The Climate Engineering Option:
Economics and Policy Implications

J. Eric Bickel[1]
Graduate Program in Operations Research
The Center for International Energy and Environmental Policy
The University of Texas at Austin

Abstract

Many scientists fear that anthropogenic emissions of greenhouse gases have set the earth on a path of significant, possibly catastrophic, changes. In response, governments have talked and emissions have increased. The failure of negotiations to reduce emissions is not surprising. Emissions reductions are likely to be expensive and cannot guarantee that we will not pass a tipping point, beyond which significant damages will occur. These facts have led some scientists and economists to propose research into climate engineering. In this paper, we analyze the potential value of one climate engineering technology family, known as solar radiation management (SRM). We find that (1) SRM may be able to effectively deal with tipping points for a fraction of the cost of emissions reductions, (2) SRM's potential benefits are on the order of tens of trillions of dollars, (3) holding SRM until a tipping point is reached or is imminent, may be politic, but is extremely risky, since it relies on a near-perfect early warning system, and (4) the scale of the required SRM intervention over the next 100 years is less than the SRM we are already inadvertently deploying via anthropogenic aerosol emissions. Thus, we conclude that SRM merits a serious research effort. If these results are promising, society should develop an SRM capability and be prepared to deploy it.

1 The Rationale for Climate Engineering Research

In this paper, we argue for the creation of a formal climate-engineering research and development program. Since it is our belief that research should be directed at ideas and technologies that may ultimately be used (i.e., not research for the sake research), we support our argument by demonstrating that climate engineering has the possibility of producing very large benefits for mankind. These benefits will only be realized through careful testing and development. Our argument proceeds as follows:

1. Anthropogenic emissions of greenhouse gasses (GHGs) will warm the earth, all else being equal. How much they will warm the earth is highly uncertain. On balance, this warming will cause economic damage.
2. It is unlikely that negotiations will have a significant impact on warming for many decades. This is supported by the fact that (1) thus far, over twenty years of negotiations have failed to reduce *emissions* and (2) lags in the climate system (e.g., the rate at which the oceans will remove CO_2 from the atmosphere and the thermal capacity of the oceans)

---

[1] Operations Research and Industrial Engineering, The University of Texas, Austin, Texas, 78712-0292, Tel: +1 512.232.8316, Fax: 512.232.1489, ebickel@mail.utexas.edu.

imply that it will take decades (perhaps over 100 years) for emissions reductions to slow or reverse warming once they do begin.

3. Managing "tipping points" or temperature thresholds in the climate system, if they exist, with emissions reductions will be costly and potentially dangerous. They will be costly because GHG concentrations would need to be reduced significantly, perhaps to preindustrial levels, to rule out the possibility of significant warming. They are dangerous because emissions reductions do not provide direct control over temperature. If we needed to cool the earth quickly (on the order of years), we simply could not do so via emissions reductions.
4. Thus, we need to consider other approaches to deal with this aspect of climate change. These approaches should seek to modify the relationship between GHG emissions and temperature changes. Such technologies are known as climate engineering (CE) and are the focus of this paper.
5. One particular CE technology, known as solar radiation management (SRM), may be able to effectively lower the risk of crossing temperature thresholds in the climate system. These technologies are believed to be relatively inexpensive, but their risks are not well understood. If their risks are acceptable, SRM technologies promise potentially large net benefits.
6. Thus, we should invest funds today to research SRM. If some of these technologies are found to be safe and effective, bearing in mind that safe and effective should be measured relative to what will happen if the technologies are not used, then they should be developed and possibly deployed.

This paper is organized as follows. In the next section we summarize our understanding of climate change and its potential impacts. In §3, we summarize the economics of climate change and identify important policy drivers. In §5, we detail the expense and impotence of emissions reductions to deal with tipping points. In §3 we discuss the different types of climate engineering. In §6 we analyze the economic benefit of different SRM policies and their ability to address climate tipping points. In §7 we summarize the policy implications of our work and conclude.

2 The Impact of Climate Change

GHGs in the earth's atmosphere cause its surface to be about 33°C (59°F) warmer than would otherwise be the case (Stocker 2003). These gases (e.g., water vapor, carbon dioxide, and methane) allow the passage of shortwave radiation (sunlight), but absorb longwave radiation (heat) and radiate a fraction of it back to the earth's surface. This "radiative forcing" warms the surface (Trenberth et al. 2009).

The oxidation of hydrocarbons to generate energy produces water and carbon dioxide (CO_2). This CO_2 production alters the earth's carbon cycle, leading to an increase in atmospheric CO_2 concentrations. All else being equal, although all else may not be equal, this increase will raise the average surface temperature of the earth. Thus far, the earth has warmed about 0.7°C (1.3°F), relative to 1900[2], while CO_2 concentrations have increased about 100 parts per million

---

[2] To convert temperature changes in °C to °F, multiply by 1.8.

(ppm)—from about 280 ppm (0.028%) to 380 ppm (0.038%). Precisely, how much of this warming can be attributed to human activity is still being debated. Even more uncertain is the likely amount of future warming, its impact on the globe in general, and its effect on the United States in particular.

2.1 Potential Damages

The Intergovernmental Panel on Climate Change (IPCC) has linked potential impacts to the degree of temperature rise, as shown in Figure 1. Above 2.0°C, the IPCC projects that two billion people will face water stress due to increased droughts; there will be widespread coral mortality; millions of people will face coastal flooding; diseases will move to new geographic locations; and ice-sheet loss will irreversibly cause several meters of sea-level rise. Above 4.0°C, billions more will face water stress; major extinctions will occur around the globe; production levels will fall; coastal wetlands will shrink; and the thermohaline circulation (THC) will weaken.

In addition to these losses, which may be attributed to gradual climate change, 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) augment the work of the IPCC and prioritize these tipping points in terms of their likelihood and proximity. They are particularly concerned about the loss of Arctic sea ice and melting of the Greenland Ice Sheet (GIS). As Arctic sea ice melts, it exposes the darker ocean waters, which leads to additional warming, known as positive feedback. A critical tipping point temperature was not identified, but 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." For the GIS, they identify warming of around 3.0ºC as a point of transition and note that disintegration could occur in as little as 300 years, leading to a sea level rise of 2 - 7 meters (6.7 – 23 feet). If the GIS disintegrates, cooling would not rebuild it at the same rate it was lost (Pattyn 2006), an effect known as hysteresis.

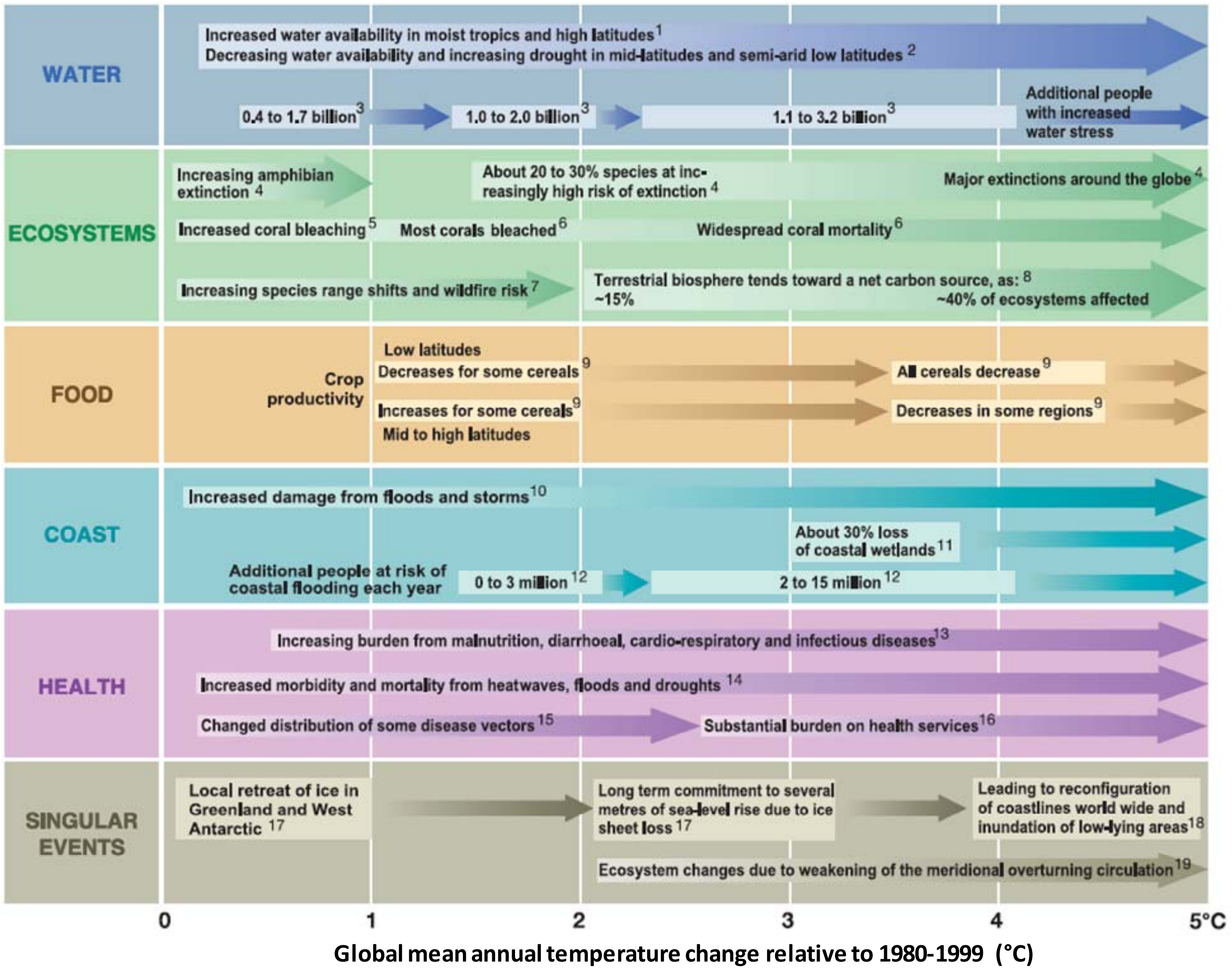

Figure 1: Examples of global impacts projected for changes associated with different amounts of increase in global average surface temperature in the 21st century. Source: IPCC (Parry et al. 2007).

2.2 Significant Uncertainty Remains

As we discuss more fully below, many aspects of climate change are uncertain. However, one of the most critical is the climate sensitivity, which is the amount, in °C, the earth will warm if atmospheric CO_2 concentrations are doubled. In characterizing our understanding of this important variable, the IPCC notes that:

> "The 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]." (IPCC 2007)

The IPCC defines *likely* as greater than a 66% probability and *very unlikely* as less than a 10% probability (IPCC 2005). Thus, even if we were certain about the concentration of CO_2 to which we could stabilize, we are still very uncertain about the magnitude of the risk we face. A doubling of CO_2 could result in impacts that span almost the entire range shown in Figure 1.

2.3 A Lack of Action

Against this backdrop of uncertainty, one thing is clear: more than 20 years of climate negotiations have failed to reduce emissions. As Lane and Montgomery (2008) write:

> "The year 2008 marks the 20th anniversary of the first meeting of the IPCC, the international body established by the UN to solve the problem of warming. The 'progress' to date has been almost purely rhetorical. Currently, according to the US Energy Information Agency, global emissions of CO_2, the most important greenhouse gas, were over a third higher than they had been in 1988. The IPCC reports that the rise in atmospheric concentrations has accelerated through the last several decades."

In fact, global CO_2 emissions grew *four times more quickly* between 2000 and 2007 than they did between 1990 and 1999 (Global Carbon Project 2008). The failure of the UN's latest climate change conference (COP15) was not a surprise, nor was the pledge to continue talking. Reducing emissions will require the world's major powers and rising powers to work in concert even though they are unlikely to benefit to the same degree. In fact, some powerful nations such as Russia and possibly China may benefit from some degree of warming (Nordhaus and Boyer 2000). Furthermore, to actually halt the rise of GHG levels in the atmosphere, the required changes to the energy system are nothing short of titanic. Developing this technology, according to Secretary of Energy Steven Chu, must await the appearance of multiple major breakthroughs in basic science (Broder and Wald 2009).

3 Climate Engineering

The facts discussed above have led some scientists and economists to consider other responese to climate change. One of these responses is known as climate engineering.

The Royal Society, in the United Kingdom, 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). This group has studied the concept and recommends a formal research program (The Royal Society 2009). In the United States, the National Academy of Sciences is exploring CE[3] and the US House of Representatives Committee on Science and Technology is holding a series of hearings on this topic. Finally, John Holdren, President Obama's Science Advisor, has recently said, "It's [climate engineering] got to be looked at" (Borenstein 2009). CE is composed of two distinct technology families: air capture and solar radiation management.

3.1 Air Capture

Air capture (AC) removes CO_2 from ambient air and sequesters it away from the atmosphere. As such, it is perhaps best thought of as a form of emissions reductions, allowing for greater than 100% reductions, or the creation of a new carbon sink. The primary attractions of AC are that (1) it separates CO_2 production from capture, adding flexibility and reduced transportation costs, and (2) it holds the possibility of reversing the rise in CO_2 concentrations. There are two

---

[3] America's Climate Choices. See: http://americasclimatechoices.org/GeoEng%20Agenda%206-11-09.pdf

shortfalls of AC, as far as managing tipping points is concerned. First, the cost to reduce CO_2 concentrations by 1 ppm is estimated to be on the order of $1 trillion (Pielke 2009). Second, AC does not directly address the climate sensitivity. As demonstrated in §5.2, because of lags in the climate system, CO_2 removal will not be able to change the climate system as quickly as may be needed. For this reason, we will focus the rest of this paper on a technology family that holds the promise of quickly cooling the earth: solar radiation management.

3.2 Solar Radiation Management

Solar radiation management (SRM) differs from air capture in that it seeks to reverse the energy imbalance caused by increased GHG concentrations by altering the climate sensitivity. It accomplishes this by reducing the amount of solar energy absorbed by the earth. This is achieved by reflecting back into space some fraction of the incoming shortwave radiation from the sun. Calculations show that reflecting only 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. Past volcanic eruptions, for example, have shown that injecting relatively small volumes of matter into the upper atmosphere can cause discernable cooling. The 1991 eruption of Mt. Pinatubo reduced global mean temperature by about 0.5°C (Crutzen 2006).

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."

SRM Version 1.0

In fact, we are already inadvertently deploying a version of SRM. The IPCC (2007) estimates that anthropogenic aerosol emissions (primarily sulphate, organic carbon, black carbon, nitrate, and dust) are currently providing a negative radiative forcing of 1.2 watts per square meter (W/m^2). Current radiative forcing is 1.6 W/m^2, including the negative forcing of aerosols; thus, aerosols *currently* offset over 50% of anthropogenic emissions. Opponents of SRM might want to consider whether or not they would like to remove this effect. 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' affect on cloud albedo. The two classes of SRM technologies that have received the most attention parallel this division: stratospheric aerosol injection and marine cloud whitening.

Stratospheric Aerosol Injection

Stratospheric aerosol injection has recently been suggested by Paul Crutzen (2006), a Nobel Laureate in Chemistry.[4] In this case, a precursor of sulfur dioxide would be (continuously) injected into the stratosphere, where it would form a layer of aerosols. This layer would reflect sunlight. The amount of sulfur required to offset global warming is on the order of 2% of the

---

[4] The Soviet climatologist Mikhail Budyko suggested this idea in the early 1970s.

sulfur that humans already inject into the atmosphere (mostly in the troposphere) via the burning of fossil fuels.

Marine Cloud Whitening
Marine cloud whitening has been suggested by Steven Salter and John Latham (Latham et al. 2008; Salter et al. 2008). In this scenario, marine clouds would be injected with seawater, forming a sea-salt aerosol. 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
Other SRM concepts include placing mirrors in space and painting rooftops white. The latter has been suggested by Secretary of Energy Chu. Although this may play an important local role, it is unlikely to scale to the degree needed (Lenton and Vaughan 2009) or help protect sensitive areas like the Arctic.

3.3 Climate Engineering Research and Development

SRM is, then, a concept with natural analogues and inadvertent use, but it has neither been formally developed nor tested. It may be found to be infeasible or too risky to be considered a viable policy option. As discussed more fully below, one goal of this paper is to argue that SRM is worthy of formalized research and development. We do not, however, lay out the details of such a research program. Rather, we refer the interested reader to a recent report by the Novim Group (2009). This report, authored by leading climate engineering researchers, outlines such an effort, whose cost has been estimated, when it is fully underway, in the low billions of dollars (Bickel and Lane 2009; Keith et al. 2010).

3.4 The Economics of SRM

In previous work, Bickel and Lane (2009), hereafter BL, summarized existing SRM concepts and their ability to respond to climate change. In particular, they investigated the preemptive use of SRM to lower climate damages and abatement costs. Their work did not consider the possibility of abrupt climate change or temperature thresholds, beyond which the earth's climate system may transition into a new condition—bringing significant damages. BL's primary conclusions were that SRM's benefits appear to greatly exceed the direct costs of deploying it, and that, therefore, society should allocate funds to explore and possibly to develop this concept.

In this paper, we extend the work of BL by considering uncertainty in critical parameters (physical and economic) and allow for climate tipping points. In addition, rather than considering preemptive deployment, we assume SRM is only deployed in situations that society has deemed to be an emergency. This could include crossing a particular temperature change threshold, such as 3.0°C, or the appearance of abrupt or catastrophic changes in the climate system.

The SRM technologies discussed above are not mutually exclusive and may even be used in concert with other approaches to climate change, such as GHG emissions reductions and adaptation. The best approach is likely to be a mixture of all these strategies (Lane and Bickel 2009). In this paper, we consider the use of SRM in conjunction with GHG controls. In addition, although our results are not limited to a specific SRM technology, we nominally consider the use of stratospheric aerosol injection (SAI). At this time, SAI is viewed as the leading SRM technology, because of its scalability and the ability to deploy it uniformly around the globe. However, it appears to be more costly than marine cloud whitening (Bickel and Lane 2009).

4 Understanding the Drivers of Climate-Change Risk

In this section we use an established model of climate change economics to understand the most important drivers of climate-change risk and uncertainty. This analysis suggests that policies that focus solely on emissions reductions may be risky because they fail to directly address the most pressing uncertainty in climate change science: the climate sensitivity.

We derive our results from a modification of the Dynamic Integrated model of Climate and the Economy – 2007 (DICE-2007) developed by William Nordhaus (Nordhaus 1994; Nordhaus and Boyer 2000; Nordhaus 2008). DICE is a deterministic optimal-economic-growth model that has been used extensively by researchers to understand the economics of climate change. DICE relates economic growth to energy use, energy use to CO_2 emissions, CO_2 emissions to atmospheric concentrations of CO_2, CO_2 concentrations to temperature increase, and finally temperature increase to economic damage. The policy variable in DICE is the annual CO_2 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 to 2605). We, however, limit our analysis to 200 years (2005 to 2205). Because of time discounting, there is negligible difference between a 200-year and 600-year study period.

DICE can 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-controls environments: no controls (NC), optimal controls (OC), and limiting temperature change to 1.5°C (L1.5C) or 2.0°C (L2.0C). Figure 2 displays the emissions reductions for OC, L1.5C, and L2.0C.[5] We see that OC would, compared to NC, begin with a 15% reduction in CO_2 emissions in 2015 (the first decade in which they could begin in DICE) and gradually phase out carbon emissions over the next 200 years. To limit temperature changes to 2.0°C reductions would start at 21% in 2015 and ramp up to 100% by the end of the century. Limiting temperature changes to 1.5°C would require completely phasing out CO_2 emissions by 2065.[6]

---

[5] The emission control rates for the temperature-constrained cases are unstable once the temperature constraint is reached. This occurs because the oceans remove CO2 from the atmosphere and thereby reduce temperature. This reduction allows DICE to temporarily loosen its emissions policy.

[6] Under OC, L2.0C, and L1.5C, CO2 concentrations peak at 660 ppm, 472 ppm, and 420 ppm, respectively.

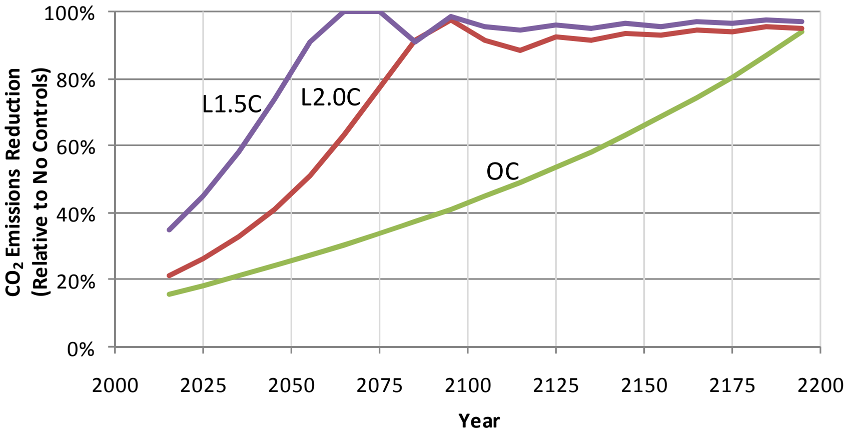

Figure 2: DICE emissions control regimes relative to No Controls.

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.

4.1 Base Case Results

The base-case damages from our DICE model are presented in Table 1. Climate damages under NC are $22.5 trillion (all dollars are present values, 2005 $). OC incur $17.4 trillion in climate damages (a $5.1 trillion reduction) and $2.1 trillion in abatement costs, spent on emissions reductions, yielding total damages of $19.5 trillion. L2.0C reduces climate damages by $4 trillion, but incurs $9.7 trillion more in abatement costs than OC. L1.5C reduces damages by an additional $2.9 trillion, but costs $17 trillion more than L2.0C. We notice that both L1.5C and L2.0C are worse than NC. These emissions control regimes reduce climate damages, but not enough to justify their expense.

Table 1: DICE Base Case Results (200-year present values; trillions of 2005 $)

Emissions Control Regime	Climate Damages	Abatement Costs	Total Damages
No Controls	$22.5	$0	$22.5
Optimal Controls	$17.4	$2.1	$19.5
L2.0C	$13.4	$11.8	$25.2
L1.5C	$10.5	$28.8	$39.3

4.2 Understanding Key Risk Factors and How to Manage Them

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 risk factors.

Nordhaus (2008, p. 127) provides a list of the most important DICE inputs and the uncertainty surrounding them. We describe these below (please see Appendix A1 for the relevant DICE equations and a more detailed discussion).

- **Climate sensitivity.** As described in §2.2, the climate sensitivity is the amount, in °C, the earth will warm if atmospheric CO_2 concentrations are doubled.
- **Fraction of CO_2 contained in the atmosphere after 10 years.** DICE uses a three-stratum model of the biosphere, which includes the atmosphere, the upper ocean, and the deep ocean. This variable measures the fraction of CO_2 that is retained in the atmosphere rather than being transferred to the upper ocean. As the reader will see, this fraction is relatively high; over 80% of the CO_2 currently present in the atmosphere will still be there in 10 years.
- **Quadratic damage parameter.** DICE's damage function is quadratic in temperature. This parameter determines how quickly damage increase 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 CO_2 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 assumes these uncertainties are independent and normally distributed and provides their means and standard deviations, which we present in Table 2. With the exception of climate sensitivity, as discussed below, we adopt Nordhaus's uncertainty ranges. The columns labeled P90 and P10 list the values of each variable such that there is a 90% or a 10% chance, respectively, that the input will fall above the value shown (i.e., the 90th and 10th quantile of the excess probability distribution). As we demonstrate below, these quantiles are useful in sensitivity analysis.

Table 2: Key DICE Uncertainties

Variable	Units	Mean	Standard Deviation	P90	P10
Climate sensitivity	°C	3.0	1.5	1.5	5.0
Fraction of CO_2 retained in atmosphere after 10 years	fraction	0.811	0.017	0.789	0.832
Quadratic damage parameter	\$trillions / $(^{\circ}C)^2$	0.0028	0.0013	0.0012	0.0045
Rate of growth in total-factor productivity	%/yr	9.20	0.40	8.70	9.70
Rate of decarbonization	%/yr	-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

Based on the IPCC statements discussed in §2.2, we assume that climate sensitivity is lognormally distributed with a mean of 3.0°C and standard deviation of 1.5°C. This distribution is shown in Figure 3. Compared to the normal distribution, the lognormal distribution is skewed to the right and excludes the possibility of negative climate sensitivities (i.e., the addition of CO_2 to the atmosphere will not cool the planet). 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°C 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.

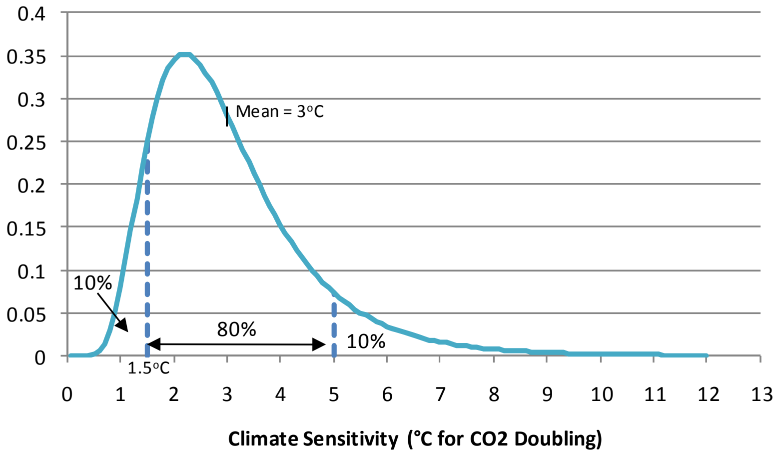

Figure 3: Lognormal probability distribution for climate sensitivity.

Since important DICE parameters are uncertain, so are the maximum temperature change and the damages incurred by following a particular emissions control regime. Understanding which parameters drive the risk of climate change is the first step in developing a risk management strategy.

Figure 4 shows the impact of input uncertainty on total damages under OC. This diagram, called a "tornado diagram," is centered at $19.5 trillion, which is the total damage estimated by DICE when all input variables are set to their base case and matches the value given in Table 1. Figure 4 details the impact on total damages of varying one input at a time. For example, if the climate sensitivity was 5.0°C and all other variables were still at their base case, then total damages would be approximately $30 trillion. If climate sensitivity was 1.5°C and all other variables were at their base case, total damages would be approximately $10 trillion - a swing of $20 trillion. Since there is an 80% chance that climate sensitivity is between 1.5°C and 5.0°C, there is an 80% chance that total damages will be between $10 trillion and $30 trillion under OC, owing to uncertainty about the climate sensitivity alone. Similarly, there is an 80% chance that total damages will be within the range shown for each variable. Thus, we see that uncertainty in the climate sensitivity, the damage parameter, and the population most contribute to our uncertainty regarding total damages. The atmospheric retention rate, the rate of decarbonization, the cost of the backstop technology and the TFP growth rate contribute relatively little to our uncertainty regarding damages.

To each bar, except Population, we add a label that describes the policy category that might be used to manage this risk. The two bars of a different color are the inputs that could be addressed via CE. SRM lowers the climate sensitivity, the largest risk, and AC decreases the atmospheric CO_2 retention rate. Adaptation addresses the relationship between warming and damage. Emissions controls (E. Ctls) increase the rate of decarbonization of the economy. Energy R&D may be able to reduce the cost of backstop technologies. Policies focused on efficiency would increase productivity.

We see that the current singular focus on emissions reductions leaves several important (perhaps the most important) policy responses off the table. In fact, according to the ranking in Figure 4, emissions controls are a distant fifth behind SRM, adaptation, population, and AC as a means dealing with the risk of climate change.

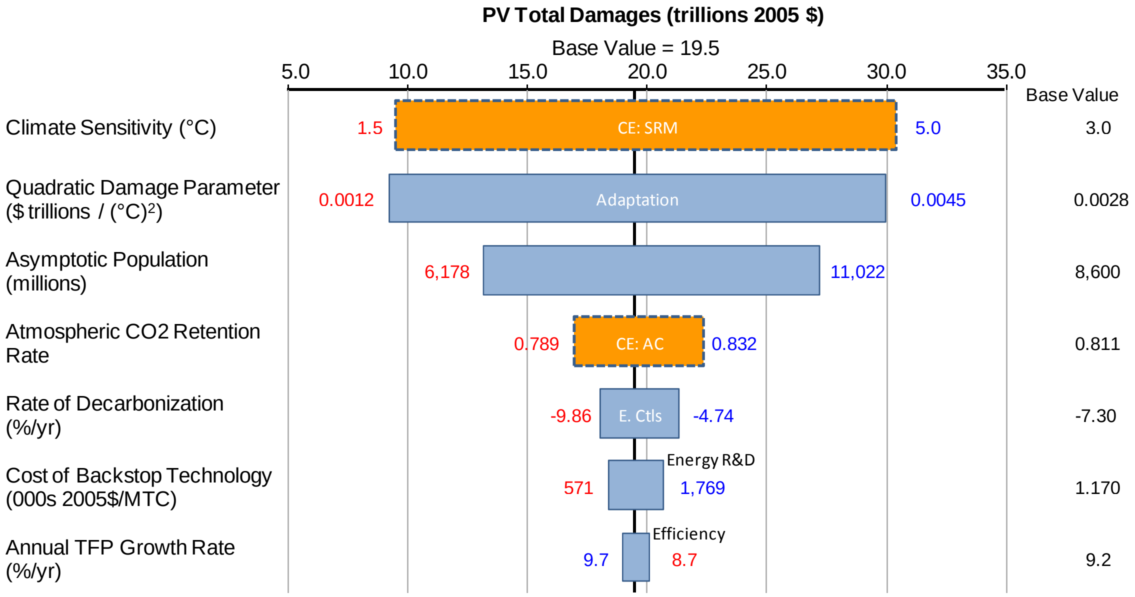

Figure 4: Sensitivity of total damages under Optimal Controls.

The sensitivity of the maximum temperature change under OC is shown in Figure 5. In this case, we see that the climate sensitivity dominates. The earth's population, the rate of decarbonizaiton of the world economy, and the retention rate of atmospheric CO_2 contribute much less to our uncertainty regarding temperature change. The damage parameter and cost of the backstop technology have only a very minor impact. Again, we see that the exclusion of SRM as a policy response fails to address the largest climate risk.

4.3 Policy Insights

This sensitivity analysis provides several policy insights.

- First, the ability to control the climate sensitivity, and thereby limit damages and temperature change, would provide large benefits—on the order of tens of trillions of dollars.
- Second, having the ability to react if temperatures rise quickly would seem prudent because, even with optimal emissions controls, we cannot rule out warming in excess of 4.0°C or even 5.0°C.
- Third, policies that focus solely on CO_2 reductions or removal, to the exclusion of the climate sensitivity, will not be as efficient (or safe) as they could (or should) be. Our climate risk is dominated by the climate sensitivity. CO_2 reductions do not address this critical climate parameter. Rather, they seek to reduce the level of CO_2 in the atmosphere and hope the climate sensitivity is not too large.
- Fourth, controlling CO_2 simply will not be able to move the climate as quickly as the ability to modify, perhaps temporarily, the climate sensitivity. This is true because the three variables related to the removal of CO_2 from the atmosphere—the rate of decarbonization, the atmospheric retention rate of CO_2, and the cost of the backstop technology—play a more modest role in damages and warming.
- Finally, while not the focus of this paper, we note that developing the capability to weaken the link between warming and damage (e.g., via adaptation) would be tremendously valuable. We see this since our uncertainty in the relationship between warming and damage is the second most critical uncertainty when projecting damages—more important than variables related to CO_2 removal.

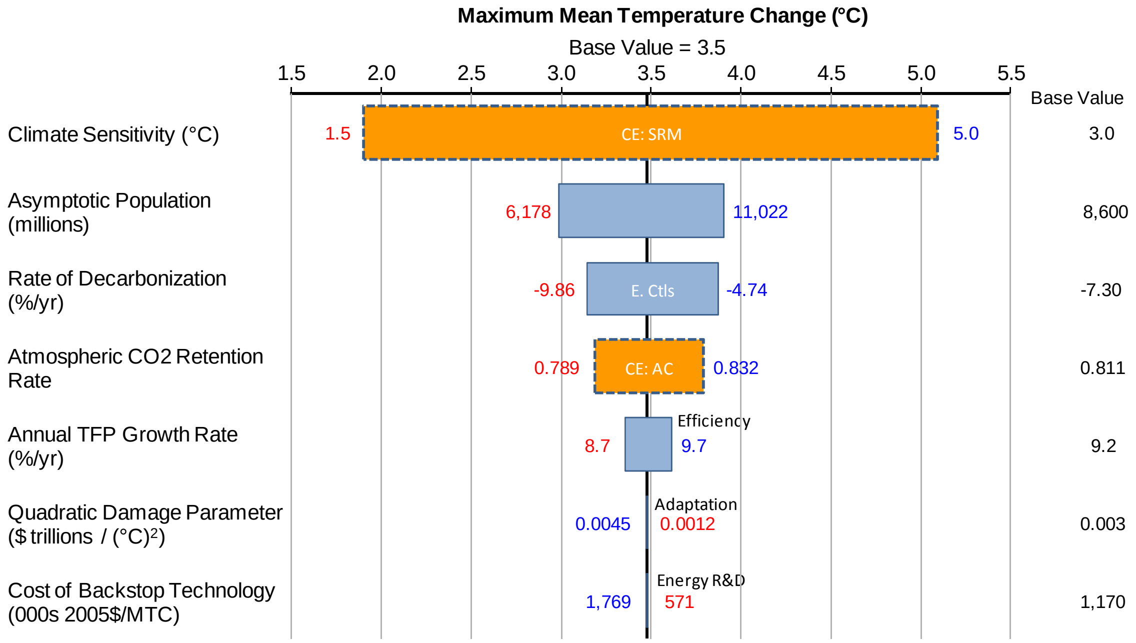

Figure 5: Sensitivity of maximum temperature change under Optimal Controls.

5 The Cost and Impotence of 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, emissions 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. The results appear in Figure 6, 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 1ºC to 10ºC—an order of magnitude. The mean or average maximum temperature change is 5.0ºC. Under OC, this range is reduced somewhat, but temperature changes in excess of 7ºC or 8ºC cannot be ruled out. L1.5C and L2.0C shift the temperature distribution to the left, but even these tight emissions control regimes leave the possibility of exceeding 3ºC or 4ºC.

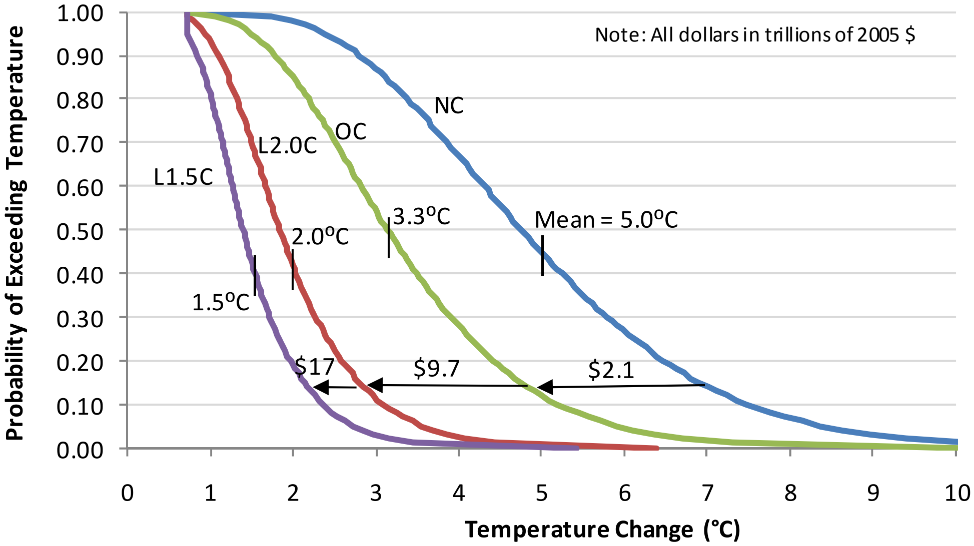

Figure 6: Probability of exceeding particular temperatures under different emissions control regimes.

Figure 6 also shows the abatement cost required to move between emissions control regimes (as detailed in Table 1), and 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 5 times a much. L1.5C costs $17 trillion more than L2.0C (about $29 trillion more than NC) and only slightly affects temperature.

Clearly, shifting the temperature distribution becomes increasingly difficult and expensive via emissions reductions. One way to see this is to calculate how much each strategy reduces temperature, relative to NC, for every $1 trillion spent on abatement. Moving from NC to OC, for example, reduces the *mean* maximum temperature change from 5.0°C to 3.3°C, or about 0.8°C for every $1 trillion dollars in abatement costs. Moving from NC to L2.0C at a cost of $11.8 trillion reduces the mean temperature change to 2.0°C, or only 0.25°C for every $1 trillion spent on abatement. Moving from NC to L1.5C costs almost $29 trillion and reduces the mean temperature by only 0.12°C for every $1 trillion on abatement.

5.1 The Cost of Reducing Tail Risks

Thus far, policy discussions have focused almost completely on emissions reductions. Part of the argument for reducing emissions has been that we are heading towards catastrophe. In this section, we demonstrate that emissions reductions are likely to be a very expensive way of dealing with the risk of significant temperature changes.

Emissions reductions lower the probability of exceeding particular temperature thresholds, but perhaps not to the degree that one might think. Table 3 details the probability of exceeding 2.0°C, 3.0°C, 4.0°C, or 5.0°C for the four emissions-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. An emissions control policy designed to limit temperature change to

2.0ºC still has about a 42% chance of temperature change greater than 2.0ºC. Even trying to limit temperature change to 1.5ºC runs almost a 20% chance of change greater than 2.0ºC.

Similar results hold for more extreme temperature changes. Under NC, there is an 87% chance of change greater than 3ºC. OC reduces this chance to 54%. Even L2.0C has an 11% chance of change greater than 3ºC; further tightening emissions controls to hold temperature changes to 1.5ºC reduces this chance to 3%. It is surprising and disappointing that a very tight emissions control regime still holds a non-negligible chance of exceeding a temperature threshold that scientists have suggested could lead to the disintegration of the GIS. Whether these risks are acceptable depends upon whether one believes crossing these thresholds constitutes dangerous interference in the climate system (UNFCC 1992).

Table 3: Probability of Exceeding Particular Temperatures under Different Emissions Control Regimes

Emissions Control Regimes	2ºC	3ºC	4ºC	5ºC
L1.5C	0.19	0.03	0.00*	0.00*
L2.0C	0.42	0.11	0.02	0.00*
OC	0.85	0.54	0.28	0.12
NC	0.98	0.87	0.67	0.45

* Probabilities are less than 0.01.

We see that, despite their significant cost, deep emissions reductions may fail to significantly reduce the probability of passing a tipping point. For example, moving from NC to L1.5C reduces the probability of exceeding 2.0ºC by only 0.03 for every $1 trillion spent on abatement (a decrease in probability from 0.98 to 0.19 at a cost of about $29 trillion). Moving from NC to OC, on the other hand, reduces the probability of exceeding 4.0ºC by 0.19 for every $1 trillion. Table 4 details these measurements of efficiency, relative to NC, for OC, L2.0C and L1.5C. Whether these investments are economic depends upon the damages that would accrue when these temperature thresholds are crossed. However, one thing is clear: managing tipping points via emissions reductions will be expensive—requiring trillions of dollars in abatement costs for single-digit decreases in tipping-point probabilities.

Table 4: Tipping Point Probability Reduction for Every $1 Trillion Spent, Relative to NC

Emissions Control Regimes	2ºC	3ºC	4ºC	5ºC
L1.5C	0.03	0.03	0.02	0.02
L2.0C	0.05	0.06	0.05	0.04
OC	0.06	0.15	0.19	0.16

5.2 The Inability to Respond in an Emergency

In addition to their expense, deep emissions reductions simply cannot quickly cool the planet; just as nearly 100 years of uncontrolled emissions have failed to quickly warm the planet. Therefore, we cannot rely on them as our sole response to a climate emergency.

This point is made clear in Figure 7. In this case, we follow OC until we reach a temperature increase of 2.0ºC, which occurs in the year 2065. At this point, we realize that we have crossed a tipping point and decide to dramatically increase emissions reductions to 80%, 90%, or 100% from the current 30%. Emissions reductions of 80% and 90% fail to cool the earth. A complete halt to carbon emissions does reduce temperature, but only slightly and gradually. It takes over 60 years to retreat below 2.0ºC, and even by the end of the 22nd century, temperatures have come down only about 0.4ºC from their peak.

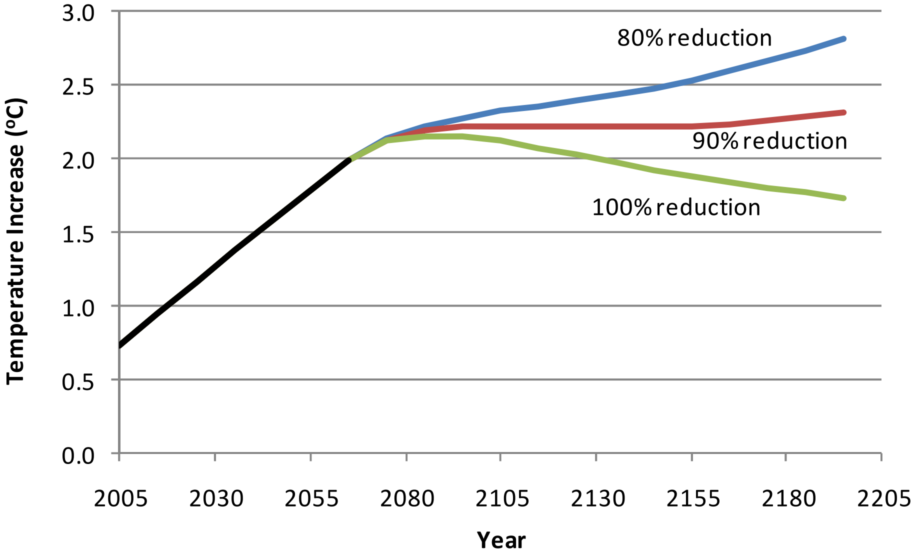

Figure 7: Temperature profile for a nearly total end to carbon emissions after 2065.

5.3 The Risk of Emissions Reductions

Relying solely on emissions reductions to manage the risk of crossing tipping points could be as risky as it is expensive. McInerney and Keller (2007) note that reducing the odds of THC collapse 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 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."

This is not surprising. Emissions reductions are a blunt policy tool. Setting aside the difficulties of securing a binding and verifiable global agreement, trying to manage low-probability events by shifting the entire temperature distribution (Figure 6) will be very expensive because we are *paying to reduce the probability at all temperatures* even if we are primarily concerned with particularly large changes. Rather, we would like to *truncate* the temperature distribution at a temperature considered dangerous. Trying to manage tipping points via emissions reductions is like buying a smaller house (or no house) to lessen the loss you would suffer in the event of a fire. Not owning a home eliminates your "tail" risk, but hardly seems an economically efficient means of risk reduction.

Climate change may bring both gradual and abrupt warming. Emissions reductions may be able to address the former. However, even steep reductions run a non-negligible chance of failing to prevent significant damages. Modest emissions reductions may be able to lower the probability of warming at reasonable cost (see Table 4), but they will remain a very costly way to avert catastrophic damage. Rather, if society is particularly worried about the presence of tipping points, it must develop a technology that can directly address the climate sensitivity. This is a role that SRM might be able to play.

6 Addressing Tipping Points via SRM

In §4 we discussed how climate change could lead to significant warming and damages. Yet, in §5 we demonstrated the inability of emissions reductions to economically deal with this risk. In this section, we provide a preliminary assessment of the value of SRM in the presence of tipping points. We find the value of SRM is potentially very large (in the trillions of dollars) and almost certainly exceeds the expense of an R&D program, which is estimated to cost about 1000 times less (Bickel and Lane 2009; Keith et al. 2010).

We assume that society follows an emissions control regime of either No Controls or Optimal Controls. 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 situations: (1) temperature 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.

6.1 Changes Made to DICE

In order 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. Please refer to Appendix A2 for additional detail.

We modify DICE's radiative forcing equation to allow for inclusion of an additional external forcing component, which is the deployment of SRM. The use of SRM directly reduces radiative forcing, and we measure SRM use in terms of watts per square meter (W/m^2). This treatment of SRM is consistent with DICE's modeling of aerosols and with the inclusion of aerosols in more sophisticated climate models (Andronova and Schlesinger 2001).

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 there is only one such tipping point, but multiple thresholds may exist. To capture this feature, we modify DICE's damage function by including an additional and permanent cost if the tipping point temperature is exceeded. This permanent loss reflects hysteresis in the climate system.

6.2 The Cost of Crossing a Tipping Point

Nordhaus (1994, p. 115) notes 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 3.5ºC, 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 estimates 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) estimates 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), McInernery and Keller (2007), and McInerney et al. (2009) extrapolate this estimate to the entire globe and assume 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 values. In particular, we will allow the tipping point temperature to vary between 1.5°C and 5.5°C and will consider values for damages of 2.5% and 5.0% of GWP. Figure 8 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 planet cools, is meant to capture hysteresis in the climate system (i.e., damages cannot simply be undone 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. We do not consider higher damage levels, because these only strengthen our argument.

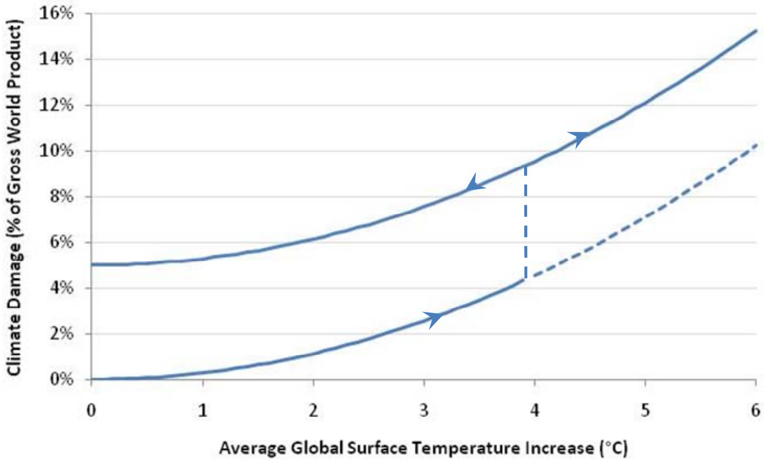

Figure 8: An example of a modified damage function that includes a tipping point at 4.0°C.

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.

6.3 SRM Deployment Decision

The structure of our decision problem is depicted graphically in Figure 9. For illustration, we assume that society adopts either NC or OC. 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. 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 §6.1, 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. We do not consider specialized strategies such as only deploying SRM in the Arctic. This is an area for future research.

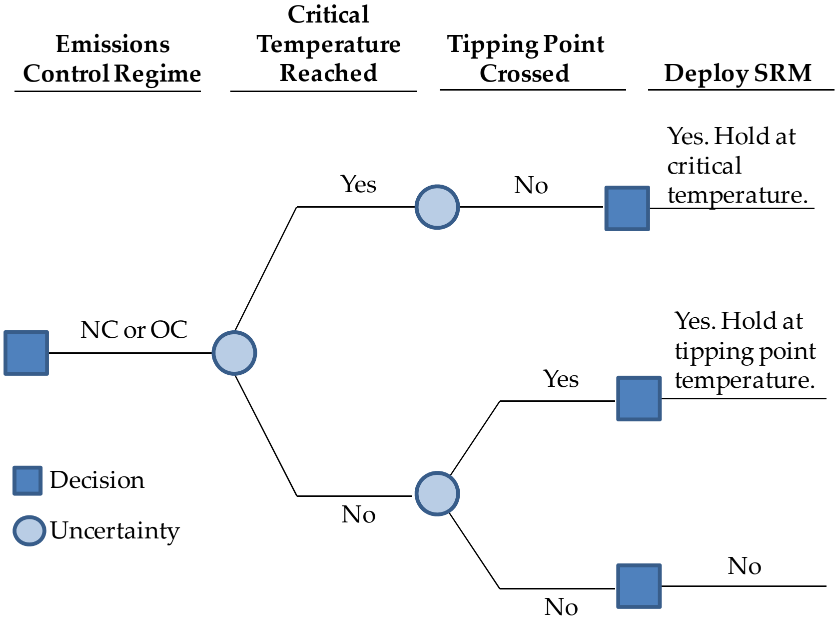

Figure 9: SRM deployment decision tree for each period.

We do not re-optimize DICE's emissions controls regime in the presence of SRM. Instead we adopt OC as specified by the original DICE model. We take this approach for two 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 a formulation does not reflect this paper's assumptions regarding when SRM may be deployed. We assume that society agrees to adopt OC and views SRM as a safety net. As demonstrated by BL, this assumption will underestimate the value of SRM because it favors costly abatement measures over SRM.

6.4 SRM Deployment Cost

BL 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.

We include only the direct costs of SRM deployment. We do not attempt to quantify the indirect costs and benefits, such as possible changes to precipitation patterns, slowing ozone recovery, whiter skies, reduced efficiency of solar power, reduction in the rate of skin cancer, or increased agricultural yields. Only systematic research and testing can determine the importance of these possible effects (see BL for a fuller discussion). Instead, we assume that society has decided it faces a climate emergency that requires deploying SRM. 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 S (1 Tg = 1 trillion grams = 1 million metric tons).[7] Rasch et al. (2008) 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 W/m^2 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. To place this number in perspective, we consider two benchmarks. First, the burning of fossil fuels emits 55 Tg S per year (Stern 2005). Thus, offseting 1 W/m^2 requires an injection equivalent to approximately 1% of the sulfur already 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),

---

[7] At this rate, 1 g of S offsets about 320,000 g (0.32 MT) of CO_2. Or, every Tg of S offsets about 40 ppm of CO_2, which is about 20 years of global emissions.

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. Robock et al. (2009) have recently revised the cost estimates for the use of military aircraft. They conclude that 1 Tg of H_2S could be injected near the equator using F-15s for a yearly cost of about $4.2 billion. However, many questions remain regarding the ability of planes to continuously inject corrosive H_2S and if droplets of the correct size would be formed. Thus, we base our cost estimates on the use of naval artillery.

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.

As the reader will see, the direct costs of SRM appear to be very low and, thus, the assumptions made in this section play a minor role in our results.

6.5 The Option Value of SRM

To determine the value of SRM, we perform two sets of Monte Carlo trials for the decision depicted in Figure 9. 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 1.5ºC to 5.5ºC at intervals of 0.1ºC—for a total of 410,000 trials. We average the 10,000 damage estimates for each tipping point and refer to these as expected total damages 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 damages with SRM. The value of SRM is the expected total damages without SRM less the expected total damages with SRM.

Figure 10 displays the results of this simulation under OC and assumes that the tipping point damage is equal to 5% GWP. The upper line is the expected total damages when SRM is never deployed. If the tipping point is remote (e.g., at 5.5ºC), the expected damage is $19.7 trillion, which is very close to the base case value of $19.5 trillion shown in Figure 4 and Table 1. As the tipping point becomes nearer, the expected damages increase significantly; at a tipping point of 2.0ºC the expected damage if SRM is not used is $41 trillion.

The middle line presents the expected damage 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 is high, then SRM is not used and the expected damages are the same as the case where society does not have an SRM capability. If the tipping point is lower, then SRM is deployed, temperatures are held at this level, and the damages are reduced. The difference between the two lines is the value of having the option to deploy SRM only if a tipping point is crossed.

The expected damages when SRM is deployed at 2.0ºC, even if a tipping point has not been crossed, are given by the lower curve. As shorthand, we refer to this as SRM2C. This coincides with the middle line when the tipping point is less than 1.5ºC, because SRM was not deployed preemptively. When the tipping point is 2.0ºC, the damages 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 2.0ºC threshold is crossed, the expected damages are constant because SRM is used to hold the temperature at 2.0ºC and the higher tipping points are not reached. The expected damages are lower in this case, even if a tipping point is not reached, because SRM prevents warming that would otherwise have taken place.

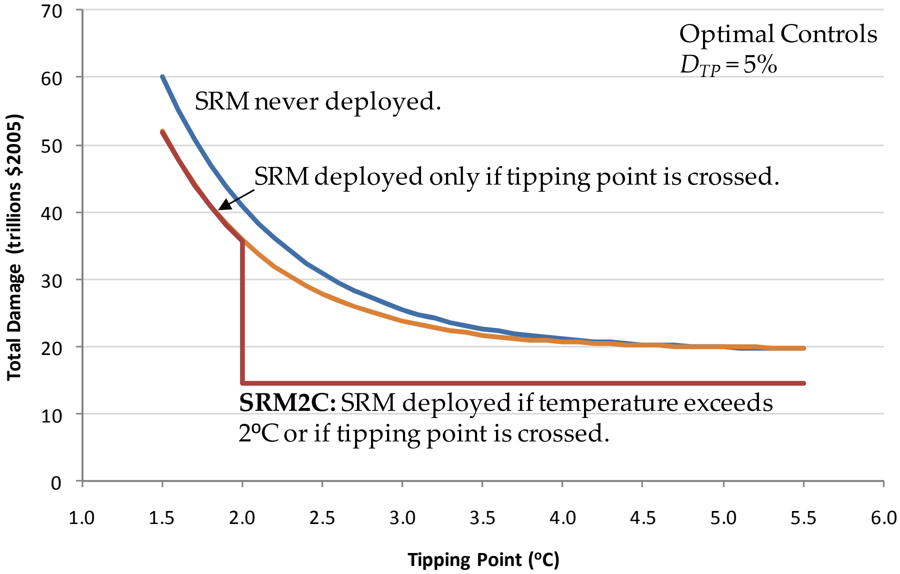

Figure 10: Expected total damages as a function of the tipping point location and conditions of SRM use.

The reduction in damage shown in Figure 10 is the option 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 Figure 11, again under OC with damages of 5% GWP. We have also added the values of deploying at 3.0°C (SRM3C), 4.0°C (SRM4C), and 5.0°C (SRM5C). We see that holding SRM until a tipping point has been crossed, the lower line, is worth $8 trillion if the tipping point is 1.5°C and that it is almost worthless if the tipping point is beyond about 4.5°C. Deploying SRM earlier adds additional value. For example, SRM2C is worth about $26 trillion 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.

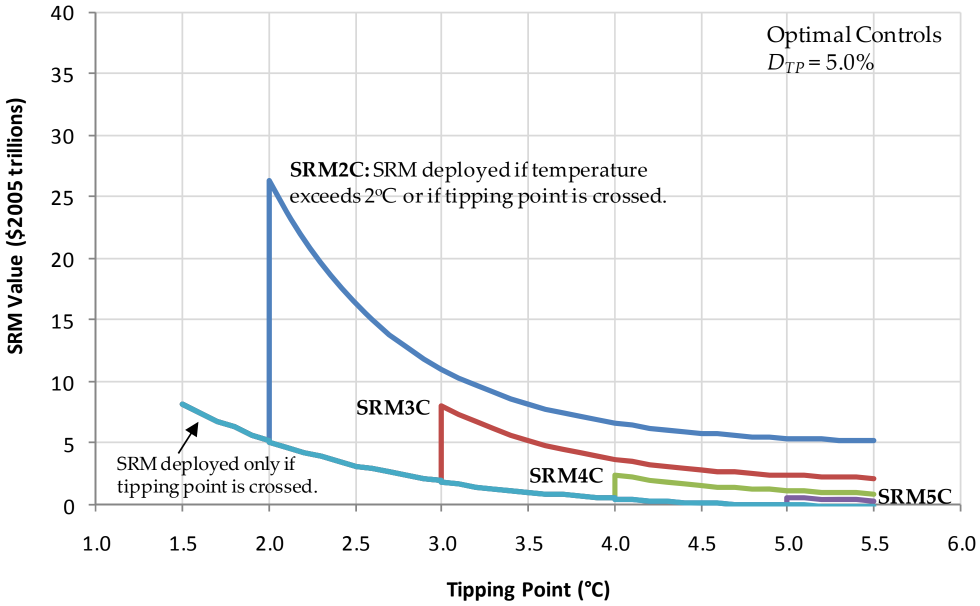

Figure 11: The value of SRM under OC as a function of the tipping point location and conditions of SRM use.

Figure 12 contrasts the value of SRM under NC and OC and for tipping point damages of 2.5% and 5.0%. The figure depicts the results of two strategies (NC or OC) and tipping point damages (5.0% or 2.5%). The SRM values under NC are even higher than OC because the rate and degree of warming are greater. Lowering the damage caused by crossing a tipping point lowers SRM value. However, the values are still quite robust. For example, even under OC with 2.5% damages (the lower right-hand figure), SRM2C could be worth $15 trillion. SRM3C is worth at least $2 trillion under these conditions. Of course, deferring SRM until a tipping point is crossed significantly lowers value. An example is the case of NC and 5% damages. If the tipping point is 2°C and SRM is deferred until this point is crossed rather than deploying it early, an additional $26.6 trillion in damages are incurred ($37.4 -$10.8).

Thus, we conclude an SRM capability is extremely valuable. It offers the possibility of quickly cooling the earth, thereby avoiding trillions of dollars in damages. 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 2009; Keith et al. 2010).

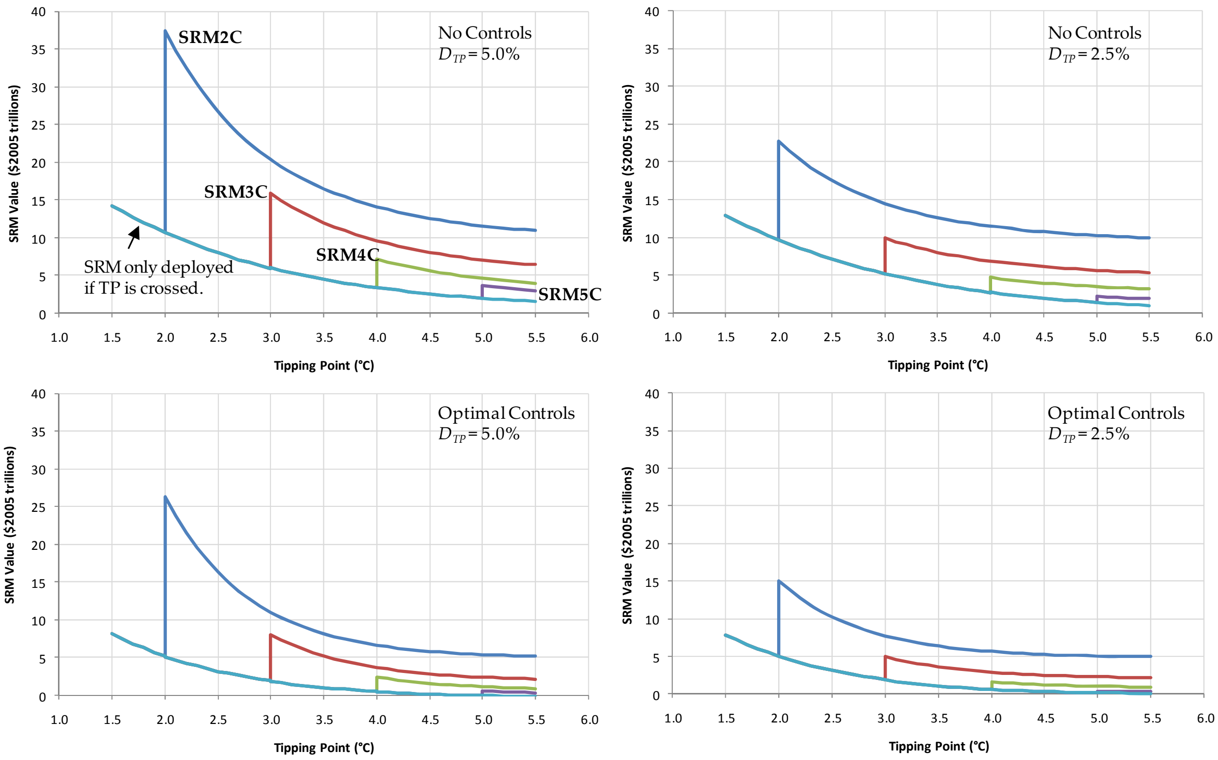

Figure 12: Sensitivity of SRM value to emissions control regime and damage level.

6.6 The Potentially Low Cost of Managing Tipping Points with SRM

As discussed in §5.1, managing tipping points with emissions reduction is likely to be quite expensive. In this section, we compare this cost to the cost of managing this risk with SRM. We find that these later costs are much more attractive.

The benefit estimates discussed above, include the cost of SRM deployment, based on the cost assumptions detailed in §6.4. These present-value costs are tabulated in Table 5. Comparing these costs to those in Table 4 illuminates the potential dominance of SRM over emissions reductions in addressing tipping points. For a cost of $0.092 trillion ($92 billion), SRM holds temperatures under 2.0°C when following a policy of NC. Under OC, the cost to hold temperatures to 2.0°C is only $0.053 trillion ($53 billion). Table 4 indicated that spending $1 trillion (10 to 20 times more) on strict emissions reductions, such as L2.0C, only reduces the *probability* of exceeding 2.0°C by a *few* percent. Thus, SRM may be better suited to addressing the significant risk of tipping points. SRM can act more quickly on the climate system and its direct costs appear to be very low.

Table 5: Present value of direct SRM costs to hold specified temperature limit

Temperature Limit (°C)	Cost of SRM Deployment (trillions 2005$)	
	NC	**OC**
2	0.092	0.053
3	0.026	0.010
4	0.008	0.002
5	0.003	0.001

6.7 SRM Usage Intensity

As mentioned at the outset, we do not consider the possible indirect damages of SRM in our benefit estimates. To get a sense for how significant of this might be, in this section, we consider the scale of SRM intervention that would be required to achieve the temperature limits analyzed above. We find that, for at least through the end of this century, these interventions are less than our current intervention in the climate system, and by some measures, much less.

The analysis in §6.5 endogenously determined the amount of SRM needed to hold temperatures at a particular level so as to avoid significant climate damages. In this section, we report the quantity of SRM needed to achieve this. Figure 13 displays SRM usage profiles required to prevent temperature rise from exceeding 2.0°C under NC and OC. Since this is the most aggressive use of SRM we consider, these values represent upper limits. 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 sulfur 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 2007).

The line labeled Mean is the average amount of SRM required in each year. The P10 are the values such that there is only a 10% chance that more SRM than this would be required. There is a 90% chance that we would require more than the P90. 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. 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 at all until the next century.

Not to minimize these interventions, but rather to place them in perspective, we consider three comparisons: (1) Human 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 already injected into the atmosphere via the burning of fossil fuels. This suggests that we may be able to implement SRM with no net sulfur injections. For example, if we could inject 2% of the sulfur that we currently place in the troposphere into the stratosphere instead, the desired cooling may be achieved with no change in emissions quantity.

Required SRM usage to hold temperatures to 2.0^{o}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 22nd century. There is a 10% chance that more than about 2.75 W/m^2 would be required in 2100. This suggests that the use of SRM in conjunction with emissions controls may pay very large dividends. While OC are economically efficient in a deterministic setting, they run an 85% chance of exceeding 2.0^{o}C and a 54% chance of exceeding 3.0^{o}C (see Table 3). The use of SRM with OC allows the temperature increase to be held below 2.0^{o}C, for certain, at a much lower cost than L2.0C, which still has a 42% of exceeding 2.0^{o}C.

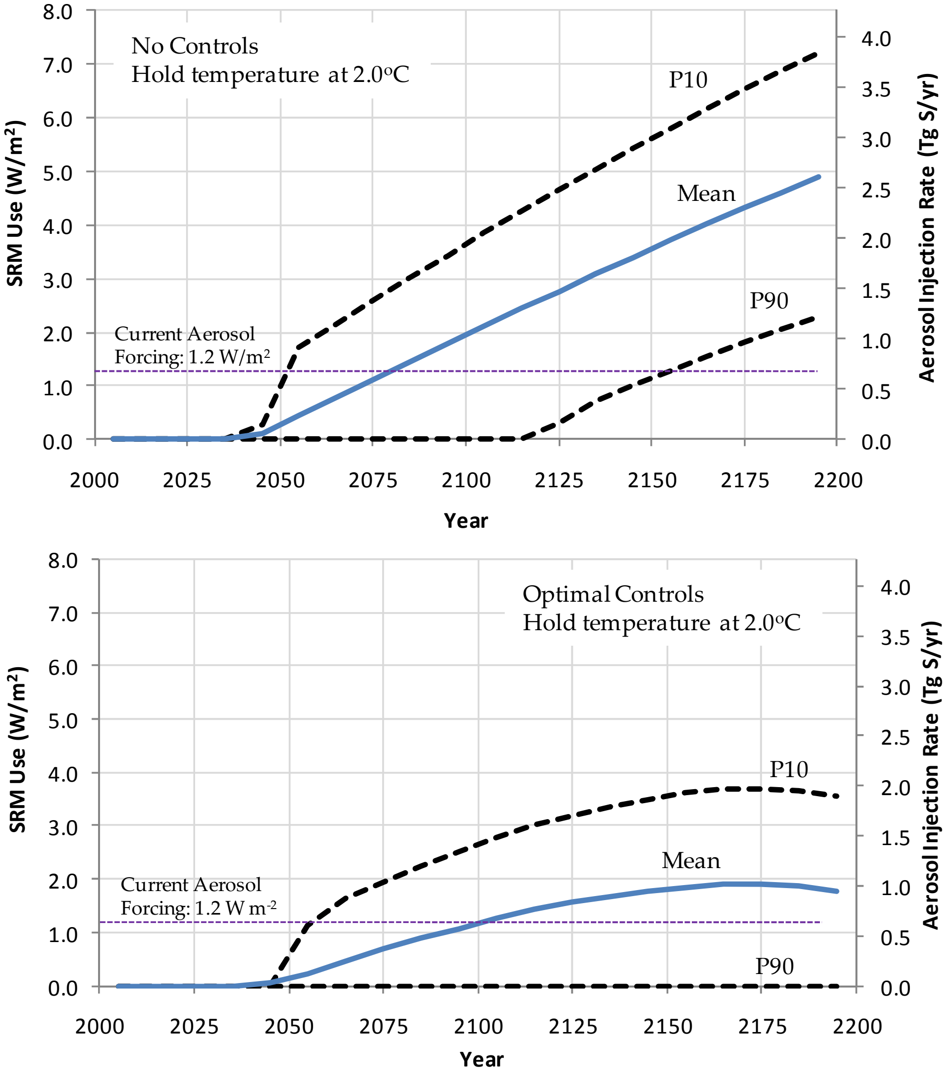

Figure 13: Required SRM usage to hold temperatures to 2.0°C under NC and OC.

Again, the ranges in Figure 13 are for holding temperatures to 2.0°C, our most aggressive case. Figure 14 displays the mean SRM usage required to hold temperature rise to 2.0°C, 3.0°C, or 4.0°C under NC and OC. We see that an average of 2 W/m^2 is sufficient to hold temperatures below 3.0°C for almost the next 150 years, and that is under NC. Holding temperatures below 4.0°C requires mean interventions that are between 0.7% and 2% of the sulfur that humans already inject into the atmosphere. Under OC, holding temperatures to 3.0°C or 4.0°C requires interventions that are about half as large as the SRM effect from current anthropogenic emissions (1.2 W/m²).

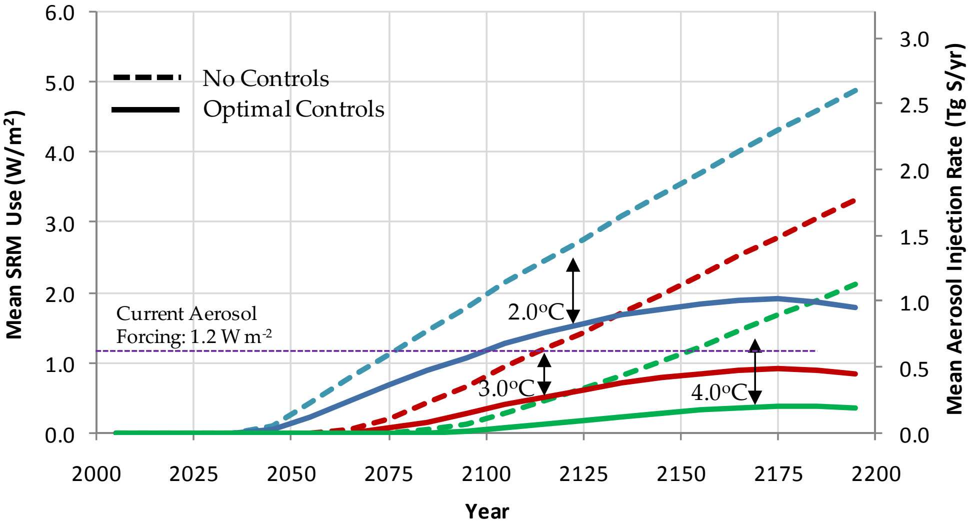

Figure 14: Mean SRM usage to hold temperatures between 2°C, 3°C, or 4°C under No Controls (dashed) and Optimal Controls (solid).

7 Policy Implications and Conclusion

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

- First, emissions reductions are unlikely to 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). This finding echoes those of other researchers who state that emissions reductions cannot reduce the risk of catastrophic change to *de minimis* levels at politically acceptable costs (Keller et al. 2005).
- Second, SRM holds the potential to avoid significant climate damages, with potential economic benefits in the tens of trillions of dollars. These benefits appear to be much larger than the costs of a research & development program (Bickel and Lane 2009; Keith et al. 2010). Thus, society should allocate research funding now to test the efficacy and safety of SRM.
- Third, deferring SRM until a tipping point is upon us may be politic, but runs the very real 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. How do we know that we are not already facing an emergency? 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, possibly perfect, early detection system.

- Fourth, the scale of the required intervention may be less than has been portrayed by members of the media, with talk of "blotting out the sun" (Svoboda 2008) and cartoons showing dirigibles spewing sulfates against a blood-red sky (Wood 2009). For example, under DICE Optimal Controls, the mean SRM intervention required to hold temperatures at 2.0^{o}C is less than 1 W/m^2 for almost the next 100 years. This is less than the current negative forcing of anthropogenic aerosols as estimated by the IPCC. If this was achieved with sulfur aerosol injections, the injection rate would be less than 2% of current sulfur emissions.

7.1 Drivers of SRM Value

As we have demonstrated, several aspects of climate change increase the value of SRM. These include:

- **Pessimism regarding emissions reductions.** The more pessimistic one is about the prospects for emissions reductions, the more valuable SRM is. This follows since a failure to reduce emissions will move us more quickly towards tipping points, if they exist.
- **Tipping points are near.** The closer we are to a tipping point, the more important SRM becomes. In fact, if a tipping point is close at hand, emissions reductions simply cannot reduce this risk to an acceptable level.
- **Tipping points are catastrophic.** If crossing a tipping point could lead to catastrophic damages, then SRM will be immensely valuable. Likewise, if the climate system exhibits significant hysteresis, then deploying SRM to prevent crossing a tipping point will be even more important.
- **Significant climate uncertainty.** The more uncertain we are about important climate-system parameters, such as the climate sensitivity, the more valuable SRM will be. For example, if we cannot rule out climate sensitivities of 8ºC, how can we not investigate the possibility of intervening to prevent this degree of warming?

7.2 Areas for Future Policy and Climate Research

Our results also suggest several important areas of research. First, we need to better understand the location and severity of climate tipping points. As our results make clear, the ability to detect a tipping point before crossing it is critical. Second, the degree of hysteresis that exists in the climate system is important and will drive the decision of when to deploy SRM. If the hysteresis is large, then we would be wise to stay far away from the threshold. Third, research into how an SRM program would be deployed needs to be undertaken. For example, how closely can we manage temperature rise with SRM? If our ability is limited to say 0.5ºC or 1.0ºC, this too will need to be considered in the deployment decision.

In previous work, Keller et al. (2004) studied the use of emissions reductions to manage the risk of THC collapse. They found that a strategy based solely on reducing emissions allows the THC to collapse when it is no longer "optimal" to maintain it. Thus, analysts should begin developing models that include SRM as a policy option. Restricting the set of possible responses to emissions reductions runs the risk of creating a *fait accompli* in the public's eyes. They might (reasonably) surmise that emissions reductions are too expensive and cannot eliminate the risk of catastrophic changes or will allow these changes to take place in the end, so why bother? A mixed strategy would leverage the ability of emissions reductions to reduce the risk of large-probability events and rely on SRM to ensure against low-probability/high-consequence events.

In the end, however, we will remain uncertain of what the climate has in store for us. Rather than debating how much damage is caused by crossing a tipping point, where it is, and whether our probability distributions are correct, perhaps we should develop a backup plan to avoid potentially catastrophic changes.

7.3 Policy Objections to SRM

While, we believe the arguments detailed in this paper make a strong case for research into SRM, several objections have been raised. We discuss some of these below.

The first is that SRM may have unintended consequences and the technology does not yet exist. This is true. However, the same can be said of emissions reductions, and yet they are considered a viable policy option. Emissions reductions may result in a global trade war, create opportunities for pork-barrel politics, produce carbon accounting rules that encourage the destruction of forests or the use of environmentally unfriendly bio-fuels (Lane 2006; Lane and Montgomery 2008; Bickel and Lane 2009). These indirect effects should be included in any analysis of the costs of emissions controls. Even if we could deploy emissions reductions "optimally," we simply do not know how to reduce global emissions by 80% at a cost society is willing to bear. Twenty years of diplomatic talk has failed to reduce emissions in the slightest. Do we want to place all of our eggs in this one basket?

Another objection to SRM is that it will require us to decide upon the "optimal temperature" (i.e., whose hand will be on the thermostat?), as if this issue does not affect emissions reductions as well. Quite to the contrary, SRM could enable countries to agree on a *maximum* temperature change, which could be much easier. This is difficult in the case of emissions controls because we cannot directly control temperature by changing emissions. Therefore, negotiations have focused on concentration targets, such as a doubling of CO_2 levels. Yet, agreeing to this concentration target brings an 80% chance that the maximum temperature change will be somewhere between 1.5°C and 5.0°C and a 10% chance of warming in excess of 5.0°C (this is the climate sensitivity; see Figure 3). Such uncertainty makes it difficult for some to understand and explain the benefits of emissions reductions.

It has also been suggested that SRM may have negative side effects, that it does not address ocean acidification, and, that it would cause additional damages if it were aborted prematurely. These points are certainly true, and we have made no effort to quantify the first and third effects, given the lack of research in this area. We do note, however, that (1) the perspective we have taken in this paper is that society has determined that we are facing a climate emergency and must act and (2) our benefit estimates are on the order of tens of trillions of dollars. In order to change the results, any indirect effects would have to reach this magnitude (in present value), which is the magnitude of climate change itself. We *do* include the fact that SRM does not address ocean acidification by *not* crediting SRM with doing anything about it. Addressing ocean acidification is a benefit of other technologies, not a cost of SRM.

Finally, some counter that researching SRM will lessen our resolve to pursue emissions reductions and thus it should be removed from consideration. This "burnt bridges" strategy is particularly objectionable. First, it reveals its proponents as advocates who have decided that (steep) emissions reductions are the best policy. The refusal to allow society to consider alternative approaches is non-scientific and may lead the public to wonder if other information has been selectively withheld from their view. Second, it is potentially tragic. As discussed above, emissions reductions simply cannot completely protect us from the possibility of catastrophic climate change. Advocates of a policy focused solely on emissions reductions are placing billions of individuals and thousands of ecosystems at risk. Third, it keeps SRM in play simply because it has not been proven infeasible. If SRM is a bad idea it would be best to learn this as soon as possible. Otherwise, we may hold out false hope. Finally, how do we know that some combination of SRM and emissions reductions (and other responses) is not the most economic and lowest-risk strategy?

7.4 Conclusion

As we noted throughout, in this paper we have assumed that society has concluded it faces a climate emergency and must deploy SRM. In this sense, SRM may be the lesser of two evils. As noted by BL:

> "The choice is not between a climate-engineered world and a world without climate change; rather, it is between the former and the world that would prevail without climate engineering."

If climate scientists are correct and we are running a significant risk of catastrophic damages, how can we not research and possibly deploy technologies that may prevent these changes? A failure to deploy SRM in a situation that would prevent tens of trillions of dollars in climate damages, the extinction of ecosystems, and the associated human death and suffering would represent dangerous noninterference in the climate system.

Acknowledgements

The author thanks the American Enterprise Institute for Public Policy Research for supporting this work. The author also thanks Lee Lane for his comments on a draft of this paper.

Appendix A1: Relevant DICE Equations

This appendix highlights the DICE equations that are directly relevant to our current 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

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

$M_{AT}(t)$ is the atmospheric concentration of CO$_2$ at the beginning of period t and $M_{AT}(1750)$ is the preindustrial atmospheric concentration of CO$_2$, taken to be the concentration in the year 1750. η is the radiative forcing for a doubling of CO$_2$ concentrations and is assumed to be 3.8

W/m². $F_{EX}(t)$ 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:

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

$E(t-1)$ is the mass of carbon that enters the atmosphere due to land-use changes. $M_{UP}(t-1)$ is the mass of carbon contained in the biosphere and upper ocean at the beginning of period *t* – 1. ϕ_{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,

$$T_{AT}(t) = T_{AT}(t-1) + \xi_1 \left[F(t) - \xi_2 T_{AT}(t-1) - \xi_3 \left[T_{AT}(t-1) - T_{LO}(t-1) \right] \right]. \tag{3}$$

ξ_2 is the climate feedback parameter, which is equal to the radiative forcing for a doubling of CO₂ concentrations, η, divided by the temperature increase for a doubling of CO₂, ΔT_{2X}. ΔT_{2X} is the climate sensitivity, which DICE assumes is 3°C. 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

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

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 Equation (4) is that damage is not a function of the rate of temperature change, which could be important in the case of SRM.

Appendix A2: Changes made to DICE

We begin by modifying DICE's radiative forcing equation (Equation (1)) to allow for inclusion of an additional external forcing component, *SRM*(*t*), which we take to be the negative forcing due to solar radiation management. The radiative forcing (W/m²) at the tropopause for period *t* is now

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

$SRM(t)$ is the change in the radiative forcing in period *t* due to SRM. Our modeling of SRM is consistent with DICE's treatment of aerosols. In addition, Andronova and Schlesinger (2001) incorporate anthropogenic aerosol emissions into a more sophisticated climate model in a similar fashion.

We assume that the climate system may contain a tipping point temperature beyond which damages are discontinuously and permanently affected. To ease explanation, we assume there is only one such tipping point, while acknowledging that multiple thresholds may exist. To capture this feature, we modify DICE's damage function (Equation (4) with $\psi_1 = 0$) as shown below

$$D(t) = \psi_2 T_{AT}(t)^2 + 1_{TP}(t) D_{TP} \,. \tag{6}$$

$1_{TP}(t)$ 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 (discussed above), we assume this damage is permanent. Or, at least that it lasts through the end of the study period.

References

Andronova, Natalia G. and Michael E. Schlesinger. 2001. Objective estimation of the probability density function for climate sensitivity. *Journal of Geophysical Research* **106**(D19) 22,605-22,611.

Bickel, J. Eric and Lee L. Lane. 2009. An analysis of climate engineering as a response to climate change, Copenhagen Consensus Center, Copenhagen. To appear in *Copenhagen Consensus Recommendations for COP-15*, Bjørn Lomborg (ed). Cambridge University Press: Cambridge, UK. http://fixtheclimate.com/

Borenstein, S. 2009. Obama looking at cooling air to fight warming. *The Associated Press*, April 8.

Broder, John and Matthew L. Wald. 2009. Big science role is seen in global warming cure. *New York Times*, February 12, 2009, A24.

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

Global Carbon Project. 2008. *Carbon budget and trends 2007*, www.globalcarbonproject.org.

Holland, Marika M., Cecilia M. Bitz and Bruno Tremblay. 2006. Future abrupt reductions in the summer arctic sea ice. *Geophysical Research Letters* **33**(23) L23503.

IPCC. 2005. *Guidance notes for lead authors of the IPCC Fourth Assessment report on addressing uncertainties*.

IPCC. 2007. Summary for policymakers. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis et al. (eds.), *Climate change 2007: The physical science basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK and New York, NY, USA.

Keith, David W., Edward Parson and M. Granger Morgan. 2010. Research on global sun block needed now. *Nature* **463**(28) 426-427.

Keller, Klaus, Benjamin M. Bolker and David F. Bradford. 2004. Uncertain climate thresholds and optimal economic growth. *Journal of Environmental Economics and Management* **48** 723-741.

Keller, Klaus, Matt Hall, Seung-Rae Kim, David F. Bradford and M. Oppenheimer. 2005. Avoiding dangerous anthropogenic interference with the climate system. *Climatic Change* **73** 227-238.

Lane, Lee. 2006. *Strategic Policy Options for the Bush Administration Climate Policy*. AEI Press: Washington, DC.

Lane, Lee and J. Eric Bickel. 2009. Solar radiation management and rethinking the goals of COP-15. Copenhagen Consensus Center: Copenhagen. http://fixtheclimate.com/

Lane, Lee and David Montgomery. 2008. *Political institutions and greenhouse gas controls.* AEI Center for Regulatory and Market Studies: Washington, DC.

Latham, John, Philip Rasch, Chih-Chieh Chen, Laura Kettles, Alan Gadian, Andrew Gettleman, Hugh Morrison, Keith Bower and Tom Choularton. 2008. Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds. *Philosophical Transactions of The Royal Society A* **366** 3969-3987.

Lenton, T. M. and N. E. Vaughan. 2009. The radiative forcing potential of different climate engineering options. *Atmos. Chem. Phys. Discuss.* **9** 2559-2608.

Lenton, Timothy M. Hermann Held, Elmar Kriegler, Jim W. Hall, Wolfgang Lucht, Stefan Rahmstorf and Hans Joachim Schellnhuber. 2008. Tipping elements in the earth's climate system. *PNAS* **105**(6) 1786-1793.

Lindsay, R. W. and J. Zhang. 2005. The thinning of arctic sea ice, 1988-2003: Have we passed a tipping point? *Journal of Climate* **18**(22) 4879-4894.

McInerney, David and Klaus Keller. 2007. Economically optimal risk reduction strategies in the face of uncertain climate thresholds. *Climatic Change* **91** 29-41.

McInerney, David, Robert Lempert and Klaus Keller. 2009. What are robust strategies in the face of uncertain climate threshold responses? Under review at *Climatic Change*.

Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver and Z.-C. Zhao. 2007. Global climate projections. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis et al. (eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report on the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK and New York, NY.

National Academy of Sciences,. 1992. *Policy Implications of Greenhouse Warming*. National Academy Press: Washington, DC.

Nordhaus, William D. 1994. *Managing the global commons: The economics of climate change*. The MIT Press: Cambridge, MA.

Nordhaus, William D. 2008. *A question of balance*. Yale University Press: New Haven, CT.

Nordhaus, William D. and Joseph Boyer. 2000. *Warming the World: Economic Models of Global Warming*. The MIT Press: Cambridge, MA.

Novim Group. 2009. Climate engineering responses to climate emergencies. Santa Barbara, CA.

Parry, M. L., O. F. Canziani, J. P. Palutikof and Co-authors. 2007. Technical summary. In: M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson (eds.), *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK, pp. 23-78.

Pattyn, Frank. 2006. Grantism: An Excel model for Greenland and Antarctic ice-sheet response to climate changes. *Computers and Geosciences* **32** 316-325.

Pielke, Roger A., Jr. 2009. An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy. *Environmental Science & Policy* **12**(3) 216-225.

Rasch, Philip J., Paul J. Crutzen and Danielle B. Coleman. 2008. Exploring the geoengineering of climate using stratospheric sulfate aerosols: The role of particle size. *Geophysical Research Letters* **35** L02809.

Robock, Alan, Allison Marquardt, Ben Kravitz and Georgiy Stenchikov. 2009. The practicality of geoengineering. *Under Review at Geophysical Research Letters*.

Salter, Stephen, Graham Sortino and John Latham. 2008. Sea-going hardware for the cloud albedo method of reversing global warming. *Philosophical Transactions of The Royal Society A* **366** 3989-4006.

Stern, D. I. 2005. Global sulfur emissions from 1850 to 2000. *Chemosphere* **58** 163-175.

Stocker, Thomas F. 2003. Changes in the global carbon cycle and ocean circulation on the millennial time scale. In: X. Rodó and F. A. Comín (eds.), *Global Climate: Current Research and Uncertainties in the Climate System*. Springer-Verlag, Berlin, Germany, pp. 129-152.

Svoboda, Elizabeth. 2008. The sun blotted out from the sky. *Salon* (April 2, 2008) http://www.salon.com/news/feature/2008/2004/2002/geoengineering/.

The Royal Society. 2009. *Geoengineering the climate: Science, governance and uncertainty.* London. http://royalsociety.org/geoengineeringclimate/

Tol, Richard S. J. 1998. *Potential slowdown of the thermohaline circulation and climate policy.* Institute for Environmental Studies: Vrije Universiteit, Amsterdam.

Trenberth, Kevin E., John T. Fasullo and Jeffrey T. Kiehl. 2009. earth's global energy budget. *Bulletin of the American Meteorological Society* **90**(3) 311-323.

UNFCC. 1992. *Framework convention on climate change.* Palais des Nations: Geneva.

Wood, Graeme. 2009. Re-engineering the earth. *The Atlantic* July/August http://www.theatlantic.com/doc/200907/climate-engineering.