM remains the first pillar in the climate policy mix and its implementation is carried out beginning with 2065. To reduce damages from climate change, resources are allocated to adaptation at unchanged time periods, but the smaller damages incurred in the constrained temperature case require less intensive adaptation.

3.2 Distributional Analysis for SRM side-effects

In this section, we consider again the case where all policy options are available, but we examine all the different side-effects scenarios generated with the help of the binomial tree representation, as detailed in Section 2.2.

Fig. 4 below illustrates two historical distributions of the average value of side-effects along each path. The first histogram (grey area) corresponds to the scenarios where SRM is part of the optimal climate policy mix, while in the second one (blue area) its use is not optimal .

As expected, SRM is not part of the optimal climate policy when side-effects are above a given threshold, here when the average α_{GE} is above 0.18. This reinforces the fact that the immediate implementation of SRM is not necessary under any of the

[5]This is consistent in particular with the findings of Wigley (2006) and Crutzen (2006).

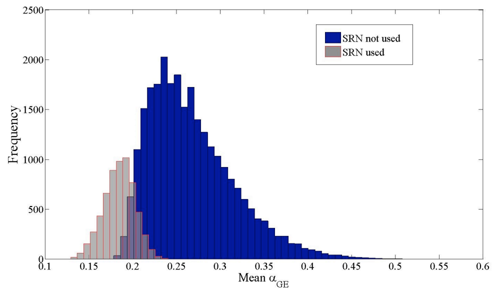

Figure 4: Historical distributions of SRM side-effects

scenarios, but will come only at later points in time when the estimated side-effects will prove smaller. For the range [0.18; 0.25], the two histograms overlap, suggesting that the use of SRM depends not only on the average value of the side-effects across time, but also on the minimum values reached at certain time points (that trigger the use of SRM for some periods).

Overall, SRM is only used in less than 19% of the simulated cases (for at least one decade), at the earliest in 2065. When used, on average, SRM starts around 2090 and last for about 45 years. Mitigation is the first pillar of the climate policy in 95% of the cases, with about 14% of scenarios where both mitigation and SRM are employed simultaneously; here mean values of $\alpha_{GE}(t_0)$ belong to the [0.16,0.24] range. Our results point to the fact that SRM fully substitutes mitigation in only about 5% of the cases; for the rest, when SRM is employed it complements the abatement of emissions. Finally, both reactive and proactive types of adaptation accompany the other climate strategies in all analyzed scenarios, where reactive adaptation is implemented on average two decades after proactive (around 2095). The constant presence of adaptation in the optimal policy mix suggests the limits of both mitigation (long implementation horizon) and SRM (sulfur side-effects) in dealing effectively with climate change; this takes place despite the fact that adaptation can alleviate maximum 50% of damages (Eq. 4). Indeed, for the majority of cases, mitigation and adaptation are together indispensable for the optimal policy mix.

4 Additional concerns over SRM

The previous section indicates that SRM should be part of an optimal climate policy when its side-effects are low. However, additional concerns may discourage the use of SRM even in that case. This section explores some of these concerns.

4.1 Atmospheric CO_2 concentration

Increased atmospheric CO_2 concentration levels trigger climate changes that may cause environmental damages. Besides these damages, higher concentration levels may have additional adverse effects on ecosystems. These effects are often termed as the "*other CO_2 problem*" (Henderson, 2006). One concern is ocean acidification. Rising atmospheric CO_2 is naturally absorbed by oceans, with several negative impacts, such as pH reductions and alterations in fundamental chemical balances (Doney et al., 2009). Additional concerns are for plant physiology and growth with impacts on agricultural production and food quality (Taub, 2010). Ignoring such environmental concerns may lead to suboptimal choices about the climate change policy portfolio, as the use of SRM is done at the expense of higher atmospheric GHG concentration levels; see gain Fig. 3. Conversely, respecting 'safe' limits for GHG concentrations will further deter the use of SRM.

Acknowledging in particular that damages to ocean ecosystems may occur with CO_2 levels as low as 450 ppm (Cao and Caldeira, 2008), we have considered different concentrations levels reached in 2100 (in our 32,768 scenarios related to SRM side-effects), to illustrate how such concerns may impact the climate policy mix. The scenarios when SRM is used (18.7% of the total cases), no case is consistent with a level of 550 ppm (or below): around 50.3% of the cases reach a level between 550 and 650 ppm, the remaining cases (around 49.7%) have levels above 650 ppm.

When constraining the concentration levels to stay below 550 ppm (at all time), the use of SRM is reduced to only 9.5% of the simulated cases. Here, to respect the concentration limit, less sulfur is injected in the atmosphere, with more mitigation done as a compensation. In conclusion, we believe that an optimal policy mix should not only limit temperature increases, but also atmospheric GHG concentration levels. Doing so, the use of SRM as a 'quick fix' should further be reduced (both in frequency and in intensity).

4.2 Wrong assumptions for SRM damages

Until now, we have evaluated the optimal policy mix via scenario analysis, assuming that the negative SRM effects were known along each scenario, namely each given path in the binomial tree. We analyze in this section the welfare costs of observing a different (random) side-effect path than the one presumed when deciding to implement SRM measures.

To do so, we first compute the *presumed* SRM damages ($D_{GE}(t, s)$) following Eq. (2) for a given (side-effect) scenario s. These damages impact the economic loss factor (ELF) as described by Eq. (3) and can therefore be considered as reductions in GDP caused by SRM. Next, we compute ex-post GDP losses ($D_{GE}(t, s')$) that arise when a different side-effect path occurs than the one assumed when designing the optimal policy ($s' \neq s$). More precisely, we simply replace in Eq. (2) $\alpha_{GE}(t, s)$ with a factor $\alpha_{GE}(t, s')$ chosen randomly from the possible side-effect paths[6], while keeping the same

[6] We base our analysis on average results from 5000 simulations of uniformly random draws from the

levels for sulfur injection. We thereafter refer to these damages as *unexpected damages*. By comparing presumed and unexpected damages, we can analyze the welfare impacts of experiencing unexpected SRM side-effects.

We believe that forming wrong assumptions regarding the SRM side-effects can only last for short periods. Indeed, although the earth system presents some inertia, the magnitude of the side-effects is ex-post identifiable via environmental feedbacks and decreases in production. However, in the short run, predictions are difficult to make with accuracy, and it might take several decades until true realizations are identified. As an illustration, we consider one to three decades, and we compare in Fig. 5 average GDP losses under known (presumed) and random (unexpected) SRM side-effect paths[7].

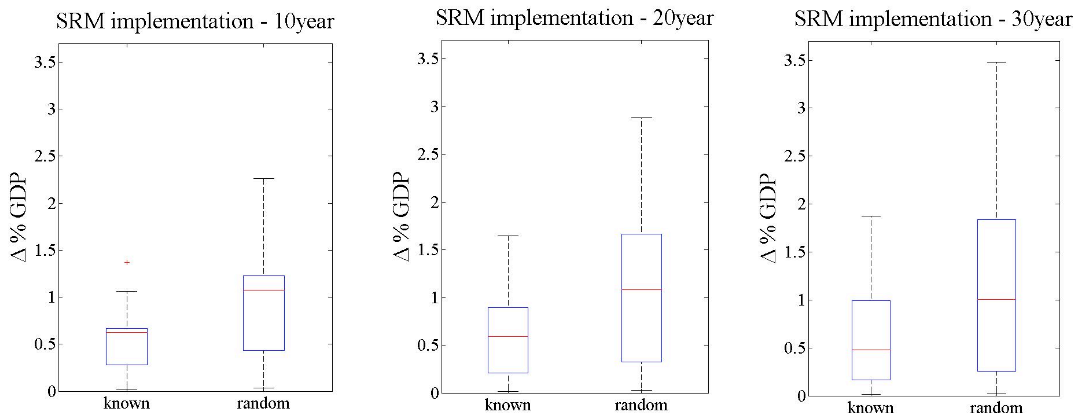

Figure 5: Distribution of average GDP losses under known and random SRM damages for different error horizons

Fig. 5 reveals that average GDP losses rise considerably when the side-effects path has a different outcome than the one assumed, even for very short-term horizons, on average up to two times more than in the presumed (known) case. For longer implementation horizons, GDP losses are augmented on average, together with their variance and their right skewness, indicating that extreme large losses have a higher chance of occurrence.

Besides estimating the losses in welfare, we are interested in understanding the necessary adjustments to the optimal policy mix after the update in beliefs. As an example, we examine the extreme case, when side-effects were assumed to be weak, but they turn out to be strong. We have seen in Section 3 that when side-effects are weak, the optimal

α_{SE} path distribution.

[7] For each scenario $s \in [1; 32768]$, we compute the unexpected damages as the sum of percentage GDP losses: $\sum_{t=1}^{\tau} D_{GE}(t, s')$, where t refers to the start period of SRM implementation in scenario s, s' is the unexpected side-effect path with $\alpha_{GE}(t, s')$, and $\tau \in \{1, 2, 3\}$ decades of SRM implementation.

starting time for SRM implementation is 2065. We assume now that the policy maker believes to be on this path and starts SRM activities as planned in 2065, and continues with the implementation for two decades; due to feedbacks on consumption, he is able later on to update his beliefs regarding the side-effects, and modify the policy mix accordingly. The realization that side-effects are actually high leads to the suspension of any SRM activities after 2085; to counteract the GDP losses from side-effects and the rapid temperature increase, mitigation and adaptation are employed heavily, with the new policy mix trying to get closer to the one considered optimal in case of strong side-effects. The carbon intensive technology is gradually phased out by the end of the 21^{st} century, but due to the long life of GHG in the atmosphere, temperature increases rapidly up to almost 3°C; to decrease the damages from temperature change, adaptation is used promptly and intensively. The expenses with the new policy mix reduce pro capita consumption until the end of the optimization horizon.

This simple analysis reinforces the precautionary approach one should have with SRM. Relying on imperfect forecasts for side-effects can lead to large welfare losses, even for short implementation horizons. In accordance with Moreno-Cruz and Keith (2013), these findings call also for the necessity to reduce the uncertainty revolving around SRM.

4.3 Unexpected interruptions in SRM

One of the main concerns about SRM is related to potential damages that would be unleashed should one be unable to continue with the dissipation of sulfur (Robock et al., 2009; Goes et al., 2011; IPCC, 2013) due for instance to technical breakdown. In this section, we analyze for a sudden SRM interruption in 2105 in the case where α_{GE} is low, namely when SRM is a significant part of the policy mix. We then rerun the model for the horizon 2105 to 2155, with the additional constraint that SRM is no longer available.

With the sudden termination of sulfur dissipation, there is no longer a mean to mask the radiative forcing associated with an atmospheric concentration level of around 810 ppm by 2105. Then, very rapidly (less than two decades) temperature deviation reaches 3°C and increases further to more than 3.5°C by the end of the model horizon (2155), see Fig. 6.

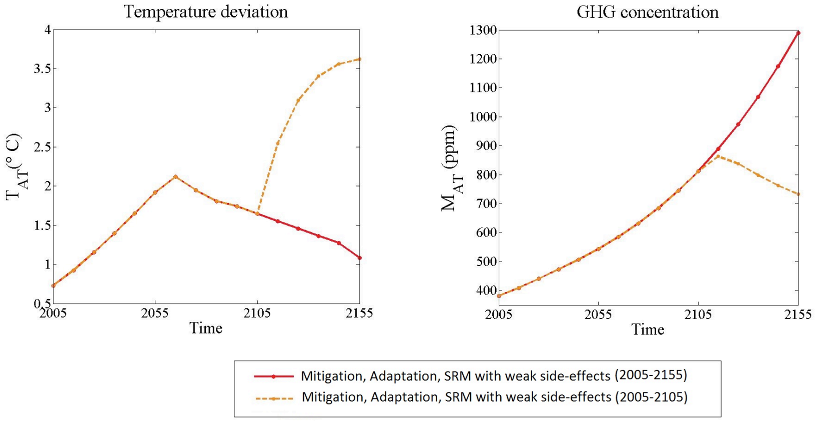

Figure 6: Changes in temperature deviation and CO_2 concentrations after SRM interruption

Under a rapid temperature increase, the optimal policy needs to adjust promptly, consisting, on the one-hand, in making a quick transition towards the low-carbon economy, and on the other hand, in allocating funds in (reactive and proactive) adaptation. The latter set of measures is successful in reducing damages, from 5% of GDP (gross damages) to a less harmful 2% level (net damages) in 2155. Although mitigation is implemented rapidly, it is unable to reduce temperature within the remaining time frame considered, due to inertia in the climate system.

With the interruption in SRM, temperature increases thus at a high speed and remains above 3°C for at least several decades. Although our model does not account for possible abrupt climate changes, such temperature pattern could imply reaching a 'tipping point' in the climate system (Lenton et al., 2008) yielding for instance a melting of the West Antarctic ice sheet or a collapse of the Atlantic thermohaline circulation, with significant impacts on ecological systems and human welfare.

5 Conclusions

In the current paper we have investigated the optimal policy mix for dealing with climate change. In addition to relying on mitigation and adaptation strategies, solar radiation management (SRM) can be employed for keeping temperature levels under control.

In this setting, the interactions between the natural and economic systems are key for understanding the optimal climate strategy, and we rely on an integrated assessment model to describe the dynamic evolution of both. To account for the specific uncertainties surrounding geoengineering, we disentangle between the different effects of SRM on atmospheric temperature levels and on ecosystem health.

Three important conclusions emerge from our analysis. First, we show that accounting for all three policy alternatives guarantees the best results from a welfare perspective.

Mitigation emerges as the strongest pillar for tackling climate change, with adaptation as an effective complement. SRM entails serious side-effects on the environment and its use is optimal in only 18% of the analyzed scenarios, with different implementation horizons depending on the severity of the side-effects. Furthermore, a policy mix that targets remaining below the 2°C increase in temperature requires early investments in mitigation and/or SRM, underlying the urgency of advancing international climate initiatives.

Secondly, we show that a climate policy that targets primarily temperature reductions, but does not address the increase in CO_2 concentrations, is not sustainable. Targeting CO_2 concentrations that remain below dangerous levels reduces the use of SRM even further in favor of mitigation.

Thirdly, we investigate the possible welfare losses, should the assumptions regarding SRM side-effects prove incorrect. We show that annual GDP losses rise considerably when the side-effects path has a different outcome than the one estimated. Larger implementation horizons lead to higher GDP losses, together with increased variance and right skewness. The adjustment of the policy mix after updates in SRM side-effects information, will give primary weight to mitigation, but its slow impact on concentrations will not be able to deter fast temperature increases above safe levels.

In our results, despite the predominant role of mitigation, we note that investments in the low-carbon economy start after 2055 at the earliest, following from specific modeling choices. First, our model assumes exogenous technological progress. With an endogenous formulation, one might expect that (R&D) investments in low-carbon technologies start much earlier to get 'on-time' the needed technologies for mitigation. And second, being derived in a cost-benefit framework, our results (and in particular the timing of the mitigation measures) critically depend on the magnitude of the estimated climate change damages, calibrated on DICE and AD-DICE. Recent papers (Stern, 2013; Pindyck) signal possible underestimations of climate change damages in the DICE-like integrated assessment models; further research could help to address these issues.

Similarly, the employment of SRM depends on a three-dimentional uncertainty, stemming from: the magnitude of side-effects, the corresponding probabilities, and problems of governance. The calibration of all involved parameters will benefit from revisions reflecting future scientific research.

Finally, in our model SRM is performed at a global level, assuming the existence of a well-functioning international cooperation. We believe that further research could improve our understanding regarding the benefits and shortcomings of relying on the SRM option, by allowing for differentiated geographical SRM impacts and investigating the strategic programs for country participation.

References

Adger, W., Agrawala, S., Mirza, M., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B., Takahashi, K., 2007. Assessment of adaptation practices, options, constraints and capacity, in: Parry, M., Canziani, O., Palutikof, J., van der Linden, P., Hanson, C. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, UK. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 717–743.

Agrawala, S., Bosello, F., Carraro, C., De Bruin, K., De Cian, E., Dellink, R., Lanzi, E., 2011. Plan or react? analysis of adaptation costs and benefits using integrated assessment models. Climate Change Economics 2, 175–208.

Bahn, O., Chesney, M., Gheyssens, J., 2012. The effect of proactive adaptation on green investment. Environmental Science & Policy 18, 9–24.

Bala, G., Duffy, P.B., Taylor, K.E., 2008. Impact of geoengineering schemes on the global hydrological cycle. Proceedings of the National Academy of Sciences 105 (22).

Barrett, S., 2008. The incredible economics of geoengineering. Environmental and Resource Economics 39, 45–54.

Bosello, F., Carraro, C., De Cian, E., 2010. Climate policy and the optimal balance between mitigation, adaptation and unavoided damage. Climate Change Economics 1, 71–92.

Brasseur, G.P., Roeckner, E., 2005. Impact of improved air quality on the future evolution of climate. Geophysical Research Letters 32.

Brovkin, V., Petoukhov, V., Claussen, M., Bauer, E., Archer, D., Jaeger, C., 2009. Geoengineering climate by stratospheric sulfur injections: Earth system vulnerability to technological failure. Climatic Change 92, 243–259.

de Bruin, K., Dellink, R., Tol, R., 2009. AD-DICE: An implementation of adaptation in the DICE model. Climatic Change 95, 63–81.

Cao, L., Caldeira, K., 2008. Atmospheric co_2 stabilization and ocean acidification. Geophysical Research Letters 35.

Carlin, A., 2007. Global climate change control: is there a better strategy than reducing green house gas emissions? Univ PA Law Review 155, 128–156.

Carlson, J.M., Doyle, J., 2002. Complexity and robustness. Proceedings of the National Academy of Sciences of the United States of America 99, 2538–2545.

Crutzen, P., 2006. Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? Climatic Change 77, 211–219.

Dickinson, R.E., 1996. Climate engineering: A review of aerosol approaches to changing the global energy balance. Climatic Change 33, 279–290.

Doney, S.C., Fabry, V.J., Feely, R.A., Kleypas, J.A., 2009. Ocean acidification: The other co2 problem. Annual Review of Marine Science 1, 169–192.

Folke, C., 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. Global environmental change 16, 253–267.

Goes, M., Tuana, N., Keller, K., 2011. The economics (or lack thereof) of aerosol geoengineering. Climatic Change 109, 719–744.

Gramstad, K., Tjotta, S., 2010. Climate engineering: Cost benefit and beyond. Working papers in economics, University of Bergen, Norway.

Gunderson, L.H., 2003. Adaptive dancing: interactions between social resilience and ecological crises. Navigating socialecological systems: building resilience for complexity and change. Cambridge University Press, Cambridge, UK , 33–52.

Henderson, C., 2006. Ocean acidification: the other co_2 problem. New Scientist .

Holling, C.S., 1973. Resilience and stability of ecological systems. Annual review of ecology and systematics 4, 1–23.

IPCC, 2007. Climate Change 2007: Synthesis Report. Cambridge University Press, Cambridge, UK.

IPCC, 2013. Climate change 2013, the physical science basis, summary for policymakers.

Janssen, M.A., Anderies, J.M., Ostrom, E., 2007. Robustness of social-ecological systems to spatial and temporal variability. Society and Natural Resources 20, 307–322.

Keith, D., 2000. Geoengineering the climate: history and prospect. Annual Review of Energy and the Environment 25, 245–284.

Kintisch, E., 2010. Hack the planet: science's best hope-or worst nightmare-for averting climate catastrophe. Wiley. com.

Klein, R., Huq, S., Denton, F., Downing, T., Richels, R., Robinson, J., Toth, F., 2007. Inter-relationships between adaptation and mitigation, in: Parry, M., Canziani, O., Palutikof, J., van der Linden, P., Hanson, C. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, UK. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 745–777.

Kravitz, B., Rasch, P.J., Forster, P.M., Andrews, T., Cole, J.N.S., Irvine, P.J., Ji, D., Kristjnsson, J.E., Moore, J.C., Muri, H., Niemeier, U., Robock, A., Singh, B., Tilmes, S., Watanabe, S., Yoon, J.H., 2013. An energetic perspective on hydrological cycle changes in the Geoengineering Model Intercomparison Project. Journal of Geophysical Research 118 (23).

Lenton, T., Held, H., Kriegler, E., Hall, J., Lucht, W., Rahmstorf, S., Schellnhuber, H., 2008. Tipping elements in the Earth's climate system. Proceedings of the National Academy of Sciences 105, 1786–1793.

Lenton, T., Vaughan, N., 2009. The radiative forcing potential of different climate geoengineering options. Atmospheric Chemistry and Physics 9.

Manne, A., Richels, R., 2005. MERGE: An integrated assessment model for global climate change, in: Loulou, R., Waaub, J.P., Zaccour, G. (Eds.), Energy and Environment. Springer. volume 3 of *GERAD 25th Anniversary Series*, pp. 175–189.

Margulis, S., Narain, U., 2009. The Costs to Developing Countries of Adapting to Climate Change: New Methods and Estimates. Global Report of the Economics of Adaptation to Climate Change Study. The World Bank. Washington, DC.

Moreno-Cruz, J.B., Keith, D.W., 2013. Climate policy under under uncertainty: a case for solar geoengineering. Climatic Change 121, 431–444.

Niemeier, U., Schmidt, H., Alterskjr, K., Kristjnsson, J.E., 2013. Solar irradiance reduction via climate engineering: Impact of different techniques on the energy balance and the hydrological cycle. Journal of Geophysical Research 118 (21).

Nordhaus, W., 2001. Global warming economics. Science 294, 1283–1284.

Nordhaus, W., 2008. A question of balance. Yale University Press .

Nordhaus, W.D., Boyer, J., 2000. Warning the World: Economic Models of Global Warming. MIT Press (MA).

Pindyck, R.S., . Climate change policy: what do the models tell us? Working paper 19244 NBER.

Ramanathan, V., Crutzen, P., Kiehl, J., Rosenfeld, D., 2001. Aerosols, climate, and the hydrological cycle. science 294, 2119–2124.

Renaud, F.G., Birkmann, J., Damm, M., Gallopín, G.C., 2010. Understanding multiple thresholds of coupled social–ecological systems exposed to natural hazards as external shocks. Natural Hazards 55, 749–763.

Robock, A., Marquardt, A., Kravitz, B., Stenchikov, G., 2009. Benefits, risks, and costs of stratospheric geoengineering. Geophysical Research Letters 36.

Schaller, N., Cermak, J., Wild, M., Knutti, R., 2013. The sensitivity of the modeled energy budget and hydrological cycle to CO_2 and solar forcing. Earth System Dynamics 4, 253266.

Shepherd, J., 2009. Geoengineering the climate; science, governance and uncertainty. The Royal Society .

Stanhill, G., Cohen, S., 2001. Global dimming: A review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. Agricultural and Forest Meteorology 107.

Stern, N., 2013. The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models. Journal of Economic Literature 51(3), 838–859.

Taub, D.R., 2010. Effects of rising atmospheric concentrations of carbon dioxide on plants. Nature Education Knowledge 3(10), 21.

Teller, E., Hyde, R., Ishikawa, M., Nuckolls, J., Wood, L., 2003. Active stabilization of climate: Inexpensive, low risk, near term options for preventing global warming and ice ages via technologically varied solar radiative forcing. Lawrence Livermore National Laboratory .

Tilmes, S., Mueller, R., Salawitch, R., 2008. The sensitivity of polar ozone depletion to proposed geoengineering schemes. Science 320, 1201–1204.

Tol, R., 2005. Adaptation and mitigation: Trade-offs in substance and methods. Environmental Science and Policy 8, 572–578.

Vaughan, N., Lenton, T., 2012. Interactions between reducing co2 emissions, co2 removal and solar radiation management. Philosophical transactions of The Royal Society .

Victor, D.G., 2008. On the regulation of geoengineering. Oxford Review of Economic Policy 24, 322–336.

Wigley, T., 2006. A combined mitigation/geoengineering approach to climate stabilization. Science 314, 452–454.