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Climate engineering and climate tipping-point scenarios

J. Eric Bickel

Abstract Many scientists fear that anthropogenic emissions of greenhouse gases have set the Earth on a path of significant, possibly catastrophic, changes. This includes the possibility of exceeding particular thresholds or tipping points in the climate system. In response, governments have proposed emissions reduction targets, but no agreement has been reached. These facts have led some scientists and economists to suggest research into climate engineering. In this paper, we analyze the potential value of one climate engineering technology family, known as solar radiation management (SRM) to manage the risk of differing tipping-point scenarios. We find that adding SRM to a policy of emissions controls may be able to help manage the risk of climate tipping points and that its potential benefits are large. However, the technology does not exist and important indirect costs (e.g., change in precipitation) are not well understood. Thus, we conclude the SRM merits a serious research effort to better understand its efficiency and safety.

Keywords Climate engineering · Geoengineering · Climate change · Tipping points · Abrupt climate change · Climate-change economics · Scenario analysis · Risk analysis

1 Introduction

The oxidation of hydrocarbons to generate energy produces water and carbon dioxide (CO2), among other compounds. This CO2 production alters the Earth's carbon cycle, leading to an increase in atmospheric CO2 concentrations (IPCC 2007a). All else being equal, this increase will raise the average surface temperature of the Earth (Stocker 2003; Trenberth et al. 2009). Thus far, the Earth has warmed about 0.7 °C (1.3 °F), relative to 1900, while CO2 concentrations have increased about 100 parts per million (ppm)—from a baseline of about 280 ppm (0.028 %).

This warming and associated climate changes such as ocean acidification are likely to bring economic damages (Parry et al. 2007). In addition, some scientists warn that the climate contains "tipping points" beyond which significant changes in the Earth system will occur. These may include loss of Arctic sea ice, melting of the Greenland and Antarctic ice sheets, irreversible loss of the Amazon rain forest, and abrupt changes in the Indian and African monsoons (Meehl et al. 2007). Lenton et al. (2008) conclude that "a summer ice loss threshold, if not already passed may be very close and a transition could occur well within this century."

Despite these concerns, two decades of climate negotiations have failed to reduce emissions. In fact, global CO2 emissions grew four times more quickly between 2000 and 2007 than they did between 1990 and 1999 (Global Carbon Project 2008). These facts have led some scientists and economists to consider other responses to climate change. One of these responses is known as climate engineering. The Royal Society, in UK, defines climate engineering (CE) as "the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming"(The Royal Society 2009).

In this paper, we investigate the potential economic benefits of using CE to lower the risk, and associated economic damages, of crossing thresholds in the climate system. Specifically, we modify an established model of

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climate-change economics to quantify the damages imposed by crossing tipping points. We then allow for the deployment of CE and estimate the reduction in damages. We analyze the use of CE under several emissions control policies. In addition, we quantify the degree of CE intervention required to hold temperature changes below 2, 3, and 4 °C.

Lenton et al. (2008) consider several tipping points in the climate system and rank them based on their proximity and potential impact. These include loss of Arctic summer sea ice, disintegration of the Greenland Ice Sheet (GIS), disintegration of the West Antarctic Ice Sheet (WAIS), halting of the Atlantic thermohaline circulation, melting of permafrost, among others. Crossing these tipping points could lead to amplified warming, in the case of Arctic sea ice loss and the melting of permafrost, or large damages in the form of rising sea levels, due to melting land-based ice. Lenton et al. (2008) conclude that "the greatest (and clearest) threat is to the Arctic with a summer sea ice loss likely to occur long before (and potentially contribute to) GIS melt." They also conclude that disintegration of the WAIS is "surrounded by large uncertainty" and given its sensitivity to warming could "surprise society."

To be clear, this paper does not argue for the deployment of CE. Rather, our goal is to demonstrate that CE could play a valuable risk management role, with attendant benefits. These benefits appear to be large enough that a formal research program should be undertaken to (i) identify and quantify the potential costs (direct and indirect) of CE and (ii) to develop the underlying technologies.

This paper is organized as follows. In Sect. 2, we discuss two different families of climate engineering. In Sect. 3, we summarize the economics of climate change and identify important risk drivers. In Sect. 4, we detail the challenge of addressing climate tipping points via emissions reductions. In Sect. 5, we analyze the economic benefit of different CE policies and their ability to address climate tipping points. Rather than model uncertainty regarding the location and severity of climate tipping points, we consider many different scenarios. In Sect. 6, we summarize the implications and limitations of our work and conclude.

2 Climate engineering

As mentioned above, the Royal Society has studied the concept of CE. After considering potential benefits and highlighting significant unknowns, the Royal Society recommended a formal research program be undertaken (The Royal Society 2009). CE is composed of two distinct technology families: air capture (AC) and solar radiation management (SRM).

AC removes CO2 from ambient air and sequesters it away from the atmosphere. The primary attractions of AC are that it (1) separates CO2 production from capture, adding flexibility and reduced transportation costs, (2) holds the possibility of reversing the rise in CO2 concentrations, thereby addressing ocean acidification and warming, and (3) should be less risky than SRM. There are two shortfalls of AC, as far as managing tipping points is concerned. First, the cost to reduce CO2 concentrations by 1 ppm is currently estimated to be on the order of $1 trillion (Pielke 2009). Second, as discussed in Sect. 4, because of lags in the climate system, CO2 removal may not be able to change the climate system as quickly as might be required. For this reason, we will focus the remainder of this paper on SRM, which holds the potential of quickly cooling the Earth.

SRM differs from air capture in that it seeks to reverse the energy imbalance caused by increased greenhouse gas (GHG) concentrations. This is achieved by reflecting back into space some fraction of the incoming shortwave radiation from the Sun. Calculations show that reflecting one to two percent of the sunlight that strikes the Earth would cool the planet by an amount roughly equal to the warming that is likely from doubling the concentration of GHGs (Lenton and Vaughan 2009). Scattering this amount of sunlight appears to be possible (Novim 2009).

SRM holds the possibility of acting on the climate system on a time-scale that could prevent the abrupt and harmful changes discussed above (Novim 2009). In fact, SRM may be the only human action that can cool the planet in an emergency. As Lenton and Vaughan (2009) note, "It would appear that only rapid, repeated, large-scale deployment of potent shortwave geoengineering options (e.g., stratospheric aerosols) could conceivably cool the climate to near its preindustrial state on the 2050 timescale."

Currently, we are inadvertently deploying a version of SRM. The IPCC (2007b) estimates that anthropogenic aerosol emissions (primarily sulfate, organic carbon, black carbon, nitrate, and dust) are providing a negative radiative forcing of 1.2 watts per square meter (W/m^2). The current net GHG radiative forcing is 1.6 W/m^2, including the negative forcing of aerosols; thus, aerosols currently offset over 40 % of anthropogenic emissions. This forcing is divided into direct (0.5 W/m^2) and indirect (0.7 W/m^2) components. The direct component is a result of sunlight being scattered by the aerosol layer. The indirect component represents aerosols' effect on cloud albedo. The two classes of SRM technologies that have received the most attention parallel this division are stratospheric aerosol injection and marine cloud whitening. In the most studied form of stratospheric aerosol injection, a precursor of sulfur dioxide would be (continuously) injected into the stratosphere, where it would add to the layer of sulfuric acid already present in the lower stratosphere (Pope et al. 2012).

This layer would reflect sunlight. It is believed that marine cloud whitening could result in cooling by injecting marine clouds with seawater, forming a sea-salt aerosol (Latham et al. 2008; Salter et al. 2008). This aerosol would result in the formation of additional water droplets and/or ice crystals, resulting in whiter and more reflective clouds.

Other SRM concepts include placing mirrors in space and painting rooftops white. Placing mirrors in space is likely to involve large fixed costs (Bickel and Lane 2010). White rooftops may play an important local role, but are unlikely to scale to the degree needed (Lenton and Vaughan 2009) or help protect sensitive areas like the Arctic.

3 The model and deterministic results

We use the Dynamic Integrated model of Climate and the Economy-2007 (DICE-2007) developed by Nordhaus (1994, 2008), Nordhaus and Boyer (2000), to understand the most important drivers of climate-change risk and uncertainty. DICE relates economic growth to energy use, energy use to CO2 emissions, CO2 emissions to atmospheric concentrations of CO2, CO2 concentrations to temperature increase, and finally temperature increase to economic damage. The policy variable in DICE is the annual CO2 emissions control rate. Reducing emissions incurs abatement costs and lowers economic growth. However, it restrains temperature changes. DICE balances these competing factors to arrive at the “optimal” emissions control program in each decade for the next 600 years (2005–2605). We, however, limit our analysis to 200 years (2005–2205).

DICE can also be used to find the emissions control regime that meets a particular temperature target, such as limiting temperature increases to 2.0 °C. We will consider four different emission control policies: no controls (NC), optimal controls (OC), and limiting temperature change to either 1.5 °C (L1.5C) or 2.0 °C (L2.0C).

Like emissions, DICE endogenously determines the real return on capital. This return is calibrated to match the empirical real return on capital, which was estimated to be 5.5 % per annum (Nordhaus 2008). We use this endogenously determined return to calculate present values. We do not consider either higher or lower discount rates. The impact of a change in the discount rate on the value of SRM is somewhat difficult to sign. In general, anything that increases the present value cost of climate change will increase the value of actions that can reduce these damages. For example, a lower discount rate will increase the present value of climate damages and thereby increase the benefit of SRM. However, a lower discount rate will increase the present value of any damages attributable to SRM as well. Bickel and Lane (2010) investigated a low discount rate case and found that it increased the value of SRM. Bickel and Agrawal (2012) also considered a low discount rate scenario and found that the net benefit of SRM was higher in many, but not all, cases.

3.1 Relevant DICE equations

This section highlights the DICE equations that are directly relevant to our work. We cannot, however, provide a full description of the DICE model and instead refer the interested reader to Nordhaus (1994, 2008) and Nordhaus and Boyer (2000).

DICE models the increase in radiative forcing (W/m^2) at the tropopause for period t (a decade in the DICE model) as

$$F(t) = \eta \log_2 \frac{M_{\mathrm{AT}}(t)}{M_{\mathrm{AT}}(1750)} + F_{\mathrm{EX}}(t). \tag{1}$$

$M_{\mathrm{AT}}(t)$ is the atmospheric concentration of CO2 at the beginning of period t and $M_{\mathrm{AT}}(1750)$ is the preindustrial atmospheric concentration of CO2, taken to be the concentration in the year 1750. η is the radiative forcing for a doubling of CO2 concentrations and is assumed to be 3.8 W/m^2. $F_{\mathrm{EX}}(t)$ represents the forcing of non-CO2 GHGs such as methane and the negative forcing of aerosols.

The mass of carbon contained in the atmosphere at the beginning of period t is

$$M_{\mathrm{AT}}(t) = E(t-1) + \phi_{11} M_{\mathrm{AT}}(t-1) + \phi_{21} M_{\mathrm{UP}}(t-1). \tag{2}$$

$E(t-1)$ is the mass of carbon that enters the atmosphere due to emissions and land-use changes. $M_{\mathrm{UP}}(t-1)$ is the mass of carbon contained in the biosphere and upper ocean at the beginning of period $t-1$. $\phi_{11}$is the fraction of carbon that remains in the atmosphere between periods $t-1$ and t. ϕ_{21} is the fraction of carbon that flows from the biosphere and upper ocean to the atmosphere between periods $t-1$ and t.

DICE uses a two-stratum model of the climate system. The first stratum is the atmosphere, land, and upper ocean. The second stratum is the deep ocean. DICE models the global mean temperature of stratum one, T_{AT}, as a function of the radiative forcing at the tropopause, $F(t)$; the temperature of the atmosphere in the previous period; and the temperature of the lower ocean, T_{LO}, in the previous period. Specially,

$$\begin{aligned} T_{\mathrm{AT}}(t) = T_{\mathrm{AT}}(t-1) + \xi_1 \big[& F(t) - \xi_2^{-1} T_{\mathrm{AT}}(t-1) \\ & - \xi_3 [T_{\mathrm{AT}}(t-1) - T_{\mathrm{LO}}(t-1)] \big]. \end{aligned} \tag{3}$$

ξ_2 is the equilibrium climate sensitivity (ECS), which specifies how much the temperature of the atmosphere (T_{AT}) will change for a unit change in forcing. In DICE, the ECS is specified as the temperature increase for a doubling of CO2, ΔT_{2X}, which DICE assumes is 3 °C, divided by η. ΔT_{2X} is sometimes, and loosely referred to as the equilibrium climate sensitivity. However, the ECS is a property of the climate system that is independent of the forcing source. Thus, in this paper, we refer to ΔT_{2X} as the CO2 equilibrium climate sensitivity (CO2-ECS). DICE assumes that the ECS is equal to $3.0/3.8 \approx 0.79$ °C/(W/m^2). Nordhaus (1994) has shown that DICE's simple climate model faithfully represents the aggregate results of larger GCMs on a decadal time-scale. It may not, however, be able to represent more rapid temperature changes. We do not alter DICE's temperature equation and therefore might underestimate the effect of strong negative or positive forcing.

DICE assumes that climate damages are a quadratic function of temperature. Damages are measured as the loss in global output. The damage in period t is

$$D(t) = \psi_1 T_{\mathrm{AT}}(t) + \psi_2 T_{\mathrm{AT}}(t)^2, \tag{4}$$

where ψ_1 and ψ_2 are chosen to fit the literature regarding climate impacts. Because DICE assumes $\psi_1 = 0$, we will omit this term to simplify the notation. The particular limitation of Eq. (4) is that damage is not a function of the rate of temperature change, which could be important in the case of SRM (Goes et al. 2011; Bickel and Agrawal 2012).

3.2 Base case results

The base case damages from DICE are presented in Table 1. Climate damages under NC are \$22.5 trillion (all dollars are present values, 2005 \$). The maximum temperature change obtained during our 200-year study period is 5.3 °C, which occurs in 2205. It is important to note that temperature would continue to rise beyond this point. OC incurs \$17.4 trillion in climate damages (a \$5.1 trillion reduction) and \$2.1 trillion in abatement costs, spent on emissions reductions, yielding total costs of \$19.5 trillion.[1]Thus, OC are structured to accept significant climate damages. The maximum temperature change under OC is 3.5 °C, which is obtained in the year 2185. L2.0C, which restricts the maximum temperature change to be 2.0 °C, reduces climate damages by \$4 trillion, but incurs \$9.7 trillion more in abatement costs than OC. L1.5C holds temperature change to 1.5 °C and reduces damages by an additional \$2.9 trillion, but costs \$17 trillion more than L2.0C.

3.3 Key uncertainties

As discussed above, DICE is deterministic. In order to test the robustness of different emissions control strategies and to deepen our understanding of important policy drivers, it is important to identify the most critical uncertainties. Nordhaus (2008, p. 127) provided a list of the most important DICE inputs and the uncertainty surrounding them. We describe these below.

- *CO2 equilibrium climate sensitivity (CO2-ECS)*. As described in Sect. 3.1, the CO2-ECS, ΔT_{2X}, is the amount, in °C, the Earth will warm if atmospheric CO2 concentrations are doubled and the climate is allowed to reach an equilibrium.
- *Fraction of CO2 contained in the atmosphere after 10 years*. This variable, ϕ_{11}, measures the fraction of CO2 that is retained in the atmosphere rather than being transferred to the upper ocean.
- *Quadratic damage parameter*. The quadratic damage parameter, ψ_2, determines how quickly damage increases with rising temperatures.
- *Rate of growth in total-factor productivity*. DICE models gross world product (GWP) as a Cobb-Douglas production function in labor and capital. This production function includes a total-factor productivity (TFP) variable that accounts for the effects of technological change (i.e., more output is produced for the same input). Thus, the rate of growth in TFP is related to the rate of technological change, which is an exogenous input in DICE.
- *Rate of decarbonization*. DICE relates CO2 emissions and economic output via a carbon intensity estimate, which is measured in metric tons of carbon (MTC) per thousand dollars of output (2005\$). The rate of decarbonization captures the speed with which this intensity can be reduced.
- *Initial cost of backstop technology*. The initial cost of backstop technology is the price in the year 2005 at which a zero-carbon energy source can replace fossil fuels. DICE assumes that this price declines with time, owing to technological change.
- *Asymptotic global population*. DICE relates GWP and energy use to population. The asymptotic global population is the long-term human population of the Earth.

Nordhaus (2008, Table 7.1) assumed these uncertainties are independent and normally distributed and provided their means and standard deviations. With the exception of the CO2-ECS, as discussed below, we adopt Nordhaus's uncertainty ranges, which we present in Table 2. The columns labeled P90 and P10 list the values of each variable such that there is a 90 % or a 10 % chance, respectively,

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[1] Adding climate damages and abatement costs is a shortcut introduced by Nordhaus (2008, p. 88) who argues that "the sum of abatement and damage costs provides a good approximation of the economic impacts." One can see this by comparing the first and second column in Table 5.1 of Nordhaus (2008).

Table 1 DICE base case results ($ are 200-year present values in 2005$ trillions)

Emission control regimes	Climate damages	Abatement costs	Total costs	Maximum temperature change (°C)
No controls	$22.5	$0	$22.5	5.3
Optimal controls	$17.4	$2.1	$19.5	3.5
L2.0C	$13.4	$11.8	$25.2	2.0
L1.5C	$10.5	$28.8	$39.3	1.5

that the input will fall above the value shown. As we demonstrate below, these fractiles are useful in sensitivity analysis.

The CO2-ECS is uncertain because we are uncertain about the ECS and the amount of forcing that will attend an increase in CO2 concentrations. In characterizing our understanding of the CO2-ECS, the IPCC (2007b) notes that

> The [CO2] equilibrium climate sensitivity…is *likely* to be between 2 °C and 4.5 °C, with a best estimate of 3 °C and it is *very unlikely* to be less than 1.5 °C. Values substantially higher than 4.5 °C cannot be excluded, but agreement of models with observations is not as good for those values [emphasis in original].

The IPCC defines *likely* as greater than a 66 % probability and *very unlikely* as less than a 10 % probability (IPCC 2005). Based on this, we assume that the CO2-ECS is lognormally distributed with a mean of 3.0 °C and standard deviation of 1.5 °C. This distribution is shown in Fig. 1. Compared to the normal distribution, assumed by Nordhaus, the lognormal distribution is skewed to the right and excludes the possibility of negative CO2 climate sensitivities (i.e., the addition of CO2 to the atmosphere will cool the Earth). With these assumptions, the P90 is very close to 1.5 °C and there is about a 60 % chance of its being between 2.0 and 4.5 °C. The P90 is about 5.0 °C, and there is a 1 % chance that the climate sensitivity is above 8.0 °C. These ranges closely match the IPCC's statement regarding uncertainty in the climate sensitivity.

Since important DICE parameters are uncertain, so are the maximum temperature change and the total costs incurred by following a particular emissions control regime. Figure 2 shows the impact of input uncertainty on total costs under OC. This diagram, called a "tornado diagram," is centered at $19.5 trillion, which is the total cost estimated by DICE when all input variables are set to their base case and match the value given in Table 1. Figure 2 details the impact on total costs of varying one input at a time—holding the emissions reduction strategy constant. For example, if the CO2-ECS was 5.0 °C and all other variables were still at their base case, then total costs would be approximately $30 trillion. If the CO2-ECS was 1.5 °C and all other variables were at their base case, total costs would be approximately $10 trillion—a swing of $20 trillion. Since there is an 80 % chance that CO2-ECS is between 1.5 and 5.0 °C, there is an 80 % chance that total costs will be between $10 trillion and $30 trillion under OC, owing to uncertainty about the CO2-ECS alone. Similarly, there is an 80 % chance that total costs will be within the range shown for each of the other variables. Thus, we see that uncertainty in the CO2-ECS, the damage parameter, and the population, most contribute to our uncertainty regarding total costs. The atmospheric retention rate, the rate of decarbonization, the cost of the backstop technology, and the TFP growth rate contribute less to our uncertainty regarding costs.

It is important to stress that we are holding the emissions reduction strategy constant. Thus, we do not allow society to either act with perfect foresight ("learn then act")

Table 2 Key DICE uncertainties

Variables	Units	Mean	Standard deviation	P90	P10
CO2 equilibrium climate sensitivity	°C	3.0	1.5	1.5	5.0
Fraction of CO2 retained in atmosphere after 10 years	Fraction	0.811	0.017	0.789	0.832
Quadratic damage parameter	$\$\text{trillions}/(°\text{C})^2$	0.0028	0.0013	0.0012	0.0045
Rate of growth in total-factor productivity	%/year	9.20	0.40	8.70	9.70
Rate of decarbonization	%/year	−7.30	2.00	−9.86	−4.74
Initial cost of backstop technology	$2005/MTC	1,170	468	571	1,769
Asymptotic global population	Millions	8,600	1,892	6,178	11,022

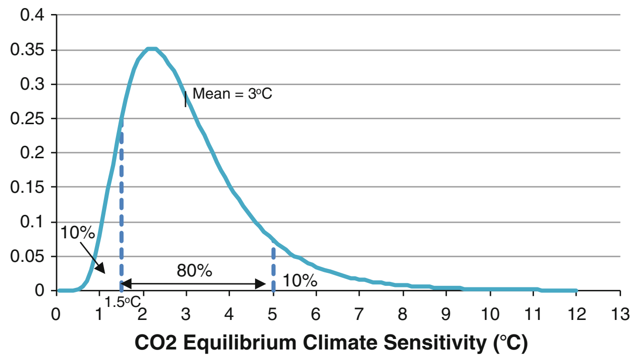


Fig. 1 Lognormal probability distribution for CO2 equilibrium climate sensitivity

regarding important uncertainties, such as the ECS, nor do we allow for a dynamic strategy ("learn, act, learn, act, …") where the emission control regime is adjusted as knowledge of the climate system evolves. The former is clearly unrealistic and the later is structurally and computationally difficult. For example, a dynamic strategy would require one to model how our knowledge of key uncertainties could change over time and implement a stochastic decision-making algorithm (e.g., stochastic dynamic programming). An example of such a model can be found in Baranzini et al. (2003). We take a simpler approach here, with the hope that our results will be more transparent and accessible.

The sensitivity of the maximum temperature change under OC is shown in Fig. 3. Recall, the base case value is 3.5 °C (see Table 1). In this case, we see that the climate sensitivity dominates our uncertainty regarding temperature changes. The Earth's population, the rate of decarbonizaiton of the world economy, and the retention rate of atmospheric CO2 contribute much less to our uncertainty. The damage parameter and cost of the backstop technology have only a very minor impact.

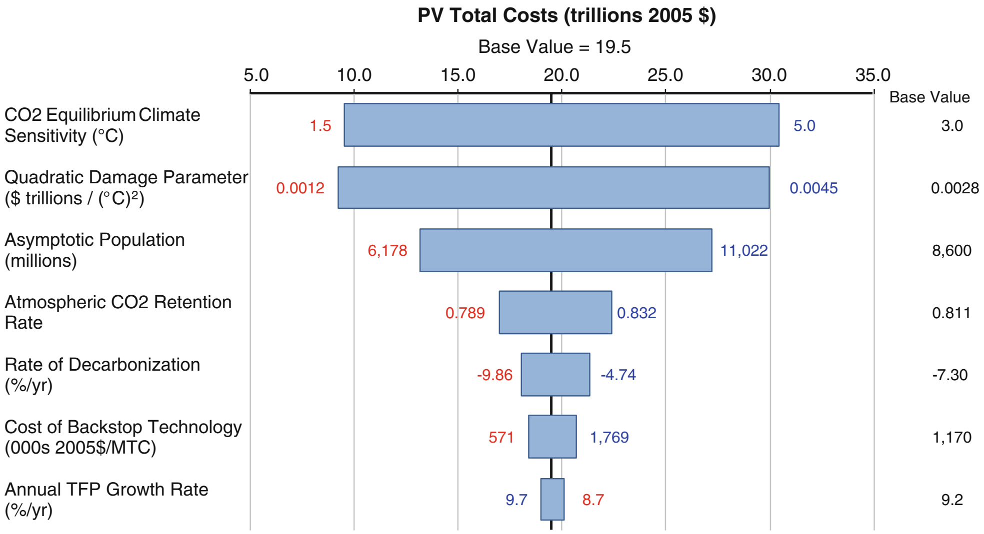
4 Reducing risk via emissions reductions

As discussed in the previous section, a handful of variables (those in Table 2) drive our uncertainty regarding temperature change and climate damages. In this section, we investigate how well one policy response, emission reductions, lowers the risk of catastrophic damages.

We begin by estimating the range within which the maximum temperature change could fall under each emissions control regime. We do this by performing a Monte Carlo simulation (10,000 trials) and sampling from the uncertainties in Table 2, again holding the emissions control regime constant. The results appear in Fig. 4, which displays the probability of exceeding a particular temperature change under NC, OC, L2.0C, and L1.5C. Our uncertainty regarding temperature changes is significant. For example, the maximum temperature change under NC could range from about 1 °C to 10 °C. The mean or average maximum temperature change is 5.0 °C. Under OC, this range is reduced somewhat, but temperature changes in excess of 7 or 8 °C cannot be ruled out. L1.5C and L2.0C shift the temperature distribution to the left, but even these tight emission control regimes leave the possibility of exceeding 3 or 4 °C.

Figure 4 also shows the abatement cost required to move between emission control regimes (as detailed in Table 1), thereby shift the temperature distribution to the left. Moving from NC to OC incurs $2.1 trillion in abatement costs and shifts the temperature distribution to the left, but a long tail remains. L2.0C costs $9.7 trillion more than OC ($11.8 trillion more than NC). We see that moving from OC to L2.0C has about the same effect on temperature as moving from NC to OC, but costs almost five times a much. L1.5C costs $17 trillion more than L2.0C (about $29 trillion more than NC) and only slightly affects the temperature distribution.

Fig. 2 Sensitivity of total costs under optimal controls



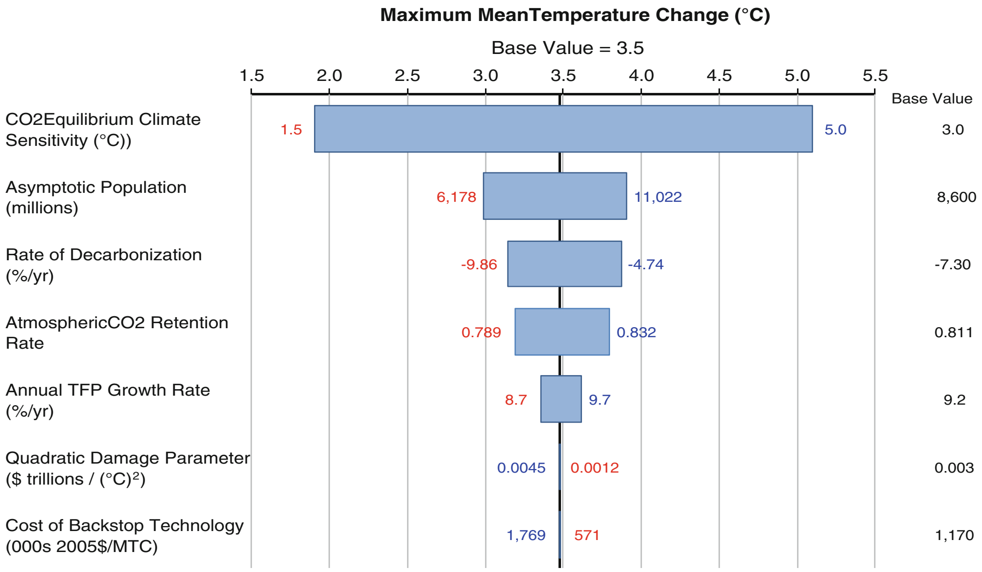


Fig. 3 Sensitivity of maximum temperature change under optimal controls

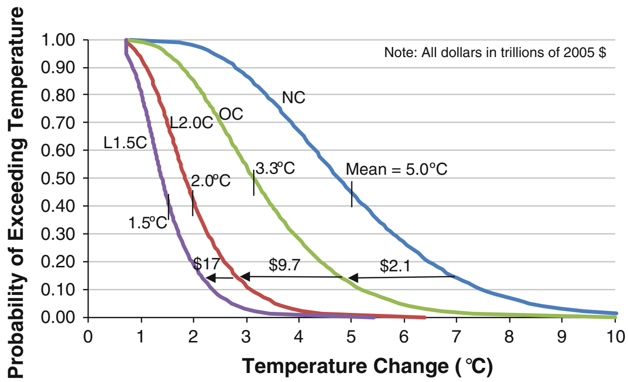


Fig. 4 Probability of exceeding particular temperatures under different emissions control regimes

Table 3 details the probability of exceeding 2.0, 3.0, 4.0, or 5.0 °C for the four emission control programs we consider. For example, OC produces an 85 % chance of exceeding 2.0 °C, a temperature change that scientists have warned is dangerous. A deterministic emission control policy designed to limit temperature change to 2.0 °C still has about a 42 % chance of temperature change greater than 2.0 °C. Even trying to limit temperature change to 1.5 °C runs almost a 20 % chance of exceeding a temperature change of 2.0 °C.

Similar results hold for more extreme temperature changes. Under NC, there is an 87 % chance of change greater than 3 °C. OC reduces this chance to 54 %. Even L2.0C has an 11 % chance of change greater than 3 °C; further tightening emission controls to hold temperature changes to 1.5 °C reduces this chance to 3 %.

We might also be concerned with the length of time we are above a threshold temperature, not simply whether or not this threshold is crossed. Figure 5 displays the average number of years that temperature changes exceeded the listed values, under each emissions control scenario. Under OC, the increase in the average temperature of the atmosphere exceeds 2 °C for almost 120 years, on average, in our simulations. Under L2.0C, this is reduced to 60 years. Yet, these are average values. In 10 % of our scenarios, the temperature increase under L2.0C exceeded 2 °C for 150 years. Thus, even strict emission control polices do not guarantee that the Earth will not exceed possibly dangerous threshold temperatures for many decades, if not more than a century.

It is disappointing that tight emission control regimes still hold a non-negligible chance of exceeding a temperature threshold that scientists have suggested could lead to the disintegration of the GIS. Thus, relying solely on emissions reductions to manage the risk of crossing tipping points could be risky. McInerney and Keller (2008) note that reducing the odds of a collapse of the thermohaline circulation (THC) to below 1-in-10 requires an almost “complete decarbonization over the next 60 years.” Reducing the odds to 1-in-100 reduces the timeframe to

Table 3 Probability of exceeding particular temperatures under different emissions control regimes

Emission control regimes	2 °C	3 °C	4 °C	5 °C
NC	0.98	0.87	0.67	0.45
OC	0.85	0.54	0.28	0.12
L2.0C	0.42	0.11	0.02	0.00*
L1.5C	0.19	0.03	0.00*	0.00*

* Probabilities are less than 0.01

only 40 years. Keller et al.(2005) estimate that it would cost 110 % of GWP (about \$60 trillion) to reduce the chance of exceeding 2.5 °C to 5 % and that reducing the probability of crossing a temperature threshold to *de minimis* levels involves costs that are "politically infeasible."

Trying to manage low-probability events by shifting the entire temperature distribution (Fig. 4) will be very expensive because we are *paying to reduce the probability at all temperatures* even if we are especially concerned with particularly large changes. This suggests that emissions reductions and SRM could work together to limit climate damages and economic costs. For example, emissions reductions could be used to lessen the risk of moderate warming (or mean warming), while SRM is used to *truncate* the temperature distribution at a temperature considered dangerous (or at least significantly reduce the probability of exceeding a particular temperature).

5 Addressing tipping points via SRM

In this section, we provide a preliminary assessment of the value of SRM in the presence of tipping points. We assume that society follows an emissions control regime of NC, OC, L2.0C, or L1.5C. In addition to emission controls, we assume that society has developed an SRM capacity that could be deployed in an emergency. Identifying an emergency and gaining agreement that one is in fact underway is likely to be difficult, and this alone argues against holding SRM in reserve. However, in this paper, we assume that society will deploy SRM in only two scenarios: (1) the average warming of the atmosphere, T_{AT}, passes a predetermined critical level T_{C}, such as 3.0 °C, or (2) a tipping-point temperature T_{TP} is crossed and significant damages begin to arise. The first case may avoid a tipping point all together, if the tipping point is beyond the deployment temperature (i.e., T_{C} is less than or equal to T_{TP}). In the second case, SRM is not deployed until tipping point has been crossed (i.e., T_{C} is greater than T_{TP}) and significant damages become apparent (within 10 years in the DICE model).

5.1 Changes made to DICE

To estimate the risk of tipping points and the benefits of SRM, we make a few modifications to DICE. These include changes to DICE's radiative forcing and damage equations. We summarize the changes below.

We begin by modifying DICE's radiative forcing equation (Eq. 1) to allow for inclusion of an additional external forcing component, SRM(t), which we take to be the negative forcing due to SRM. The radiative forcing (W/m^2) at the tropopause for period t is now

$$F(t) = \eta \log_2 \frac{M_{\mathrm{AT}}(t)}{M_{\mathrm{AT}}(1750)} + F_{\mathrm{EX}}(t) - \mathrm{SRM}(t). \tag{5}$$

SRM(t) is the change in the radiative forcing in period t due to SRM. The use of SRM directly reduces radiative forcing, and we measure SRM use in terms of watts per square meter (W/m^2). Our modeling of SRM is consistent with DICE's treatment of aerosols, which are included in DICE through the F_{EX} term. In addition, other papers (Andronova and Schlesinger 2001; Bickel and Lane 2010; Goes et al. 2011; Bickel and Agrawal 2012) incorporate anthropogenic aerosol emissions in a similar fashion.

We next assume that the climate system contains a tipping-point temperature beyond which damages are discontinuously and permanently affected. To ease explanation, we assume that there is only one such tipping point while acknowledging that multiple thresholds may exist. In addition, we allow for the possibility that SRM itself may cause damage. To capture these features, we modify DICE's damage function (Eq. 4 with $\psi_1 = 0$) as shown below

$$D(t) = \psi_2 T_{\mathrm{AT}}(t)^2 + 1_{\mathrm{TP}}(t) D_{\mathrm{TP}} + \theta \frac{\mathrm{SRM}(t)}{\eta}. \tag{6}$$

$1_{\mathrm{TP}}(t)$ is an indicator state variable that takes the value 1 if the global mean surface temperature, T_{AT}, ever exceeds T_{TP}, and takes the value 0 otherwise. D_{TP} is the additional damage caused by crossing the tipping point. Owing to hysteresis in the climate system, we assume this damage is permanent. Or at least that it lasts through the end of the study period. θ is the damage caused by SRM, as a percent of GWP, when SRM offsets radiative forcing equal to a doubling of CO2 concentrations (η). This approach was introduced Goes et al. (2011), who assumed that θ could range between 0 and 2 %.

5.2 The cost of crossing a tipping point

Nordhaus (1994, p. 115), noted the difficulties of calibrating DICE's damage function to catastrophic damages, which might be equivalent to a major war or "50 years of Communist rule." As an example, he alters DICE's damage function such that it is proportional to the change in atmospheric temperature raised to the 12th power, instead of the 2nd power. In this case, damages are 60 % of GWP at a temperature change of 3.5 °C, instead of about 8 %. The near-term impact of this change on emissions is modest, with reductions rising sharply as the threshold is approached. In another approach, Nordhaus estimated the willingness to pay to avoid catastrophic damages as a function of temperature increase (Nordhaus and Boyer 2000, p. 87). In this setting, one-half of DICE's 10 % GWP damages at 6.0 °C represents a willingness to pay to avoid catastrophic damages (Nordhaus 2008, p. 144).

Tol (1998) estimated that the economic cost in Western Europe of a collapse of the THC would be from 0 to 3 % of that region's gross product. Keller et al. (2004), McInerney and Keller (2008), and McInerney et al. (2009) extrapolated this estimate to the entire globe and assumed that damages from a collapse of the THC would be uniformly distributed between 0 and 3 % of GWP.

Thus, the location and severity of climate tipping points are uncertain. Therefore, rather than make any particular assumption, we will investigate a range of possible scenarios. In particular, we will allow the tipping-point temperature to vary between 1.5 and 5.5 °C and will consider values for damages of 2.5 and 5.0 % of GWP. Figure 6 provides an example of our modified damage function when the tipping point is at 4.0 °C and the tipping-point damage is 5 % GWP. As temperature increases, we move to the right along the lower curve. Once temperature change reaches 4.0 °C, the upper curve supersedes the lower curve and continues to apply for any further temperature changes, including reductions. The shift of the damage curve upwards, even if the Earth cools, is meant to capture hysteresis in the climate system (i.e., damages cannot simply be reversed via cooling, once they have occurred).

The effect of our tipping-point model, in this case, is to make the damages at 4.0 °C approximately equal to the damages in 6.0 °C in the standard DICE model. This damage could represent the willingness to pay to avoid catastrophic loss, or it could represent the onset of actual damages resulting from, say, collapse of the THC.

Clearly, more sophisticated damage functions could be constructed. For example, one could allow the degree of hysteresis to vary with temperature; the tipping point could be related to the number of years the atmosphere is above a particular temperature or related to the rate of temperature change; multiple tipping points could be included. These are all important improvements and worthy of future research. However, our goal is more modest: to provide a preliminary assessment of the impact of tipping points on the economic benefit of SRM.

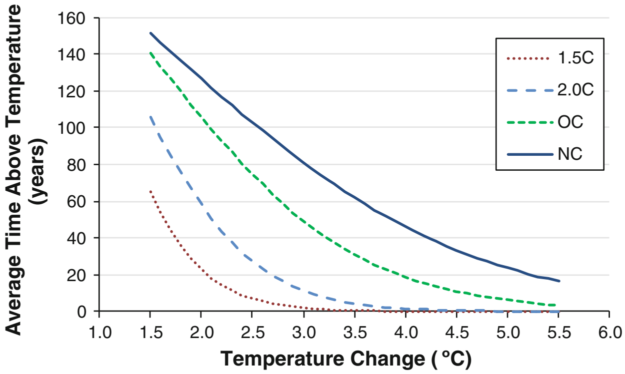


Fig. 5 Average number of years the average temperature of the atmosphere exceeds the listed value

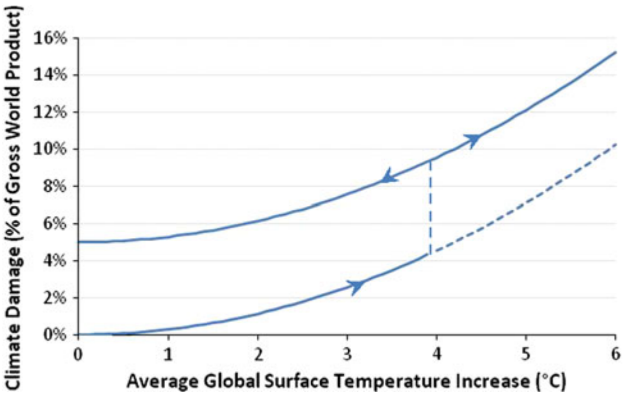


Fig. 6 An example of a modified damage function that includes a tipping point at 4.0 °C

5.3 The indirect cost of SRM

The use of SRM may result in indirect costs and benefits. Possible damages include, but are not limited to, reductions in precipitation (Robock 2008a, b), slowing in the recovery of the ozone layer (Wigley 2006; Rasch et al. 2008a; Tilmes et al. 2008), whitening of the sky (Robock 2008a), and rapid warming if CE is stopped (Wigley 2006; Goes et al. 2011; Bickel and Agrawal 2012). Possible benefits include, but may not be limited to, reduced rates of skin cancer (Teller et al. 2003), and increased plant activity (Robock 2008a).

The physical processes underlying GHG warming and SRM differ. GHGs absorb short-wave radiation (i.e., sunlight) and reradiate long-wave radiation (i.e., heat) in all directions. SRM, conversely, seeks to reflect more short-wave radiation back into space. Because of these different modes of action, SRM will not be able to completely offset the effects of increasing GHG concentrations, either in terms of the climate properties affected (e.g., temperature or precipitation) or geographically. Current understanding suggests that SRM cannot, within a single region, simultaneously restore temperature and precipitation to their preindustrial levels. However, when averaged geographically, around the globe, Moreno-Cruz et al. (2011) find that "… SRM almost perfectly compensates for the temperature changes from rising (GHGs), but decreases precipitation relative to the (1990s) baseline."

Regionally, just as GHGs cause some regions to warm more than others, SRM will cause some (e.g., high-latitude regions) to cool more than others (Ban-Weiss and Caldeira 2010). Further, SRM could result in some regions being worse off than they would have been under unabated climate change. This issue appears to be most prominent in

Western Africa and Eastern Asia (Moreno-Cruz et al. 2011). However, SRM may still be able to deliver a Pareto-optimal improvement in all regions. For example, if one implements SRM only the point where Western Africa is no worse than it would have been under unabated climate change, SRM may still be able to offset over 50 % of the damages caused by GHG warming (Moreno-Cruz et al. 2011). This finding leads Moreno-Cruz to conclude that "… contrary to what has been suggested previously in the SRM discourse (Robock et al. 2010), a globally optimal level of SRM can compensate for a large proportion of damages at a regional level."

Estimates quantifying the potential damages attributable to SRM are lacking and, indeed, this is the primary motivation for a research program. Goes et al. (2011) and Bickel and Agrawal (2012), considered values for θ of 0 and 2 %. In this paper, we expand this range slightly and assume θ is either 0 or 3 %. As a point of reference, unabated climate change is projected by DICE to cause damages of about 1.4 % of GWP in 2065, which is the year CO2 concentrations are doubled. Thus, our high-end value assumes the SRM is more than twice as damaging as climate change itself.

5.4 SRM deployment decision

The structure of our decision problem is depicted graphically in Fig. 7. For illustration, we assume that society adopts an emissions control policy. The temperature of the atmosphere is then observed in each time period (a decade). If the specified critical temperature is reached, then SRM is deployed. To simplify our analysis, we assume that uncertainty regarding the CO2-ECS is completely resolved at the time SRM is deployed. Given our treatment of uncertainty, this implies that the ECS is also revealed at this time, since $\Delta T_{2X} = \eta \varepsilon_2$. As the reader will see, the earliest SRM is deployed in our analysis is 2045. Thus, while this assumption is certainly not true, an additional 30 years of observations may narrow this uncertainty to some degree. To address this problem in a more complete way, we would need to model how uncertainty in the ECS evolves over time. This will complicate both our analysis and its presentation in a way that is unlikely to change our conclusion that SRM merits research. Our assumption does, however, allow one to perfectly control temperature with SRM. Future research could relax this assumption and determine how much imperfect control reduces the benefit of SRM as a risk management tool.

Using the known CO2-ECS, the required amount of SRM in each time period is determined endogenously such that the temperature never exceeds the predetermined critical temperature. We do, of course, permit emissions reductions to result in cooling. If the critical temperature has not been reached, but a tipping point has been crossed, then SRM is deployed. Again, the SRM requirement is determined endogenously such that temperature does not further increase. In this later case, temperature does pass the tipping point and additional damages, as discussed in Sect. 5.1, are incurred. This case is meant to represent a scenario where society realizes it has crossed a threshold and acts to prevent further warming. One could, of course, analyze a scenario where SRM is used not just to prevent future warming, but to cool the planet. If neither the critical temperature nor the tipping point has been crossed, then SRM is not deployed and is held in reserve. To allow time for the development of an SRM capability, we do not allow deployment prior to 2025 (again, in the cases we analyze, SRM is deployed in 2045 at the soonest in any event). We do not consider specialized strategies such as only deploying SRM in the Arctic. This is an area for future research. We also do not analyze cases where SRM substitutes for emissions reductions.

It should be noted that we are affording SRM a level of response that we do not grant to emissions reductions. In particular, we do not allow emissions reductions to be ramped up if we cross a temperature threshold or a tipping point. We believe this is justified within the current paper given that (i) political, economic, and technological considerations suggest that quickly ramping up emission reductions is difficult and (ii) physical considerations curtail the ability of emissions reductions to quickly cool the Earth, which is the necessity we analyze here. More importantly, we are analyzing the incremental addition of SRM to four emissions scenarios. We are quantifying how much value is created by *adding* SRM to emissions reductions, not how much value is gained by substituting SRM for emissions reductions.

We do not re-optimize DICE's emission control regime in the presence of SRM. Instead we adopt the emissions control regimes detailed above. We take this approach for

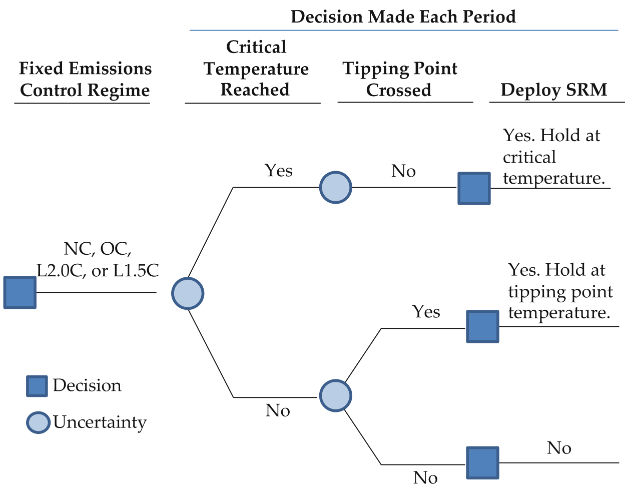


Fig. 7 SRM deployment decision tree for each period

three reasons. First, re-optimizing DICE to find the level of optimal controls in the presence of an SRM capability that could be deployed in any period is likely to be computationally intense. Second, such an analysis would require estimates of the indirect costs of SRM, which we do not have. Indeed, the fact that these estimates are lacking is the motivation for this work and our argument that research needs to be undertaken. Third, and most importantly, such a formulation does not reflect this paper's assumptions regarding when SRM may be deployed. *We assume that society agrees to adopt some level of emissions reductions and views SRM as a safety net; it does not take the potential safety provided by SRM in the form of greater emissions.*

5.5 SRM deployment cost

Bickel and Lane (2010) summarize current estimates regarding the cost to deploy two different SRM technologies: stratospheric aerosol injection and marine cloud whitening. In this paper, we nominally assume that SRM is deployed using aerosol injection and base our cost estimates on this. To estimate the direct costs of SRM, we require assumptions regarding the forcing efficiency of sulfate aerosols, their residence time, and the cost to lift them to the stratosphere.

Based on the Mount Pinatubo eruption, Crutzen (2006) estimates that the radiative forcing efficiency of sulfate aerosol is -0.75 W/m^2 per Tg of sulfur (S).[2] Rasch et al. (2008b) use a coupled atmospheric model to better understand the role of aerosol particle size in forcing. They consider "large" particles (effective radius of 0.43 microns) that might be associated with a volcanic eruption and "small" particles (effective radius of 0.17 microns) typically seen during background conditions. Rasch et al. do not report their forcing efficiencies, but based on their work, we estimate a forcing efficiency of between -0.50 and -0.60 W/m^2 for volcanic size particles and around -0.90 W/m^2 for the small particles. Given the uncertainty in these estimates and in the size of the particles themselves, we follow Crutzen and assume an efficiency of -0.75 W/m^2 per Tg S. Particle residence time is another critical factor, which is also affected by particle size. Rasch et al. find residence times of between 2.6 and 3.0 years for the volcanic particles and between 2.4 and 2.8 years for the small particles. We assume a residence time of 2.5 years for simplicity.

In order to offset 1 W/m^2, we require a sulfur burden of 1.3 Tg S (1/0.75). Assuming a residence time of 2.5 years, we would require yearly injections of 0.53 Tg S. Not to minimize this intervention, but to provide perspective, we consider two benchmarks. First, the burning of fossil fuels emits 55 Tg S per year into the troposphere (Stern 2005). Thus, offsetting 1 W/m^2 requires an injection equivalent to approximately 1 % of the sulfur currently emitted via fossil fuels. Second, Mount Pinatubo injected about 10 Tg S into the stratosphere (Crutzen 2006), which is almost 20 times larger than what is required to offset 1 W/m^2.

The mass of material that must be injected depends upon the choice of precursor. Common candidates include hydrogen sulfide (H_2S) and sulfur dioxide (SO_2). The molecular masses of H_2S and SO_2 are 34.08 g/mol (1.1 times that of S) and 64.07 g/mol (2.0 times that of S), respectively. The use of SO_2 would require about twice the investment as H_2S, and we therefore assume the use of H_2S as a precursor.

The National Academy of Sciences (1992) considered the use of 16-inch naval artillery rifles, rockets, balloons, and airplanes to inject material into the stratosphere. The costs of naval artillery and balloons were about the same, whereas the cost of rockets was estimated to be about five times greater. The NAS estimated that it would cost $40 per kg (2005 $), or $40 billion per Tg, to place aerosols in the stratosphere. Approximately $35 per kg of this cost is the variable cost of the ammunition and the personnel. The remaining $5 per kg is the capitalized cost of the equipment, which was assumed to have a 40-year lifetime. These direct costs are very low, on the order of $0.1 trillion in present value, while, as the reader will see, the benefits of SRM are potentially 100–200 times greater. Thus, the assumptions made in this section play a minor role in our results.

5.6 The value of SRM

To determine the value of SRM, which includes the direct cost of deployment and indirect costs/benefits, we perform two sets of Monte Carlo simulations for the decision depicted in Fig. 7. In the first set, we assume that society does not have an SRM capability or fails to deploy it. We then sample from the uncertainties in Table 2 by performing 10,000 trials at tipping points ranging from 1.5 to 5.5 °C at intervals of 0.1 °C—for a total of 410,000 trials. We average the 10,000 costs estimates for each tipping point and refer to these as *expected total costs without SRM*. Next we assume that society has the capability to hold temperatures at a particular level by deploying SRM. We perform another set of trials (10,000 at each tipping point) and calculate the *expected total costs with SRM*. The value of SRM is the expected total costs without SRM less the expected total costs with SRM.

Figure 8 displays the results of this simulation under OC and assumes that the tipping-point damage is equal to 5 % GWP and that SRM causes no damage. The upper line is the expected total costs when SRM is never deployed. If

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[2] 1 Tg = 1 trillion grams = 1 million metric tons.

the tipping point is remote (e.g., at 5.5 °C), the expected costs is $19.7 trillion, which is very close to the base case value of $19.5 trillion shown in Fig. 2 and Table 1. As the tipping point becomes nearer, the expected costs increase significantly; at a tipping point of 2.0 °C, the expected cost, under OC, if SRM is not used is $41 trillion.

The middle line presents the expected costs when SRM is held in reserve and only used in the event a tipping point is crossed, which incurs the tipping-point damage. If the tipping-point temperature is high, then SRM is not used and the expected costs are the same as the case where society does not have an SRM capability. If the tipping point is closer, then SRM is deployed, temperatures are held at this level, and the costs are reduced. The difference between the two lines is the benefit of having the ability to deploy SRM only if a tipping point is crossed.

The expected costs when SRM is deployed at 2.0 °C, even if a tipping point has not been crossed, are given by the lower curve. As shorthand, we refer to this scenario as SRM2C. This coincides with the middle line when the tipping point is less than 2.0 °C, because SRM was not deployed preemptively. When the tipping point is 2.0 °C, the costs are far less than when not using SRM, because the use of SRM prevents crossing this threshold. This is the value of deploying SRM preemptively. Once the 2.0 °C threshold is crossed, the expected costs are constant because SRM is used to hold the temperature at 2.0 °C and the higher tipping points are not reached. The expected costs are lower in this case, even if a tipping point is not reached, because SRM prevents warming that would otherwise have taken place.

The reduction in cost shown in Fig. 8 is the value of SRM. This is the present value of having the capability to deploy SRM and exercising this ability under the stated conditions. This value is presented in Fig. 9, again under OC with tipping-point damages of 5 % GWP and 0 % SRM damages. We have also added the value of SRM under emissions control polices of NC, L2.0C and L1.5C. SRM2C is worth about $26 trillion, under OC, if the tipping point is 2.0 °C. Even if the tipping point is beyond 5.0 °C, SRM2C is still worth around $5 trillion because preventing warming reduces damages even if a threshold would not have been crossed. If the tipping point is closer than 2.0 °C, then SRM2C's value is reduced, but is still substantial, because while the tipping point is crossed, preventing further warming offsets additional damages. However, it is clear that holding SRM in reserve until a tipping point is crossed reduces the value of SRM and increases climate damages.

Under a policy of NC, SRM2C is more valuable, because (i) the risk of crossing a tipping point is higher, (ii) if a tipping point is crossed, it is likely to be sooner, and (iii) even if a tipping point is not crossed, other economic damages would have been higher, had SRM not been deployed to hold temperature changes to no more than 2.0 °C.

Even under tighter emissions control regimes, such as L2.0C or L1.5C, SRM could still be worth many trillions of dollars. For example, under a policy designed to limit temperatures change to no more than 2.0 °C, a damage-free SRM capability is worth about $15 trillion if the tipping point is at 2.0 °C. Even a "distant" tipping point at 4.0 °C results in substantial SRM value under strong emissions controls. SRM's value is reduced under L1.5C, but could still offset trillions of dollars in climate damages if the tipping point is near. Thus, SRM could be very valuable even if society adopts strong emissions controls.

Figure 10 contrasts the value of a damage-free SRM program under differing emissions control regimes and SRM deployment decisions (SRM2C vs SRM3C), for tipping-point damages of 2.5 and 5.0 %. Lowering the damage caused by crossing a tipping point lowers SRM's value. However, the values are still quite robust. For example, even under SRM3C and OC with 2.5 % damages (the

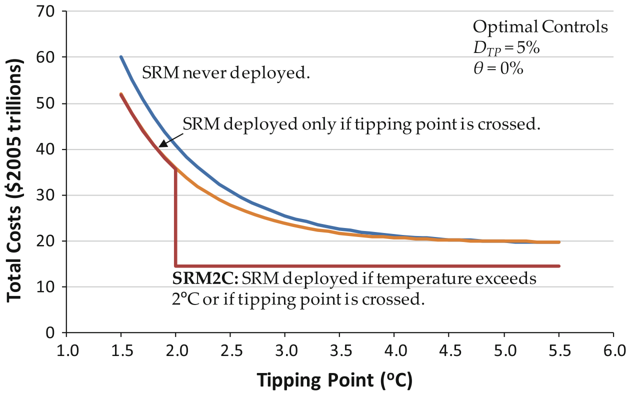

Fig. 8 Expected total costs as a function of the tipping-point location and conditions of SRM use

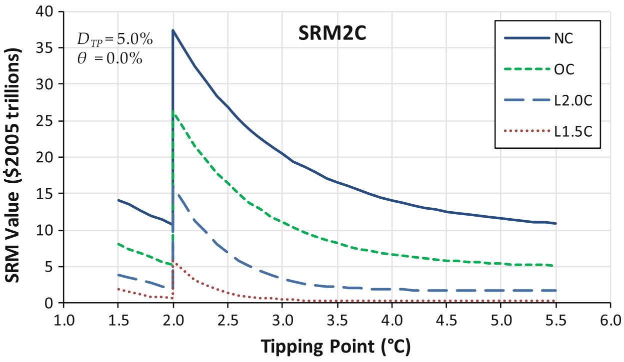

Fig. 9 The value of SRM2C as a function of the tipping-point location and the emissions control regime

upper right-hand figure), the value of SRM could be around \$5 trillion.

We now allow for the possibility that SRM may cause damage. Figure 11 supplements Fig. 10 by assuming that SRM causes 3 % damages at a forcing equivalent to a doubling of CO2 concentrations (i.e., $\theta = 3\ \%$). In this case, the value of SRM is reduced at all tipping points. For very low tipping points, such as 1.5 °C, the value of SRM is negative. This occurs in the case of SRM2C, for example, because crossing a tipping point at 1.5 °C incurs the tipping-point damage and then relatively larger amounts of SRM are needed to hold temperatures at this level. In other words, society is suffering from the damages imposed by SRM without the benefit of avoiding a tipping point. In this situation, L1.5C emission policy incurs the lowest damages because it requires the least amount of SRM.

However, over most of the region in Fig. 11, the value of SRM is very large. Except for strong emission control regimes and an SRM deployment policy that holds its use until temperatures changes exceed 3 °C (the two right-hand figures), an SRM capability is still worth trillions of dollars even though SRM itself is damaging—even more damaging than crossing a tipping point in the climate system. This occurs because relatively small amounts of SRM are needed initially to prevent temperatures from exceeding particular thresholds. Under our damage equation, which follows Goes et al. (2011), low uses of SRM result in low damages (recall, we assumed SRM damages scale linearly with use). In return for these damages, society avoids crossing a tipping point in the climate system that results in large and irreversible damages. This result may not hold if SRM damages increase more rapidly. Whether or not this is the case is a question for a well-designed research program.

Therefore, we conclude that a functional SRM capability could yield large benefits, even if it is not damage free. The SRM values we find here almost certainly exceed the cost of an R&D program, whose costs estimated in the low billions of dollars (Bickel and Lane 2010; Keith et al. 2010).

5.7 SRM usage intensity

In this section, we consider the scale of SRM intervention that would be required to achieve the temperature limits analyzed above. This analysis is confined to the quantity of SRM usage, or its intensity. The level of damages associated with this usage is unknown.

The analysis in Sect. 5.6 endogenously determined the amount of SRM needed to hold temperatures at a particular level so as to avoid climate damages. Figure 12 displays SRM usage profiles required to prevent temperature rise from exceeding 2.0 °C under NC and OC (L2.0C and L1.5C are omitted in the interest of space, but result in lower usage intensities). Since this is the most aggressive

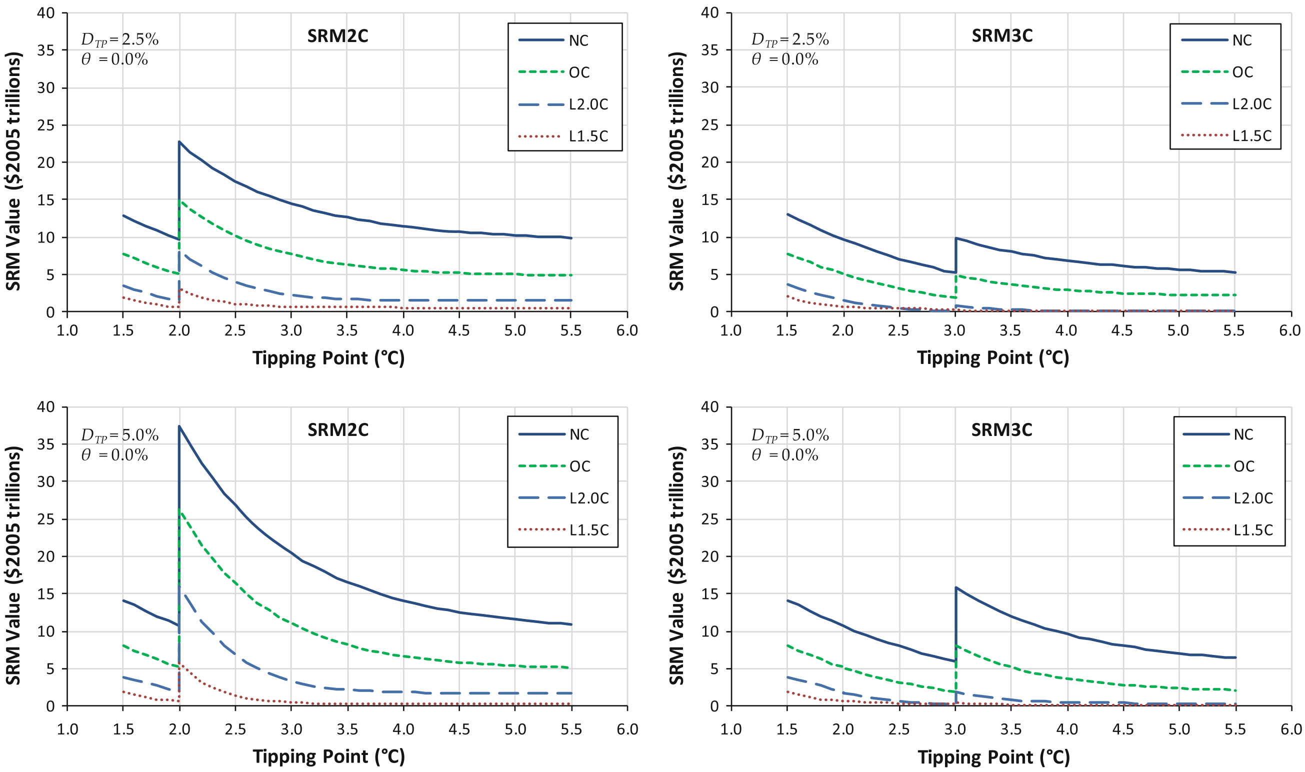

Fig. 10 Sensitivity of damage-free SRM value to emissions control regime, tipping-point damage level, and SRM deployment strategy

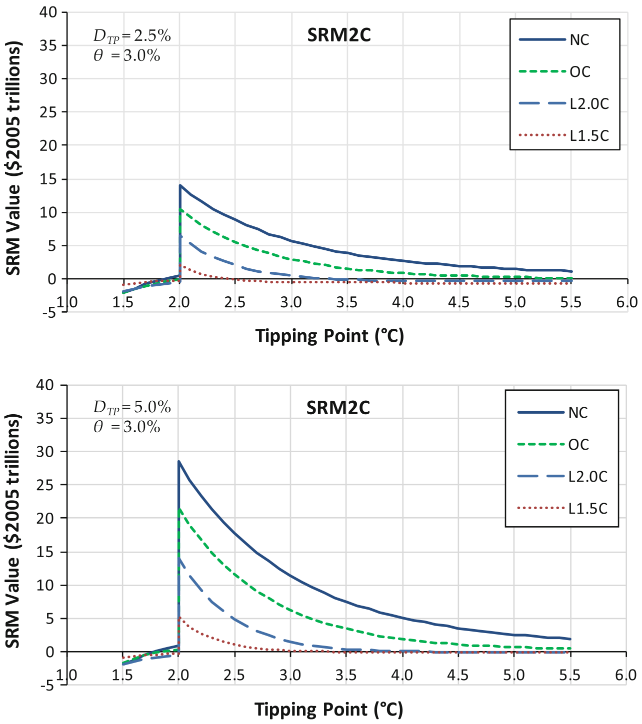

Fig. 11 Sensitivity of damage-causing SRM value to emissions control regime tipping-point damage level and SRM deployment strategy

use of SRM we consider, these values represent upper limits of our analysis. The left-hand vertical axis is the quantity of SRM in W/m^2. The right-hand axis is this required rate of aerosol injection in Tg of S per year. These injection rates assume a forcing efficiency of -0.75 W/m^2 and a residence time of 2.5 years. We have also added a reference line at 1.2 W/m^2, which is the IPCC's estimate of the negative forcing (0.5 W/m^2 direct and 0.7 W/m^2 indirect) produced by current anthropogenic aerosol emissions (IPCC 2007b).

The line labeled mean is the average amount of SRM required in each year. The P10 are the values such that there is a 10 % chance that more SRM than this would be required in any year. There is a 90 % chance that we would require more SRM than the P90 in any year. In both cases, we see that deployment would not begin until 2045.

Under NC, the mean SRM usage is below 1.2 W/m^2 through 2075 and less than 2 W/m^2, or about 1 Tg S, per year through the end of this century. A mean usage equivalent to a doubling of CO2 emissions (3.8 W/m^2) is not reached until after 2150. The P10 does not exceed 2 W/m^2 until after 2085. The P90 is not positive until 2115, implying that even under NC, there is some chance that SRM would not need to be deployed until the next century. Beyond 2100 usage exceeds 2 W/m^2 and could exceed 4 W/m^2 by middle part of the next century.

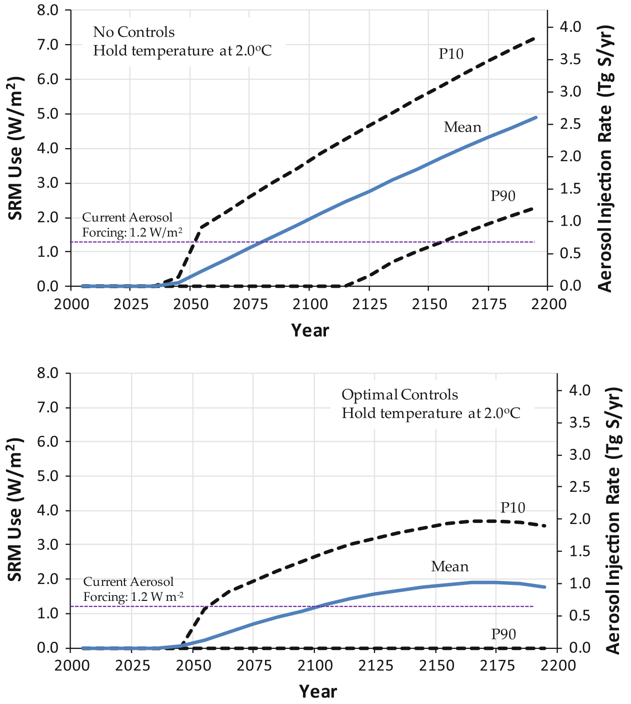

Fig. 12 Required SRM usage to hold temperatures to 2.0 °C under NC and OC

Not to minimize these interventions, but rather to place them in perspective, we consider three comparisons: (1) Anthropogenic aerosol emissions currently provide negative forcing of 1.2 W/m^2, (2) 2 W/m^2 is about 0.6 % of the incoming solar radiation of 341 W/m^2 (Trenberth et al.

2009), and (3) 1 Tg S per year is less than 2 % of the sulfur that is currently injected into the atmosphere via the burning of fossil fuels (Stern 2005).

As shown in Fig. 12, required SRM usage to hold temperatures to 2.0 °C is lowered under OC. The mean usage by the end of the century is approximately equal to the current negative forcing of anthropogenic aerosols (1.2 W/m^2) or 0.6 Tg S per year—approximately 1 % of the current anthropogenic sulfur emissions. Mean usage never exceeds 2 W/m^2 and only achieves this level in the later part of the twenty-second century. There is a 10 % chance that more than about 2.75 W/m^2 would be required in 2100.

6 Conclusion: the need for research

In this paper, we have analyzed the ability of emissions controls and SRM to deal with climate tipping points. Several important insights emerge from this analysis.

- First, emissions reductions may not be a cost-effective way of reducing the risk of catastrophic change to acceptable levels. Although initially these reductions might be able to reduce the probability of modest warming, it becomes increasingly expensive to completely remove the "tails" of the temperature distribution (i.e., low probabilities of significant warming). In other words, paying to shift the entire temperature distribution is a costly way of addressing tail risks. This finding echoes that of other researchers who state that emission reductions cannot reduce the risk of catastrophic change to *de minimis* levels at politically acceptable costs (Keller et al. 2005).
- Second, adding SRM to a policy of emissions controls, even a strict one, holds the potential of avoiding significant climate damages, with potential economic benefits in the tens of trillions of dollars, even if SRM itself causes damage. These benefits appear to be much larger than the costs of a research and development program (Bickel and Lane 2010; Keith et al. 2010). However, while we include indirect costs in our analysis, significant uncertainty remains as to their magnitude and how they would scale with SRM use. Thus, society should allocate research funding now to test the efficiency and efficacy of SRM.
- Third, deferring SRM until a tipping point is upon us runs the risk that we will fail to deploy SRM in time. Asserting that SRM should be held in reserve until, we recognize that we are in an emergency situation places a great deal of faith in our ability to anticipate the threshold. As a case in point, Lindsay and Zhang (2005) suggest that the Arctic sea ice has already passed a tipping point, whereas Holland et al. (2006) disagree. If society chooses to use SRM in this way, we will need to develop a very good early detection system.

Any assessment of SRM will be limited by the current state of knowledge, the rudimentary nature of the concepts, and the lack of prior research and development efforts. The inputs to our analysis are admittedly speculative; many questions surround their validity, and many gaps exist in them. Many important scientific and engineering uncertainties remain. Some of these pertain to climate change itself, its pace, and its consequences. Still others are more directly relevant to SRM's effects, positive and negative, and the necessary technology. In addition, we have made many modeling simplifications. The most significant of these is the assumption that the ECS is perfectly revealed once a temperature threshold is crossed, which allows SRM to perfectly control temperature. This assumption should be tested as others investigate to what extent SRM can be used to control the climate system.

To address this lack of understanding, Blackstock et al. (2009), specified a ten-year research and development (R&D) program divided into two phases. Phase 1 would consist of laboratory experiments and computational modeling. Its goal would be to explore the climate response to differing levels of SRM intervention. This phase would not include any direct intervention in the actual climate. Phase 2 would begin intentional interventions into the climate system. These interventions would be limited in their duration, magnitude and/or spatial range. They would not aim to offset increased GHG concentrations; rather, they would seek to understand SRM's efficacy. Blackstock et al. (2009) estimate that elements of Phase 1 would take place over the entire ten-year period but that field experiments would only begin in year five (see their Fig. 5). At the successful conclusion of Phase 2, a third phase consisting of monitored deployment would follow.

In sum, the logic underlying this paper is straightforward: If one believes that thresholds exist in the climate system beyond which significant damages will occur, then a technology that could quickly offset the radiative forcing of greenhouse gasses may be tremendously beneficial. Like any technology, this benefit must be compared to the economic costs, including environmental impacts, associated with its use. These costs are currently unknown and can only be addressed via a carefully planned and executed research program.

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