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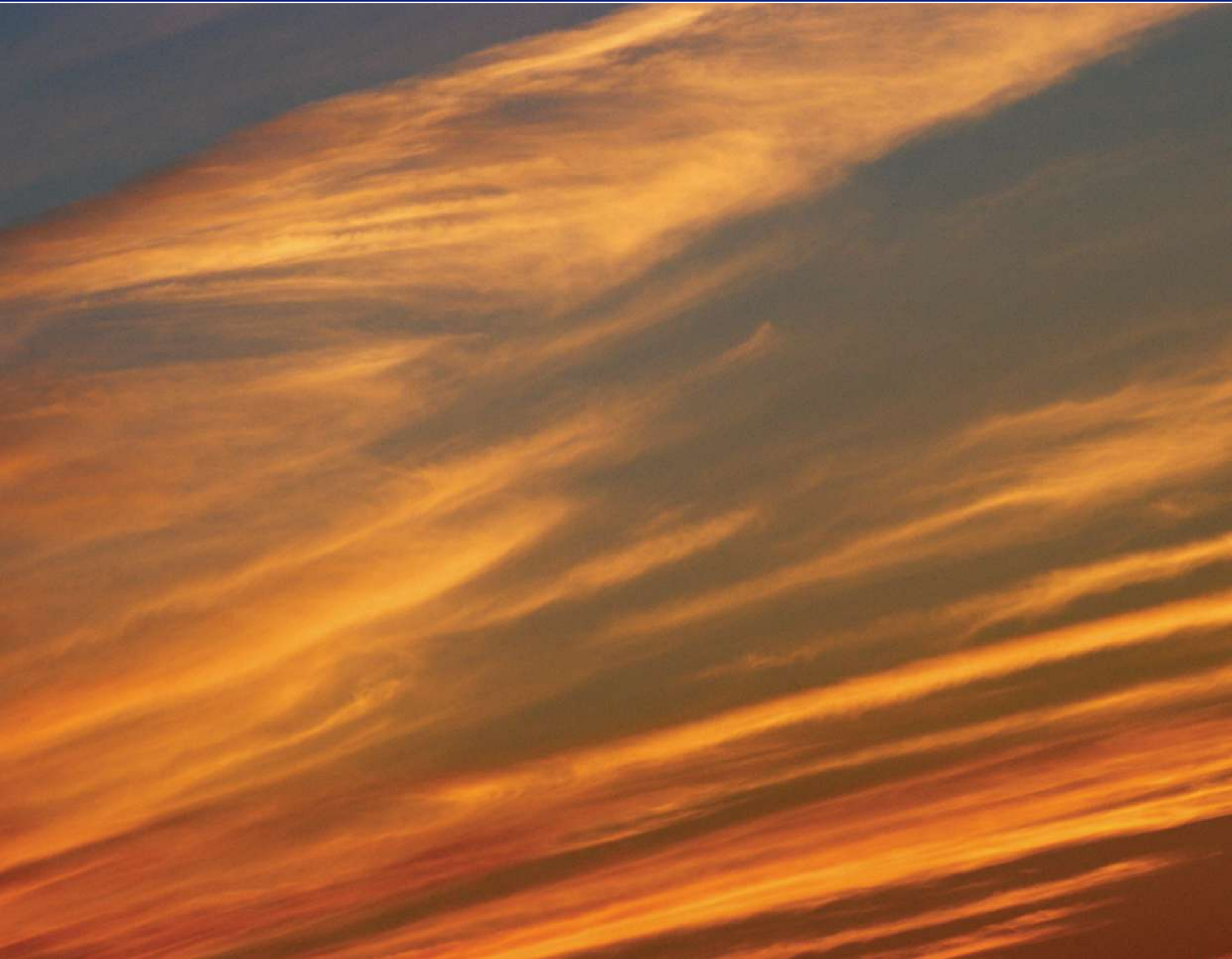

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An Analysis of Climate Engineering as a Response to Climate Change

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ABSTRACT

This paper offers a preliminary and exploratory assessment of the potential benefits and costs of climate engineering (CE). We examine two families of CE technologies, solar radiation management (SRM) and air capture (AC), under three emissions control environments: no controls, optimal abatement, and limiting temperature change to 2°C. Our analysis suggests that SRM offers potentially large net benefits, but that many important uncertainties remain. The near-term net benefits of AC appear to be much lower than those of SRM. However, we argue that both deserve to be investigated further.

In the case of SRM, we focus on two specific technologies: the injection of aerosols into the stratosphere and the increase of marine cloud albedo. We estimate direct benefit-cost (B/C) ratios of around 25 to 1 for aerosols and around 5000 to 1 for cloud albedo enhancement. Technological progress might significantly lower direct cost estimates of stratospheric aerosols and thus raise the expected benefits. Yet, large uncertainties remain about the science and engineering of actually deploying SRM. Only a substantial research program could resolve these uncertainties, but the very large potential net benefits of SRM offer strong *prima facie* evidence for including R&D on SRM as a part of any portfolio of climate policies during the next decade.

Therefore, we suggest that the Copenhagen Consensus allocate an average of approximately 0.3% of its $250 billion annual climate-change budget ($750 million per year) to SRM and AC research over the next decade. SRM is the higher priority, owing to its larger and earlier net benefit potential. This research program should explicitly focus on identifying possible side effects, especially those which might imply non-trivial costs.

We estimate that the benefit of a single watt per square meter of SRM results in almost a 35% decrease in climate damages and abatement costs (over $6 trillion) under an emissions control regime of optimal abatement. Furthermore, when considering only the impact on temperature, we show that a single watt per square meter of SRM has the same economic benefit as capturing and sequestering almost 65% of yearly CO_2 emissions, which, in conjunction with AC's significant costs, argues in favor of SRM in the near term.

In addition to quantitative benefit and cost estimates, we stress the potential importance of transaction costs and "political market failures." Some of these costs could be significant, but may be less so than with other strategies for coping with climate change.

COPENHAGEN CONSENSUS ON CLIMATE

The Copenhagen Consensus Center has commissioned 21 papers to examine the costs and benefits of different solutions to global warming. The project's goal is to answer the question:

"If the global community wants to spend up to, say $250 billion per year over the next 10 years to diminish the adverse effects of climate changes, and to do most good for the world, which solutions would yield the greatest net benefits?"

The series of papers is divided into Assessment Papers and Perspective Papers. Each Assessment Paper outlines the costs and benefits of one way to respond to global warming. Each Perspective Paper reviews the assumptions and analyses made within an Assessment Paper.

It is hoped that, as a body of work, this research will provide a foundation for an informed debate about the best way to respond to this threat.

CONTENTS

1 CONSIDERING CLIMATE ENGINEERING AS A RESPONSE TO CLIMATE CHANGE

1.1 Climate Change and Benefit-Cost Analysis

The task of this paper is to answer a question that has been posed as part of the Copenhagen Consensus (CC) exploration of climate policy. That question is:

> "If the global community wants to spend up to, say $250 billion per year over the next 10 years to diminish the adverse effects of climate changes, and to do most good for the world, which solutions would yield the greatest net benefits? – i.e. what are the costs and benefits of different viable climate interventions…given some reasonable assumptions about sensible policies for the rest of 21st century?"

To address this question, the authors agreed to summarize the existing literature regarding the costs and benefits of geoengineering, supplement these estimates where needed and feasible, and to provide benefit-cost ratios for at least two geoengineering alternatives. Based on this analysis, the current paper argues that some portion (0.3%) of the hypothetical $250 billion a year should be devoted to the task of researching and developing two geoengineering areas: solar radiation management (SRM) and air capture (AC). As the reader will see, we argue that more emphasis should be placed on SRM, but that AC merits some research support.

The reader should not interpret our focus on climate engineering as implying that other responses to climate change are unneeded. The proper mix and relative priority of various responses to climate change is in the purview of the expert panel, to which our paper is one input. The reader might also note that, with but one exception, every scenario considered in this paper is accompanied by greenhouse gas control measures.

The US Environmental Protection Agency describes geoengineering (GE) as "the intentional modification of Earth's environment to promote habitability" (EPA, 2009). Many experts prefer the term "climate engineering" (CE) as more accurately describing the most widely discussed current concepts of modifying climate to curtail harmful effects of global warming, and we will adopt this term.

Following the CC project framework, this paper applies benefit-cost analysis (BCA) to gain insight into the net economic benefits that society might achieve by deploying climate engineering. A finding that net benefits may be large, but are uncertain, suggests that society should devote some current resources to researching and developing this capacity. Some people object to BCA, and to CE, on what they regard as ethical grounds. Ethical conjectures are notoriously resistant to empirical falsification, and this paper will not attempt to join this debate. Instead, we adopt the viewpoint that climate-change policies, including the possible use of CE, should be designed to maximize the welfare of human beings over time. "Welfare" in this context includes the consumption of both market and non-market goods, such as environmental services (Nordhaus, 2008).

Other objections to BCA rest on more purely pragmatic grounds. BCA is often difficult to apply because either costs or benefits may be difficult, or maybe even impossible, to quantify with confidence. Analysts may be tempted to overlook or to assume away some of these hard-to-quantify factors in hopes of keeping the analysis tractable. To choose an example that this paper will address, BCA often ignores transaction costs, and a whole school of economics has grown up around the task of correcting the mistakes to which this simplification can sometimes lead (North, 1990). Transaction costs are, indeed, hard to quantify. The existing climate policy literature has made no attempt in this direction, and this paper will offer only a qualitative discussion of some salient points about the main issues. It suggests, however, that the transaction costs associated with SRM may be smaller than those that apply to some other climate strategies.

Likewise, we do not attempt to perform a probabilistic BCA, though one is clearly needed. We take this approach for two reasons. First, an important aspect of the CC project framework is ensuring a consistency among the papers, which is harder to maintain in a probabilistic setting. Second, the state of knowledge about both the benefits of CE and its costs is primitive. Even base case estimates for many important benefit and cost parameters are unknown. Thus, where the existing literature contains quantitative estimates, this paper will select what we regard as the best available. It will do so with the caution that today's estimates are very much subject to change. Where possibly important factors have not been quantified, this analysis will point to their nature and discuss their potential significance.

In sum, we adopt what we hope readers will regard as a pragmatic approach to BCA. As one economist has observed, "… everyone who urges a change in policy (or resists one) is at least implicitly comparing costs with benefits" (Cooper, 2000). Making the basis of this comparison more explicit seems, on principle, likely to facilitate a more reasoned discourse.

The Budget Constraint and the Assumption of "Sensible" Policies

At this point, the Copenhagen Consensus budget constraint does not play much of a role in the issues raised by CE. Currently, CE is a concept deserving, we believe, research and development. It is not ready for deployment. How much money should go into the concept's exploration depends in part on the results of the initial research. However, the rudimentary state of knowledge about the concept suggests that an investment of perhaps 0.3% ($750 million per year) of the global total proposed by the CC guidelines might be an appropriate average yearly expenditure for the first decade. As R&D progresses, and assuming that results were favorable, spending would increase from tens of millions of dollars in early years to the low billions of dollars. Extended large scale field tests might be needed for perhaps an additional five years. Thus, spending in the first decade would not approach the budget constraint, although deployment could involve costs in the tens to hundreds of billions.

The paper focuses on a BCA of deploying CE beginning in 2025. That choice rests on the proposition that the very large net benefits found in this analysis of CE make a convincing case for incurring upfront costs to research, to develop, and to demonstrate the concept. The paper, in this regard, does assume that future policies will be "sensible," in that it assumes that R&D of a concept promising large net benefits would lead, at some point, to an effort to realize those benefits in practice.

However, the analysis also considers some policies that are not sensible - or perhaps one should say that it looks at some policies that do not appear to be optimal within the framework of a somewhat blinkered BCA. The paper considers how these options might affect the performance of CE, and it looks briefly at how CE might affect the results of a few badly structured greenhouse gas control regimes. Some consideration of non-optimal policies can offer useful insights about how CE might function in the real world in which policy choices are rarely optimal (North, 1990).

1.2 Description of Human-Induced Climate Change

Greenhouse gases (GHGs) in Earth's atmosphere cause the planet's surface to be about 30°C warmer than would otherwise be the case (Stocker, 2003). These gases allow the passage of short-wave radiation (sunlight), but absorb long-wave radiation (heat) and radiate a fraction of it back to the Earth's surface (Trenberth et al., 2009). This fact has been well-established for a very long time.

It is equally clear that human activities can add to the GHG stocks in the Earth's atmosphere. The burning of fossil fuels, deforestation, and agriculture and animal husbandry are all practices that have this effect (IPCC, 2007). All else being equal, although all else may not be equal, higher GHG concentrations will raise global mean temperatures (IPCC, 2007).

The policy implications of this relationship, though, remain far from clear. Hard to predict demographic and economic trends will influence future emissions. Technologic change is also powerful driver of emissions, and its future direction and pace are still more opaque than are those of population and output. How well or poorly will societies adapt to climate change? The answer remains in doubt, but it will greatly affect the size of the costs and benefits that societies will experience.

The state of climate science compounds the uncertainties (IPCC, 2007). How an increment of GHG will impact future temperature remains the subject of lively dispute. Man-made GHG emissions may interact in poorly understood ways with clouds, eco-systems, ocean currents, chemical cycles, and myriad other factors. These interactions may produce non-linear effects. Some feedback loops may amplify the warming impetus of larger GHG stocks. Some may dampen it. Science understands some of the interactions well, but many remain murky.

Even more doubts shadow predictions of what to expect from whatever warming does occur. Some experts believe that the climate system includes tipping points at which temperature, or other factors, may generate rapid and potentially very destructive changes. Where these tipping points may lie, how many (or few) of them there may be, whether they are near or far, what happens if they are crossed – all these questions are unanswered.

The trajectory of GHG emissions also depends on future policy choices by many nation-states and how their policies evolve. On this score, the historical record is clear:

> "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 [carbon dioxide], 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."(Lane and Montgomery, 2008)

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).

Thus, twenty years of protracted diplomatic talk and laborious scientific study have so far failed to move the needle on emission rates. During this period, greenhouse gas output has fallen in some countries, but, where such declines have occurred, "underlying changes in economic structure may have played a bigger role than climate policy" (Lane and Montgomery, 2008). For example, most Kyoto Protocol signatories are failing to reduce emissions, much less meet their targets (UNFCCC, 2009). The reductions that were achieved were heavily concentrated in Central and Eastern Europe, whose economies contracted and were restructured after the fall of the Soviet Union (UNFCCC, 2008). The overall trend remains clear, and the prospects daunting.

1.3 Three Aspects of GHG Emissions Cause Concern

GHG emissions may actually cause three quite distinct kinds of problems. These problems differ in the likelihood of their occurrence, their probable timing, and the incidence of their costs and benefits.

Gradual Climate Change

Gradual warming is likely to unfold over long periods of time, but its pace may vary from decade to decade. The process is likely to bring both benefits and costs. Benefits will include some higher crop yields from longer growing seasons and CO_2 fertilization. Mortality from cold would be likely to fall, as would heating costs. At the same time, gradual warming will impose costs. Some crop yields will fall, sea levels will rise, some storms may grow in intensity, more intense heat waves will occasion health problems and cooling costs, and in some cases the range of tropical diseases may spread. While societies will adapt, as they have to prior climate changes, adaptation will often not be free. Many poorer societies currently lack the human and physical capital required to make the needed changes. Some valuable unmanaged eco-systems may also fall short on adaptive capacity.

Geographically, the incidence of costs and benefits will vary. Benefits are likely to be concentrated in higher latitudes, whereas most costs are likely to appear in climates that were warmer to begin with. Over time, though, even in regions with initially cooler temperatures, costs will climb relative to benefits. Nonetheless, in the midst of these changes, some positive, some negative, much of the industrial sector is likely to be unaffected. The pace of economic growth is generally expected to outrun that of gradual climate change (Schelling, 2002). Thus, if climate changes gradually, the harm that it could occasion would take place in the context of a growing global economy.

Rapid Climate Change

Rapid high-impact climate change might occur relatively swiftly and could produce very large social costs. The timing and probability of such change are speculative. However, the risk cannot be ruled out. One current worry is that man-made warming could trigger large-scale methane release from the Arctic and sub-Arctic tundra (Corell et al., 2008). Methane, itself, is a powerful greenhouse gas. Hence, man-made warming might unleash a self-reinforcing process. This warming might, in turn, accelerate the melting of the Greenland and Antarctic ice sheets. The latter would hasten the rise in sea levels, possibly doing serious economic harm to coastal cities. Other speculation has focused on major shifts in the pattern of ocean currents. Such a shift might reorganize the distribution of temperatures and precipitation.

Compared to gradual climate change, rapid change scenarios promise little upside (Barrett, 2007a). The mere fact that a change happens rapidly is likely to raise the costs of adapting to it, and rapid change is often assumed to be quite destructive, even though its probability is low and highly uncertain (Weitzman, 2007).

Ocean Acidification

Finally, the ocean becomes more acidic as it absorbs CO_2 from the atmosphere (Royal Society, 2005). Some studies suggest that, over time, this process could disrupt marine eco-systems and perhaps cause economic harm (Royal Society, 2005). This risk, whatever its severity, is not strictly-speaking climate change, but it is another aspect of CO_2 discharges.

Acidification and warming are likely to interact. Acidification is believed to weaken the ability of coral reefs to recover from bouts of bleaching caused by warm ocean temperatures (Kleypas et al., 2006). Corals are productive and economically valuable, and acidification might also harm other species near the base of the ocean food chain. The severity of the problem is poorly understood at the moment, but is causing concern among some scientists.

The uncertain state of knowledge about acidification greatly complicates the task of formulating an efficient policy response to it. At least some analysis suggests that even the most severe GHG controls might fail to halt the destruction of most coral reefs. The CO_2 already in the atmosphere could cause enough acidification to destroy all (or most) of the existing reefs (Cao and Caldeira, 2008). Conversely, novel geoengineering technologies beyond the scope of this paper might be able to reverse acidification at least in some areas (Rau et al., 2007). At this point, then, acidification appears to be a potentially important matter, but its relevance to CE remains doubtful. SRM does not address ocean acidification, and, accordingly, our BCA gives SRM *no* credit for doing anything about it.

1.4 Time Scales

CO_2, once in the atmosphere, will remain there for a century or more. Attempts to abate GHG emissions are also subject to lengthy time lags. Major technological changes often take a long time to mature, and new technology is often slow to disseminate globally (Edgerton, 2007). Electrification of the global economy has been in train for over one hundred years and is still incomplete. Electrification was spurred forward by the large net benefits that accrued to those investing in it.

GHG controls will demand still more far-reaching changes in technology. Developing much of that technology, according to Secretary of Energy Steven Chu, must await the appearance of multiple major breakthroughs in basic science (Broder and Wald, 2009). Effective GHG controls, moreover, will require nearly world-wide efforts (Jacoby et al., 2008). The need for such wide-ranging change is likely to extend the amount of time that the process will require. That many low-GHG technologies cost more than those they seek to replace will further delay their spread. By inference, new laws and regulations will have to be adopted before such technologies can gain acceptance. A great deal of time may, therefore, separate the onset of serious efforts to limit emissions and the actual stabilization of climate.

This potential lag creates tension between the risk of rapid climate change and the slow speed with which GHG controls can take effect. Steep GHG cuts are substantially more costly that gradual ones (Richels et al., 2004). Yet, should it appear that a tipping point was imminent, controls might do little to stabilize the situation.

1.5 Climate Engineering

With these challenges as a backdrop it is easy to grasp why proposals to seriously study climate engineering are gaining adherents. Both the National Academy of Sciences in the US and the Royal Society in Britain are exploring the concept. The American Meteorological Society is also evaluating it. Such prominent scientists as Edward Teller, Paul Crutzen, Ralph Cicerone, Alan Robock, and Tom Wigley have highlighted the need for study, and John Holdren, President Obama's new science advisor, has recently said, "It's [climate engineering] got to be looked at" (Borenstein, 2009). Economists like Scott Barrett, William Nordhaus, Thomas Schelling, and Lawrence Summers have also suggested further exploration (Lane and Montgomery, 2008; Barrett, 2007b; Summers, 2007).

Solar Radiation Management

Types of SRM Options

SRM aims at offsetting the warming caused by the build-up of man-made GHGs in the atmosphere by reducing the amount of solar energy absorbed by the Earth. As discussed above, greenhouse gases in the atmosphere absorb long-wave radiation (thermal infrared or heat) and then radiate it all directions—including a fraction back to Earth's surface. This creates an energy imbalance and rising temperatures. SRM does not attack the underlying cause of the warming, higher GHG concentrations. Rather, it seeks to reflect back into space a small part of the Sun's incoming short-wave radiation. In this way, temperatures are lowered even though GHG levels are elevated. At least some of the risks of global warming can, thereby, be counteracted (Lenton and Vaughan 2009).

Reflecting into space 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 pre-industrial levels of greenhouse gases (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 (Lane et al., 2007).

Several concepts have been proposed for accomplishing SRM:

> "Shortwave geoengineering proposals … start with reflecting away (or shading out, as seen from Earth) a fraction of incoming solar radiation by placing objects in a solar orbit, e.g. at the inner Lagrange point (L1) (Angel, 2006). Alternatively, sunshades could be placed in an Earth orbit (NAS, 1992; Pearson et al., 2006). Once solar

radiation enters the atmosphere, its reflection back to space could be enhanced by adding sulphate aerosol (Crutzen, 2006) or manufactured particles (Teller et al., 1997, 2002) to the stratosphere. Adding such aerosols to the troposphere (NAS, 1992) has been ruled out due to negative impacts on human health, the greater loading required than the equivalent intervention in the stratosphere, and the need for multiple injection locations (Crutzen, 2006; MacCracken, 2006). However, increasing the reflectivity of low level marine stratiform clouds by mechanical (Latham, 1990) or biological (Wingenter et al., 2007) generation of cloud condensation nuclei (CCN) is being considered. Finally, the reflectivity of the Earth's surface could be increased, with recent proposals focused on the land surface, including albedo modification of deserts (Gaskill, 2004), grasslands (Hamwey, 2007), croplands (Ridgwell et al., 2009), human settlements (Hamwey, 2007), and urban areas (Akbari et al., 2008)." (Lenton and Vaughan, 2009)

The various SRM options differ importantly in the scale of their promise and in the range of their possible use. For example, none of the concepts for modifying the albedo of the Earth's surface represents a global level solution. Then too, objects on the Earth's surface get dirty, raising maintenance costs. There is also a risk that many of these options might disrupt surface eco-systems. Surface level approaches may still be locally useful as a counter to the urban heat island effect. Hence, they may become, niche technologies, and on that basis may warrant further study. They cannot, however, offer large net benefits on a global scale. This paper will, therefore, address the sunshade, stratospheric aerosols and marine cloud whitening at greater length in §2. It does so because these concepts might be able to offset warming on a global scale.

SRM and Institutions

Compared to GHG control options, SRM involves no infringement of economic freedom. An observation recently applied to AC applies at least equally to SRM. "…technological fixes do not offer a path to moral absolution, but to technical resolution. Indeed, one of the key elements of a successful technological fix is that it helps to solve the problem while allowing people to maintain the diversity of values and interests that impede other paths to effective action (Sarewitz and Nelson, 2008). The institutional pros and cons of SRM are discussed at greater length in the section below describing the political transaction costs of SRM.

Air Capture

AC, the second family of climate engineering concepts, would work on a different principle. It focuses on removing CO_2 from the atmosphere and securing it in land or sea-based sinks. Thus, AC, unlike SRM, ignores short-wave radiation. Instead, it attacks frontally the impact of GHG concentrations on long-wave radiation.

> "Air capture may be viewed as a hybrid of two related mitigation technologies. Like carbon sequestration in ecosystems, air capture removes CO_2 from the atmosphere, but it is based on large-scale industrial processes rather than on changes in land use, and it offers the possibility of near-permanent sequestration of carbon." (Keith and Ha-Duong, 2003)

Like carbon capture and storage (CCS), air capture involves long-term storage of CO_2, but air capture removes the CO_2 directly from the atmosphere rather than from the exhaust streams of power plants and other stationary sources. AC may eventually be a useful option in coping with mobile GHG emission sources. As one expert describes the concept:

> "For distributed, mobile sources like cars, on-board capture at affordable cost would not be feasible. Yet, in order to stabilize atmospheric levels of CO_2, these emissions, too, will need to be curtailed…extraction of CO_2 from air could provide a viable and cost-effective alternative to changing the transportation infrastructure to non-carbonaceous fuels. Ambient CO_2 in the air could be removed from natural airflow passing over absorber surfaces. The CO_2 captured would compensate for CO_2 emission from power generation two orders of magnitude larger than the power… Air extraction is an appealing concept, because it separates the source from disposal. One could collect CO_2 after the fact and from any source. Air extraction could reduce atmospheric CO_2 levels without making the existing energy or transportation infrastructure obsolete. There would be no need for a network of pipelines shipping CO_2 from its source to its disposal site. The atmosphere would act as a temporary storage and transport system." (Lackner et al., 2001)

A recent survey described a number of possible air capture technologies (Pielke, Jr., 2009). It noted that, "The most straightforward means of air capture is simply through photosynthesis." Thus, biomass could fuel power plants operating with carbon capture and storage systems. Similar concepts involve fertilizing the ocean using nitrogen, iron, or phosphorous as a route to increasing carbon storage in deep ocean sinks. Inadvertent phosphorous fertilization is already occurring (Lenton and Vaughan, 2009).

Other approaches propose to use chemical reactions capable of capturing carbon from the air on an industrial scale (Keith et al., 2006). One such approach envisions capturing CO_2 in sodium hydroxide in cooling-tower-like structures. The chemicals required for this process are "inexpensive, abundant, and relatively benign …" (Keith et al. 2006). In the view of some experts, a well-funded R&D program might make such a technology available on a large scale. Unfortunately the process requires relatively large energy inputs, which may also affect its monetary costs (Keith et al., 2006).

The Institutional Case for AC

As compared to GHG controls, AC offers major institutional advantages. AC circumvents many of the problems that are plaguing GHG controls. For example, with GHG controls, new technologies will compete with each other and with existing technologies. As a result, "we can expect ongoing technical and political debates about efficacy of specific technologies, as seen for biofuels today…" (Sarewitz and Nelson, 2008). There is, however, no unambiguous metric for evaluating the myriad rival GHG control technologies. In the absence of such a metric, debate tends to be protracted, and the task of GHG control is, therefore, relatively imperious to R&D-generated solutions (Sarewitz and Nelson, 2008).

The performance of AC, in contrast, is relatively straightforward: How much CO_2 does an AC technology capture and at what cost? Furthermore, despite the cost challenges that it presents, AC is building on a base of existing scientific knowledge. CO_2 capture is clearly possible and several well-understood chemical processes exist for doing it. Finally, and perhaps most importantly, AC, like SRM, might be structured to have relatively minimal impacts on economic freedom (Sarewitz and Nelson, 2008). (AC would not necessarily have this feature if it were financed through the offset provisions of a cap-and-trade scheme.) These potential institutional virtues argue strongly in favor of R&D effort aimed at lowering the costs of AC.

Air Capture and Solar Radiation Management

Although air capture is often classified along with SRM as climate engineering, the two concepts differ in important ways. First, as discussed above, they differ in how they address warming: SRM directly reduces shortwave radiation, and AC directly reduces long wave radiation through, the removal of CO_2 from the atmosphere. Second, as we demonstrate in §3.4, some SRM technologies can affect temperature more quickly than AC. This feature may be particularly important if one is concerned about rapid warming and abrupt change. The time-lag involved with AC lowers its benefit. A recent paper compared AC to SRM on this dimension. It concluded:

> "Thus, 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. However, some carbon cycle geoengineering options could make a useful contribution of similar magnitude to identified mitigation "wedges" (Pacala and Socolow, 2004). In the most optimistic scenarios, air capture and storage by BECS, combined with afforestation and bio-char production appears to have the potential to remove $\sim$100 ppm of CO_2 from the atmosphere giving $\sim -1.3\text{W m}^{-2}$. Combined iron, nitrogen and phosphorus fertilisation of the ocean can only achieve a maximum $\sim$20 ppm CO_2 drawdown and -0.24Wm^{-2} on the 2050 timescale." (Lenton and Vaughan, 2009)

Thus, AC may have a useful role to play in climate policy. In fact, AC may offer major advantages relative to GHG controls. As noted, it seems well-suited to the task of controlling mobile source emissions. Moreover, many institutional factors are likely to distort the application of GHG controls and to inhibit their spread (Lane and Montgomery, 2008). AC might sidestep some of these factors.

Finally, SRM and AC appear to differ in terms of cost. As will be discussed in §4, some of the SRM concepts appear to have very low deployment costs. The costs of AC, on the other hand, may be on the order of $500 per metric ton of carbon (MTC), and are not competitive with near-term mitigation technologies such as CCS (Keith et al., 2006). The high costs of AC and the long time scales it would require to become effective are serious drawbacks relative to SRM. On the other hand, AC, by seeking to remove CO_2 from the atmosphere, reduces some of the risks that remain with SRM.

In effect, AC raises issues that differ fundamentally from those that surround SRM. The remainder of this paper will focus primarily, although not exclusively, on the benefits and costs of SRM. We understand that Perspective Paper author Roger Pielke, Jr., will more carefully address the costs and benefits of AC. We also note that this division of labor is consistent with the agreement the authors made with the Copenhagen Consensus regarding their participation in this project.

2 DEFINITION AND DESCRIPTION OF SRM SOLUTIONS

Several technologic concepts have been proposed as possible means of effecting SRM. Whatever technology might be used, there are also choices about the mode of deployment. The way these issues are resolved will affect both costs and benefits.

2.1 Three SRM Concepts Merit Evaluation

At least two of the available options appear to be promising candidates for affecting global climate: stratospheric aerosols and marine cloud whiting. A discussion of the space-based sunshade is included because the concept has been widely discussed. In this section, we define these technologies. We explore their benefits and costs in §3 and §4.

Marine Cloud Whitening

One current proposal envisions producing an extremely fine mist of sea water droplets. These droplets would be lofted upwards and would form a moist sea salt aerosol. The particles within the aerosol would be less than one micron in diameter. These particles would provide sites for cloud droplets to form once they rise to the marine cloud layer. The up-lofted droplets would add to the effects of natural sea salt and other small particles, which are called, collectively, cloud condensation nuclei (Latham et al., 2008). The basic concept was succinctly described by one of its developers:

> "Wind-driven spray vessels will sail back and forth perpendicular to the local prevailing wind and release micron-sized drops of seawater into the turbulent boundary layer beneath marine stratocumulus clouds. The combination of wind and vessel movements will treat a large area of sky. When residues left after drop evaporation reach cloud level they will provide many new cloud condensation nuclei giving more but smaller drops and so will increase the cloud albedo to reflect solar energy back out to space." (Salter et al., 2008)

Just as volcanoes have provided the natural experiment suggesting the efficacy of stratospheric aerosol, the long white clouds that form in the trails of exhausts from ship engines illustrate this concept. Sulfates in the ships' fuel provide extra condensation nuclei for clouds. Satellite images provide clear evidence that these emissions brighten the clouds along the ships' wakes.

> "Since, in the scheme we propose, the aim is to increase the solar reflectivity of such low-level maritime clouds and since a fine salt aerosol provides an admirable replacement for the sulphates whose effectiveness is evident …, it seemed appropriate for the sprays to be dispersed from seagoing vessels (rather than, say, low-flying aircraft) and for the source of the sprays to be drawn from the ocean itself." (Salter et al., 2008)

The plan's developers conceive of an innovative system:

> "Energy is needed to make the spray. The proposed scheme will draw all the energy from the wind. ... The [ships'] motion through the water will drive underwater 'propellers' acting in reverse as turbines to generate electrical energy needed for spray production. Each unmanned spray vessel will have a global positioning system, a list of required positions and satellite communications to allow the list to be modified

> from time to time, allowing them to follow suitable cloud fields, migrate with the seasons and return to port for maintenance." (Salter et al., 2008)

Thus, the plan rests on an integrated system of technologies. One key to the system is the wind-driven rotor system developed in the early 20th Century by Anton Flettner. This system allows the ships to be powered by wind but to avoid the high handling and maintenance costs of sails. It also promises superior handling:

> "The rotors allow a sailing vessel to turn about its own axis, apply 'brakes' and go directly into reverse. They even allow self-reefing at a chosen wind speed. Flettner's rotor system weighed only one-quarter of the conventional sailing rig which it replaced. The rotor ships could sail 20° closer to the wind than unconverted sister ships. The heeling moment on the rotor flattened out in high wind speeds and was less than the previous bare rigging. With a wind on her quarter, the ship would heel into the wind. The only disadvantage of these vessels is that they have to tack to move downwind. Energy has to be provided for electric motors to spin the rotors, but this was typically 5–10 per cent of the engine power for a conventional ship of the same thrust." (Salter et al., 2008)

Clearly this power system offers significant advantages for the tasks implied by marine cloud whitening.

Preliminary calculations suggest that the marine clouds of the type considered by this approach contribute to cooling, and that augmenting this effect could, in theory, produce enough cooling to offset a doubling of atmospheric GHG concentrations. The logistical problems do not appear to be unmanageable. Analyses using the general circulation model of the Hadley Center of the UK Meteorological Office offer quantitative support for the scheme's feasibility. Thus a recent study observed of results produced using this model:

> "These indicate that warming due to a doubling of the carbon dioxide content of the atmosphere could be roughly compensated for–when taking account of the negative forcing due to the production of anthropogenic aerosol to date–by a doubling of the droplet number concentration Nd in three extensive regions of maritime stratocumulus clouds (off the West coasts of Africa and North and South America), which together cover about 3% of the global surface. If the anthropogenic aerosol factor is discounted, Nd would need to be roughly quadrupled. If only clouds covering this specially selected 3% of the Earth's surface were modified, instead of all marine stratocumulus clouds, the critical value of top-of-cloud albedo-change required to compensate for a doubling of carbon dioxide concentration would rise from 0.02 (mentioned earlier) to about 0.16. The associated values of enhanced [albedo] are within natural bounds." (Bower et al., 2006)

An important aspect of this result is the relatively low percentage of the total marine cloud cover that would have to be enhanced in order to produce the desired cooling.

The concept's developers have devised a deployment strategy, which they describe in the following terms:

> "Suitable sites for spraying need plenty of incoming sunshine to give something to reflect. They must have a high fraction of low-level marine stratocumulus cloud. They

> should have few high clouds because these will reduce incoming energy and send the reflected energy down again. There should be reliable but not extreme winds to give spray vessels sufficient thrust. There should be a low density of shipping and icebergs. It helps to have a low initial density of cloud condensation nuclei because it is the fractional change that counts. This suggests sea areas distant from dirty or dusty land upwind. Owing to a possible anxiety over the effect of extra cloud condensation nuclei on rainfall, areas upwind of land with a drought problem should be avoided." (Salter et. al., 2008)

A British effort is developing hardware with which to test the feasibility of this concept. This effort seeks to resolve a number of technological and scientific problems. Among the technical issues, two stand out:

> "Two crucial technological questions so far unanswered are: (a) how do we produce the seawater aerosol of the required sizes and number concentrations? (b) How do we disseminate these particles to ensure that sufficient numbers of them enter the clouds to be adulterated?" (Bower et al., 2006)

Stratospheric Aerosols

Inserting aerosols into the stratosphere is another approach. Indeed this concept of SRM has probably been more widely discussed than any of the others. The reason for its prominence is not difficult to discern. The volcanic record offers a close and suggestive analogy to this approach. Examples include the eruptions of Tambora, Krakatau, El Chichón, and Pinatubo. Such eruptions loft particles into the atmosphere. The particles enhance Earth's brightness (*i.e.* planetary albedo). They scatter back into space some of the sunlight that would otherwise have been absorbed by, and warmed, the surface. As more sunlight is scattered back into space, the planet cools. The cooling from the large Pinatubo eruption that occurred in 1991 was especially well-documented (Robock and Mao, 1995).

The obvious question is whether it would be possible to emulate the cooling that tropical eruptions have so often produced. The goal would be to inject sub-micron sized particles into the stratosphere. The particles would scatter sunlight back to space. Compared to volcanic ash, the particles would be much smaller in size. Particle size is important:

> "All matter scatters electromagnetic radiation. Small particles appear to be the most effective form for climate engineering. The goal is to maximize matter-radiation interaction favoring forms of the greatest electromagnetic cross-section for sunlight. Thus, the particles of greatest interest would be those with dimensions of the order of the wavelength of the optical radiation to be scattered, as such particles tend to scatter radiation with the highest specific efficiency and minimal mass usage." (Caldeira and Wood, 2008)

Smaller particle sizes also offer the advantage of reflecting sunlight while not impeding the passage of long wave radiation (Lenton and Vaughan, 2009).

Smaller particles would also remain in the air masses into which they were injected for longer times than does most of the matter from volcanoes. Again, the goal is to decrease the mass that must be lofted in order to achieve cooling. Eventually, though, even the smaller particles would descend from the stratosphere into the lower atmosphere. Once there, they would

precipitate out. The total mass of such particles would amount to the equivalent of a few percent of today's sulfur emissions from power plants (Lane et al., 2007).
Injecting the particles near the equator and at higher altitudes lengthens their life in the atmosphere. A longer atmospheric life reduces the total mass that must be put into the stratosphere in order to achieve a given change in global mean temperature. If adverse effects appeared following the introduction of such a scheme, most of these effects would be expected to dissipate once the particles were removed from the stratosphere.

Sulfur dioxide (SO_2), as a precursor of sulfate aerosols, is a widely discussed candidate for the material to be injected. Other candidates include hydrogen sulfide (H_2S) and soot (Crutzen, 2006). A fairly broad range of materials might be used as stratospheric scatterers:

> "Among dielectrics, many alternatives have been proposed (e.g., NAS, 1992) and all appear to be fundamentally workable. Liquid SO_2 (or perhaps SO_3) appears to be optimized for mass efficiency, transport convenience and relative non-interference with all known processes of substantial biospheric significance, although fluidized forms of MgO, Al_2O_3 or SiO_2 (e.g., as hydroxides-in-water) seem competitive in most pertinent respects." (Caldeira and Wood, 2008)

It might also be possible to develop engineered particles. Such particles might improve on the reflective properties and residence times now envisioned with dielectrics (Teller et al., 2003). Engineered particles, in comparison with sulfates or similar materials, would raise material costs per unit of weight, but the total mass needed to deflect the desired quantity of sunlight would fall. The feasibility of these concepts may hinge on the feasibility of fabricating materials able to maintain the desired optical properties in the atmosphere's chemically active environment.

As a matter of logistics, the challenge seems large, but manageable. The volumes of material needed annually do not appear to be prohibitively large. One estimate is that, with appropriately sized particles, material with a combined volume of about 800,000 m^3 would be sufficient. This volume roughly corresponds to that of a cube of material of only about 90 m on a side (Lane et. al., 2007). The use of engineered particles could, in comparison with the use of sulfate aerosols, potentially reduce the mass of the particles by orders of magnitude (Teller et al., 2003).

Several proposed delivery mechanisms may be feasible (NAS, 1992). The choice of the delivery system may depend on the intended purpose of the SRM program. In one concept, SRM could be deployed primarily to cool the Arctic. Such a deployment might be in response to a threat of methane release or it could serve as a large scale experiment moving toward a larger scale deployment. With an Arctic deployment, large cargo planes or aerial tankers would be an adequate delivery system (Caldeira and Wood, pers. comm., 2009). A global system would require particles to be injected at higher altitudes. Fighter aircraft, or planes resembling them, seem like plausible candidates. Another option envisions combining fighter aircraft and aerial tankers, and some thought has been given to balloons (Robock et al., 2009).

A Space Sunshade

A third approach that has also been widely discussed is the concept of an orbiting sunshade in space.

> "The inner Lagrange point L1 point is in an orbit with the same one-year period as the Earth, in-line with the sun at a distance where the penumbra shadow covers, and thus cools, the entire planet. A presentation on this concept proposed several approaches for overcoming the various engineering and economic challenges a sunshade presented although those challenges remain daunting." (Lane et al., 2007)

A new version of this concept has been proposed. It envisions a different system for implementing the actual scattering of the incoming sunlight:

> "Previous L1 concepts have envisaged very large space structures. The alternative described here has many free-flyers located randomly within a cloud elongated along the L1 axis. The cloud cross-section would be comparable to the size of the Earth and its length much greater, approximately 100,000 km. This arrangement has many advantages. It would use small flyers in very large numbers, eliminating completely the need for on-orbit assembly or an unfolding mechanism. The requirements for station-keeping are reduced by removing the need for the flyers to be regularly arrayed or to transmit any signals." (Angel, 2006)

The concept is immensely complex and intricate. It would include large scale development and ground operations, as well as the flyer production and transportation. The plan entails infrastructure investments several orders of magnitude greater that the two previously discussed SRM technologies. As such, its fixed costs would be far higher than theirs and would probably be a much larger percentage of the total costs (see §4.3).

Such an approach does offer some advantages. Once in place, the sunshade could have a lifetime of many decades. In part because of damage from cosmic rays, current spacecraft such as communications satellites last for roughly 20 years when placed in high orbit. The flyers envisioned for the sunshade, however, are simpler than satellites and can be better protected against radiation damage. These features should allow them to achieve lifetimes greater than or equal to 50 years. Proponents believe that the sunshade could be stabilized by modulating solar pressure. This would avoid the need for expendable propellants and the need to lift their weight (Angel, 2006).

Although this concept clearly entails a very large fixed cost, the program managers could halt cooling at any time. To do so, they merely need to reorient the shield. Thus, in a physical sense, the plan is reversible. The impacts on the Earth may be less uncertain since the shield would only alter the flux of solar radiation (Govindasamy and Caldeira, 2000). The sunshade would not change the composition of the atmosphere and ocean beyond their loading with greenhouse gases (Lane et al., 2007). These factors lower the risk of an *ex post* decision to halt cooling. However, such a decision still cannot be ruled out given uncertainties about unwanted effects of cooling on the climate itself (discussed in §2.3). Should such a policy reversal occur, the huge fixed costs of the sunshade would likely have to be almost entirely written off. Other disadvantages of the approach include the enormous area and mass required. These features make the concept technically very challenging to construct. The concept raises daunting issues related to materials, launch costs, propulsion and station keeping.

The first two of these approaches, then, stratospheric aerosols and marine cloud whitening, appear to be the most promising. Research could, of course, uncover fatal flaws in either of these two concepts. Alternatively, a research effort might also bring forth other concepts. Until resources are committed to exploring this, it is hard to know how wide or narrow the range of feasible options actually is.

2.2 Possible Deployment Strategies

In addition to the question of which technology (or combination) might be best, having an SRM option would pose strategic choices. The transition from R&D to deployment may be a somewhat complex process.

The R&D Stage[1]

With SRM, absent a big climate crisis, the risks of taking action will loom very large in the policy process. Politicians' fear of being linked to a disaster will ensure that extensive testing and evaluation will take place before deployment will be possible. Superficially, it might seem that, with enough money, rigorous testing and evaluation might be reconciled with a tight deployment schedule. In fact, some delay is simply built into the process.

One or more large field tests will almost certainly be required before full deployment will be either possible or desirable. These field tests will have to be conducted over at least a few years. The effects of a prolonged intervention may differ from those of a brief one. This argument has already surfaced with regard to the applicability of the Mt. Pinatubo analogy. If anything out of the ordinary does happen during the field tests, and the odds are that something will happen someplace, it will be necessary to ascertain if it was linked to the experiment (Caldeira and Wood, pers. comm., 2009). The inference seems clear: field tests are likely to consume a number of years –perhaps 5 to 7 years would be a reasonable minimum.

Deployment Options

As suggested by the discussion of R&D, the final stages of R&D may blend without very clear demarcation into the initial phases of deployment. Arctic cooling is one widely discussed option for a possible regional deployment of SRM (Caldeira and Wood, 2008). Many climate concerns center on this region. Climate change there has appeared to be especially pronounced. Further, the Arctic seems to be potentially vulnerable. "Arctic sea-ice is disappearing at rates greater than previously observed or predicted (Kerr, 2007) and the southern part of the Greenland ice sheet may be at risk of collapse (Christoffersen and Hambrey, 2006)" (Caldeira and Wood, 2008). Robock et al. (2008) have performed simulations that suggest that aerosol injections could maintain or increase Arctic sea ice. However, these simulations also suggest that cooling and possible side effects would not be confined to the Arctic.

In itself, disappearance of Arctic sea ice offers substantial benefits. It would shorten global trade routes and boost world trade by lowering transport costs. It would also open new opportunities for resource extraction. However, some scientists have speculated that current trends, were they to involve melting of the grounded glaciers of Greenland, might lead to a relatively rapid

1 Since the completion of this paper, a report discussing R&D issues surrounding climate engineering has been published by the Novim Group. Please see Blackstock, Jason J., David S. Battisti, Ken Caldeira, Douglas M. Eardley, Jonathan I. Katz, David W. Keith, Aristides A. N. Patrinos, Daniel P. Schrag, Robert H. Socolow, and Steven E. Koonin. 2009. "Climate Engineering Responses to Climate Emergencies," http://novim.org/.

rise in global sea levels, the release of large quantities of methane, from arctic tundra, or even disruption of ocean currents (Stocker, 2003; Gulledge, 2008). These concerns have helped to fuel thinking about a regional cooling plan. Were such an effort to be undertaken, it would probably proceed in phases. Each phase could constitute an experiment producing information about the costs, benefits, and risks of further expansion. Taken as a whole, the effort might serve as a starting point for weighing the further expansion to lower latitudes.

SRM would also pose other risk management choices. Some have proposed, for example, that it should be deployed preemptively in conjunction with GHG controls. The goal would be to improve prospects of forestalling harmful climate change (Wigley, 2006). Others regard such proposals as politically unrealistic and propose that SRM technologies be developed and held in readiness (Barrett, 2007b). In this view, SRM would be deployed only in the event of evidence that very threatening climate change was happening or was imminent. This second approach, in effect, accepts some additional risk of harm from stumbling on unseen tripwires in exchange for avoiding the risks of deploying SRM. Both approaches accept that climate strategy will involve some mix of SRM and GHG limits (and perhaps AC). They differ in the assessment of the relative risks of SRM on the one hand and of the risks of unseen climate thresholds on the other.

Another option might be to defer SRM deployment until background conditions have changed. For instance, deploying stratospheric aerosols before about mid-century entails some risk, although it may be a modest one, of slowing the recovery of stratospheric ozone levels. Delaying SRM deployment until around mid-century would eliminate this risk. It might also greatly ease the task of reaching international consensus on deployment to wait until even high-latitude countries had exhausted the expectation of net benefits from warming.

In this paper we analyze the preemptive use of CE in conjunction with GHG control measures (or, in one case, without them) on a global basis. We do not attempt to analyze the option of holding a CE capacity in reserve, though this is an important question. Our main analysis assumes CE is deployed in 2025 and continued at least through the end date of the analysis. We chose 2025 as a benchmark in the belief that it might allow time for adequate research and testing. In addition, owing to the above mentioned concerns regarding ozone depletion and national interest conflicts, we include a briefer analysis of a 2055 starting date.

2.3 The Kinds of Costs Implied by SRM

The costs of SRM fall into three broad categories. These include the *direct* costs, such as the expense of developing and deploying SRM technology. They also encompass the *indirect* costs, which might be thought of as the harm that might result from using these technologies. Finally, they include the *transaction* costs entailed by SRM. These costs might include the resources consumed in bargaining to secure agreement to use SRM or the costs of conflict that its use might occasion. Transaction costs also include routine considerations such as the costs of monitoring and measuring the system's performance or nations' contributions to it.

Direct Costs

Deploying SRM would entail direct costs, the resources consumed in building and operating the planes, balloons, ships or satellites needed to reflect the desired amount of sunlight. It would also require resources to develop these systems and to assess their impacts and side effects.

Deployment Costs

As estimated and discussed in §4, the deployment costs of the three technologies vary greatly. Of them, the sunshade is by far the most costly. For stratospheric aerosols, using conventional technologies, the total present value of deployment costs is less than $1 trillion. Marine cloud whitening costs are estimated to be almost an order of magnitude lower than either a sunshade or aerosol injection. The primary reason for this difference is that the SRM intervention takes place near the Earth's surface and therefore requires less energy to deploy. This large cost edge comes with some possible penalty in the unevenness of the geographic distribution of the cooling effects.

For selectively cooling the Arctic, the costs appear to be much lower for either of the two best approaches. The lower altitude of the tropopause over the Arctic decreases the costs of delivering aerosols to the stratosphere in this region, and the smaller area to be covered diminishes costs. Benefits, however, would be reduced as well.

Development Costs

At this point, no fully worked out concept for implementing SRM exists (Robock et al., 2009). Thus, all SRM concepts entail at least some R&D investment. Likewise, a fully worked about R&D program has not been developed. Therefore, in this section, we offer a preliminary sketch of how such a program may progress and at what level it might be funded.

Some scientists propose a phased approach. In this notion, likely begin with modeling and "paper" studies. These activities have modest budgetary impacts. Laboratory testing would begin as work progressed. Depending on the results of the earlier exploration, field trials might eventually follow. Later, the process could lead to a major experiment perhaps at one tenth the scale of full global deployment. Arctic cooling is a possible candidate as such an experiment. Regional cooling might begin small and gradually increase in scale (Caldeira and Wood, pers. comm., 2009).

The broader literature on the economics of innovation suggests that the process will involve more than a simple one way progression from research to development to demonstration. Rather, problems will arise that are likely to require a looping back into more basic research (Nelson and Winter, 1982). This pattern may be another factor in suggesting that R&D is likely to be time consuming.

Defensive research, exploration of possible harmful effects from SRM, is likely to be a more important cost item than actual hardware development. Hardware development, in fact, may imply only modest cost. For stratospheric aerosols, concepts based on current technology would, with a few years of development effort, be capable of injecting the desired gases into the stratosphere (Robock et al., 2009). More advanced delivery systems would doubtless require more research, but they, too, do not demand breakthroughs in basic science (Robock et al., 2009). In the case of marine cloud whitening, the expected R&D costs are clearly quite low. Indeed, they appear to be almost negligible (Salter et al., 2008).

In contrast, careful monitoring of changes of the climate system response would demand a major effort. Questions would include what albedo changes were produced when, where, and in what spectral bands. The prominence of defensive research costs is warranted given the possibility that unwanted side effects could far exceed deployment costs. The next section on indirect costs will discuss at greater length the potential importance of side effects. Consistent with this emphasis, satellite costs might prove a major expense at the stage of field experiments. It may be possible however, to limit these costs by using drones rather than satellites as platforms for the monitoring systems. The former may also offer more flexible deployment.

Whatever type of platform is chosen, monitoring will clearly be a major element in the concept's R&D cost structure. This fact, in turn, argues that much of the total budget could properly fall within the purview of a broader climate research agenda. GHG control policy, adaptation, and CE strategies would all benefit from greater knowledge about the causes, detailed effects, and timing of future climate change. Many of the research projects needed to explore CE are likely to be more widely useful. At the same time, it may not be entirely safe to assume that future climate science spending patterns will, in fact, respond to these needs.

An SRM research program budget might start at about $10 million per year and then ramp up to $100 million per year as initial field tests began. For comparison, today, the US government alone is spending about $10 billion a year on climate science and technology. Costs would scale up again as the project started to engage in large-scale field tests. The estimates of early expenditures are slightly more aggressive than those generated by the US government program for CE research. This program was proposed during the Bush Administration but was not actually funded. In 2001, the interagency panel that devised this plan proposed a gradually rising budget that entailed a total five year cost of $98 million (US DOE, 2002). The Arctic cooling experiment might be feasible for annual costs of around $1 billion (Caldeira and Wood, pers. comm., 2009).

Resource costs might exceed budgetary figures. Given the apparently high rates of return earned by R&D expenditures, the opportunity costs associated with specialized resource inputs into R&D may well exceed these resources' market prices (Nordhaus, 2002). By inference, R&D investments that appear to be cost-beneficial may not be if a high proportion of their inputs are drawn from other high payoff R&D. In the past, this kind of resource redeployment supplied about half of the inputs used to increase specific kinds of federal R&D spending (Cohen and Noll, 1991). It is nonetheless quite clear that R&D costs could have only a trivial impact on the benefit-cost ratios that will be presented in §4.

The space sunshade concept is, of course, an exception. The project's scale and the relative novelty of the technologies it calls for seem to portend very substantial R&D costs. The high R&D costs likely to be associated with the sunshade do not, though, imply that the more down to earth concepts would require comparable resource commitments, and if R&D resource constraints remain tight, one obvious response might be to severely limit research on this concept or to omit it altogether.

Indirect Costs

SRM is likely to involve indirect costs as well as direct ones. GHG controls will certainly incur such indirect costs (Barrett, 2007b). In this respect, then, SRM resembles GHG curbs. The latter, for instance, might increase other kinds of emissions, cause leakage, cause harm from use of some biofuels, and, through its high direct costs, curtail societies' capacity to adapt to climate change.

With regard to the scale of the indirect costs of SRM, the literature offers virtually no guidance, and that dearth limits what can be said in this study. One might note in passing that little more is available for the task of assessing GHG controls where many analyses have simply ignored indirect costs. However, indirect costs may be a larger share of SRM's total costs than they are with GHG controls and AC given the much higher direct costs of the latter two strategies and the fact that these technologies, in some sense, return the Earth to a prior state. As a result, as one recent assessment noted, fears about indirect costs are probably a much more important impediment to SRM's acceptance than are concerns about its direct costs (Robock et al., 2009). It is, then, important to at least describe the main kinds of indirect costs that SRM might occasion.

Negative Side Effects

Changing global temperatures without lowering the level of GHG concentrations is a source of much of the concern about SRM. One risk is the possible lessening of rainfall. A possible weakening of the Indian or African monsoons is a particular worry. In the wake of the Pinatubo eruption, there was some diminution in rainfall, and some model results suggest this might be a result of SRM strategies as well (Robock, 2008).

If SRM were to have this effect, the lost output might amount to a significant increase in the total costs of its use. Between 2001 and 2005, Indian agriculture and forestry produced output worth between \$96 billion and \$135 billion, annually (UN Statistics Division, 2008). The monsoon-dependent part of Indian agriculture ranges from slightly less than half to about two-thirds. A ten percent loss of the monsoon-dependent production might add \$4.5 billion to \$9 billion to the total cost of SRM. This figure is not intended to actually quantify the potential costs from this hypothetical effect. It is merely meant to signal that, if the effect is real, it could be important.

Although this point clearly warrants serious study, the underlying climate science, itself, remains unsettled: "Studies with general circulation models (GCMs) investigating the response of the ISM [Indian Summer Monsoon] to increased concentrations of GHGs and sulphate aerosols (Meehl and Washingon, 1993; Lal et al., 1995; Hu et al., 2000; May, 2002) were so far not able to provide a clear answer" (Zickfeld et al., 2005). On the other hand, Robock et al. (2008) perform simulations that suggest aerosol injections, which result in a decrease in radiative forcing of 1 W m^2, in conjunction IPCC's A1B emission scenario, decrease global precipitation by about 1.7% and adversely affect the Indian and African monsoons. Rasch et al. (2008), on which Robock is an author, qualify this result by noting

> The NCAR results [performed by Rasch] ... suggest a general intensification in the hydrologic cycle in a doubled CO_2 world with substantial increases in regional maxima (such as monsoon areas) and over the tropical Pacific, and decreases in the subtropics. Geoengineering … reduces the impact of the warming substantially. The Rutgers simulations [Robock et al. 2008] show a somewhat different spatial pattern, but, again, the perturbations are much smaller than those evident in an 'ungeoengineered world' with CO2 warming.
>
> Robock et al. (2008) have emphasized that the perturbations that remain in the monsoon regions after geoengineering are considerable and expressed concern

> that these perturbations would influence the lives of billions of people. This would certainly be true. However, it is important to keep in mind that: (i) the perturbations after geoengineering are smaller than those without geoengineering; (ii) the remaining perturbations are less than or equal to 0. 5 mm d^{-1} in an area where seasonal precipitation rates reach 6–15 mm d^{-1}; (iii) the signals differ between the NCAR and Rutgers simulations in these regions; and (iv) monsoons are a ***notoriously*** difficult phenomenon to model [emphasis in original].

In principle, if the monsoon effect were to be confirmed, it could constitute a significant cost item, but none of the existing studies made any effort to actually place a dollar value on the expected harm. As in many other instances, making a knowledgeable decision about SRM would require significant advances in more general climate science.

It should be noted that not all SRM technologies are equally at risk on this score. The more localized nature of marine cloud whitening may represent a positive advantage. With this system: "Owing to a possible anxiety over the effect of extra cloud condensation nuclei on rainfall, areas upwind of land with a drought problem should be avoided" (Salter et al., 2008). In a sense the more localized nature of marine cloud whitening operations is an offset to the potential disadvantages of the patchy effects of this approach.

Moreover in considering possible impacts on precipitation and other negative side effects, it is important to be clear about the relevant comparison.

> *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.*

Work by Caldeira and Wood (2008) indicates that a high-temperature high-GHG world involves far larger changes in precipitation patterns than does a low-temperature high-GHG world, echoing the findings of Rasch et al. (2008). In other words, controlling temperature might at least limit the damage from climate change even if it did not entirely prevent it (Caldeira and Wood, 2008). This point is directly relevant to the example of the ISM. Many models predict that warming itself is likely to cause severe problems for India's agricultural sector. It might, then, be fair to conclude: "While a major effort should be put into the study of all possible side effects of keeping sea temperatures at present values (or other values of our choosing), many of the side effects appear to be benign and less dangerous than those of large, unbridled temperature rises" (Salter et al., 2008).

In addition to possible changes in precipitation, SRM may entail risks of other unwanted consequences. Some of these worries seem potentially much more serious. It is also possible that further research might uncover some hitherto unknown effect of SRM that could be harmful enough to render a technology, or even the whole concept, infeasible. Ozone depletion and the potential loss of protection from ultraviolet radiation that it provides, has been suggested as a possible side effect of SRM. This risk may be greatest until chlorine concentrations return to their 1980s levels, because sulfate aerosols added to the stratosphere may retard the ozone layer's recovery (Tilmes et al., 2008). Again, this is a matter that would demand further study. Some have suggested that this risk, while real, may not be pronounced:

> "This particular risk, however, is likely to be small… With current elevated chlorine loadings, ozone loss would be enhanced. This result would delay the recovery of stratospheric ozone slightly but only until anthropogenic chlorine loadings returned to levels of the 1980s (which are expected to be reached by the late 2040s)." (Wigley, 2006)

Rasch et al. (2008) note that while ozone depletion may in fact take place, the attenuation of ultraviolet-B radiation by the sulfate cloud may offset this effect in terms of its impact on human health. Again, the studies that have raised the issue have not sought to quantify the dollar value of the possible harm.

In §3.3 we consider delaying the deployment of SRM until 2055 to further lower the impact on ozone levels. In this case, we demonstrate that delaying SRM until 2055 still produces large benefits and results in almost the same maximum temperature change. Marine cloud whitening may be immune from this particular concern, as it does involve the injection of particles into the stratosphere.

Others concerns, while perhaps meriting some further study, appear to be less important. For instance, some concern had arisen over acid precipitation if SO_2 were injected into the stratosphere. These fears, though, appear to be exaggerated. Thus a recent study concluded: "Analysis of our results and comparison to the results of Kuylenstierna et al. (2001) and Skeffington (2006) lead to the conclusion that the additional sulfate deposition that would result from geoengineering will not be sufficient to negatively impact most ecosystems, even under the assumption that all deposited sulfate will be in the form of sulfuric acid" (Kravitz et al., 2009).

Others have suggested that stratospheric aerosol injections would whiten skies, interfere with terrestrial astronomy, and reduce the efficiency of solar power (Robock, 2008b). Just how significant these effects would be is an open question, particularly for the low levels of SRM that we consider in this paper (low being less than a complete offsetting CO_2 emissions). Furthermore, it may be the case that society will have to choose between whiter skies, for example, and accepting the risk of a planetary emergency.

<u>The Lost Benefits of Warming</u>

The most clear cut indirect cost of SRM, although not perhaps the most important, would spring from the loss of some of the benefits of warming. In most temperate countries, warming will bring at least some benefits as well as costs, and for some countries benefits may well exceed costs – at least for a number of decades (Nordhaus, 2008). Cooling the climate relative to the business-as-usual trend, would sacrifice these benefits. By inference, SRM that occurred while warming was still producing significant net benefits in some localities would vitiate these potential gains, and interests that incurred net losses as a result might well object. These costs would occur regardless of whether aerosols or cloud whitening produces the cooling. Indeed, were GHG controls able to cool the planet as rapidly as some might wish, they too would be likely to provoke resistance on this score. Cooling the Earth inherently brings losses as well as gains.

The Political Transaction Costs of SRM

Policy making is subject to political transaction costs. Implementing any policy entails costs of striking a bargain, assessing compliance with it, and enforcing its terms. Bargaining can be costly in its own right. Moreover, political structures and rules can sometimes block or distort the choice of the best response to a problem. The resulting lost benefits can be thought of as part of the political transaction costs of adopting a policy. Transaction cost levels, however, may vary among climate policy options. Some policies, for instance, may offer more tempting targets than others for pork barrel politics or for other forms of rent seeking. Ultimately, one would like to compare the political transaction costs of SRM with those of other responses to climate change. *Ex ante*, though, such comparisons are necessarily speculative. No one can yet know how the process will distort the various options.

The Level of Conflict over SRM

Conflicting interests tend to drive up the costs of reaching and maintaining an agreement. Clearly, nations differ as to their perceived interests in curtailing warming. Divergent national interests have helped to push the transaction costs of a global bargain on GHG controls above its expected benefits (Bial et al., 2001).

Nations are also likely to differ over SRM. Absent presence of a global climate crisis, an early move to deploy SRM is likely to generate conflict (Victor et al., 2009). However, in contrast to GHG control, SRM does not require active efforts from all, or even from several, nations. It merely requires acquiescence from all major powers (Barrett, 2007b). The latter test is easier than the former (Barrett 2009). Further, the net benefits of SRM, unlike those of GHG curbs, may be large enough to buy-off the few states with both the power to deter the use of SRM and an interest in opposing it. Side payments of the type envisioned here may have ambiguous impacts on their recipients (Easterly, 2006). Nonetheless, if SRM can indeed produce large global net benefits, the resources needed to buy acquiescence are likely to be available.

Within nation states, SRM draws strong ethical objections in some quarters. Many environmental advocacy groups passionately oppose even researching it (Tetlock and Oppenheimer, 2008). Their resistance might well take the form of litigation, which would add to the transaction costs of SRM. Alternatively, they might, at some point, be able to win commitments to GHG control measures with net costs as part of the political price for a decision to advance SRM. Hypothetically, as suggested by the Nordhaus analysis of the Gore and Stern proposals, the global costs of meeting such demands might run into the trillions of dollars. In reality, important economies remain largely beyond the influence of environmental advocacy groups. That fact is likely to limit the effects of the environmentalists' demands. One possible result may be to ensure that nations with relatively weak environmental lobbies will take the lead in researching and deploying SRM. That prospect may, in turn, curtail the green advocacy groups' influence on policy even in countries where they enjoy higher levels of support.

Rent seeking

While governments provide public goods, they also often become vehicles for the pursuit of unearned income (rent seeking). Rent seeking usually ends up consuming resources and leaving society as a whole worse off (Olson, 1982). In other cases, groups acting out of ideology may be able to distort policy (North, 1990). Rent seeking and ideology can cause actual policies to diverge widely from those that would maximize economic well-being. Nothing precludes policies that do net harm, and their adoption is common (North, 2005). Many specific GHG controls proposals show that such harmful choices are common within the realm of climate policy (Lane and Montgomery, 2008).

SRM policy may not, though, be an especially apt vehicle for rent seeking. At the moment, it appears that SRM technologies might be deployed by relatively few planes, balloons, sailing ships, or other fairly low-cost systems. To be sure, all these concepts need development before they could be used, but none, at least compared to GHG controls, currently seem to require especially high costs to develop or even to deploy. SRM may, therefore, be so low cost that would-be suppliers have little interest in attempting to distort decisions about which systems to develop or deploy. Further, in the US at least, legislators may feel that SRM offers rewards in local jobs and spending that are too small to justify the effort needed to steer development efforts to their home districts. The same may not be true of AC, which would encompass a massive industrial operation that could conceivably be located anywhere.

The converse may be that SRM is too efficient for its own political good. The US, Congress tends to fund R&D based largely on the "distributive benefits" that it offers, *i.e.* on the value of its development costs as a source of local spending and jobs (Cohen and Noll, 1991). SRM may not be very rewarding from this point of view, and would-be input suppliers have not so far committed resources to urging government support for its development.

<u>The Costs of Discontinuity – and the implied risks of avoiding it</u>

Finally, governments have often found it difficult to bind themselves and their successors to future actions (North et al., 2009). At least in theory, this fact poses a difficulty for SRM (and for GHG controls, for that matter). In the event that global GHG controls remain patchy and ineffectual for an extended time, a country that substituted SRM for adaptation, over a long period, would face high costs were it to later halt SRM. To avoid such costs, a nation embarking on SRM would have to be able and willing to commit to conducting it for a very long period (Matthews and Caldeira, 2007). This consideration seems likely to lead to a great deal of cautions and careful research before an initial deployment might be politically acceptable. Further, the high cost of rapid rebound warming would itself deter a state from frivolously abandoning a long-running system (Barrett, 2007b). If a decision to stop an SRM program was made, a strong argument could be made for phasing it out gradually. In effect, the high costs of halting SRM may encourage policy continuity without any special institutional arrangements designed to guarantee it.

Continuity, though, carries a downside. Harmful side effects of SRM might appear only after decades. In that case, governments might have few alternatives to either accepting the side effects or incurring the costs of the discontinuity. Physically the SRM program could be rapidly turned-off. Practically, this step may be expensive (Goes et al., 2009).

2.4 Nature of the Potential Benefits of SRM

Some benefits of SRM stem from its possible direct impact on climate change and on the costs of coping with it. Some forms of SRM might also produce other desirable effects. The latter, should they materialize, would also be relevant.

Direct Benefits of CE

Developing a capacity to geoengineer climate would produce three types of potential benefits. First, it would allow societies to avoid some of the damages from climate change. In particular, SRM may offer real advantages as a means of averting potential harm from catastrophic climate change, but, in some deployment modes, it may also lower the harm from continuous climate change. Second, it would allow lower mitigation costs to produce a given level of protection from the harm of climate change. Third, it would lower adaptation costs.

In §3 we estimate these benefits for SRM and AC through the use of the Dynamic Integrated model of Climate and the Economy (DICE) (Nordhaus, 2008). Differing assumptions about possible GHG control regimes changes the size of the benefits from the use of SRM. It also shifts the mix between the first and second type.

Indirect Benefits

With stratospheric aerosols it may be possible to lower UV radiation striking the surface of the Earth. This effect would lower skin cancer rates and increase agricultural productivity. The potential savings are estimated to be large, perhaps on the order of $1 trillion per year (Teller et al., 2003) - although some scientists have challenged the proposition that scatterers can be designed and maintained in the atmosphere to operate with the required degree of precision (Lane et al., 2007).

3 GEOENGINEERING BENEFIT ESTIMATES

The primary challenge in estimating climate engineering B/C ratios is that rigorous benefit and cost estimates, and surrounding uncertainty, do not exist. This is a deficiency that we attempt to remedy to some extent when considering benefits. On the cost side, too, we provide new analysis, but rely on published estimates to a much larger extent.

To date, the primary studies of CE's benefits (Crutzen, 2006; Wigley, 2006; Caldeira and Wood, 2008) measure benefits in terms of CE's ability to alter climate parameters such as global mean temperature change and sea level rise, rather than in economic terms. Nordhaus (1994) is a notable, and early, exception. He found that costless climate engineering, which completely offset global warming, had a net benefit of almost $9 trillion (2005 $), which was DICE's estimate of the present value of climate damages at that time. While Nordhaus' assessment is helpful, we require an updated estimate and seek to understand the benefit of more modest CE deployments - for example, those that ameliorate, but do not completely offset, the effects of climate change.

Likewise, our cost estimates are preliminary. In addition, most estimates were developed under the assumption of a deployment that would offset the warming associated with doubling of CO_2 concentrations. Again, we seek cost estimates that consider lesser interventions.

Therefore, in this paper, we have undertaken a new study of CE benefits and costs. To make our analysis as general as possible, we estimate the economic benefit of a generic climate engineering technology that would be able either to reduce radiative forcing directly, such as solar radiation management, or to remove CO_2 from the atmosphere permanently, such as air capture. We use the DICE-2007 model (Nordhaus, 2008) to estimate the benefits of climate engineering. DICE is a well-established integrated-assessment climate change model, which allows our results to be placed within the context of existing economic analyses of climate change. Furthermore, and perhaps more importantly, the use of DICE allows us to estimate the impact of CE on key policy variables such as emissions control rates and carbon taxes. Of course, our use of DICE entails the acceptance of DICE's assumptions and limitations. The reader should not take this as an indication of our agreement with these assumptions or the degree to which we believe DICE faithfully models important aspects of natural and human systems. DICE is a model, a very useful model in our opinion, but, as a model, it is necessarily an imperfect reflection of reality. Recent meta-analysis has confirmed that one of DICE's primary outputs, the social cost of carbon, is in the "mainstream" of peer-reviewed estimates (Tol, 2008).

As the reader will see, we consider several CE deployment examples. This analysis helps to build intuition and insight. We do not attempt to analyze specialized strategies or determine the "optimal" use of climate engineering. For our cost estimates, we start with published studies of particular climate engineering technologies. We then scale these for our level of deployment.

3.1 The DICE Model, Discount Rates, and DALYs

DICE is an optimal-economic-growth model that relates economic growth to emissions of CO_2, CO_2 emissions to temperatures, and temperature to climate damage. In so doing, DICE solves for the optimal emissions control rate, CO_2 emissions, temperature, abatement costs, and climate damages, among other variables, in each decade for the next 600 years (2005 to 2605). We, however, limit our analysis to 200 years (2005 to 2205). We selected a study period of 200 years because, as the reader will see, the climate system reaches equilibrium under constant forcing over this time scale. This is not the case with other natural choices such as 100 years. In addition, maximum temperature changes are also obtained within this time frame, and we wish to investigate the impact of SRM on this parameter. Because of time discounting, most of the net benefits occur over the next 100 years and therefore a 100-year study period would not materially change our results.

Since DICE endogenously determines CO_2 emissions, we do not consider particular emissions scenarios. Instead, we will consider the impacts of CE in three different emission controls environments: no controls (a lack of emissions controls), optimal controls, and limiting temperature change to 2°C. In addition, we will analyze the effect of SRM on a policy based on a very low discount rate like that assumed in the *Stern Review* (Stern, 2007). Finally, we assess the impacts of combining optimal controls and a delayed CE. Such delay might occur owing to concerns regarding stratospheric ozone depletion or some high-latitude countries' reluctance to halt warming in the next few decades.

Like emissions, DICE endogenously determines the real return on capital based on the pure rate of social time preference (ρ) and the marginal utility of consumption elasticity (α). These two parameters, related through a Ramsey growth model, are calibrated ($\rho = 1.5\%$, $\alpha = 2$) 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. This has the following benefits. First, it facilitates the comparison of our results to those of

Nordhaus (2008). Second, using a different discount rate would be internally inconsistent with the DICE model (and the real economy). While our real discount rate varies, it averages about 5.5% for the first 50 years and about 4.5% over our 200-year study period. As a short-hand, we will refer to this as the "market discount rate" scenario. We will, in addition, analyze a low discount rate scenario of approximately 2% real, based on the *Stern Review*.

Nordhaus and Boyer (2000) estimate that the health impacts of climate change amount to approximately 7% of the total global damages. Thus, we do not attempt to alter DICE's damage equation or its assumptions regarding the value of disability adjusted life years (DALYs). Doing so would require a significant refitting of the DICE model and is unlikely to alter our main conclusions.

3.2 Changes Made to DICE

In order to estimate the benefits of climate engineering we must make a few changes to DICE. These include changes to DICE's radiative forcing and carbon cycle equations.We begin by modifying DICE's radiative forcing equation 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 m^{-2}) at the tropopause for period *t* (a decade in the DICE model) is

$$F(t) = \eta \log_2 \frac{M_{AT}(t)}{M_{AT}(1750)} + F_{EX}(t) - SRM(t) \quad (1)$$

$M_{AT}(t)$ is the atmospheric concentration of CO_2 in gigatons of carbon (GtC) 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. DICE sets the 1750 CO_2 concentration at 596.4 GtC (~280 ppm)[2]. η is the radiative forcing for a doubling of CO_2 concentrations and is assumed to be 3.8 W m^{-2}. $F_{EX}(t)$ represents the forcing of non-CO_2 GHGs such as methane and the negative forcing of aerosols. $SRM(t)$ is the change in the radiative forcing (W m^{-2}) in period *t* due to SRM. Thus, our modeling of SRM is consistent with DICE's treatment of aerosols. We do not require that the quantity of SRM be constant, but will focus on this case.

We next modify DICE's atmospheric CO_2 concentration equation. The mass of carbon contained in the atmosphere (GtC) at the beginning of period *t* is:

$$M_{AT}(t) = E(t-1) + \phi_{11} M_{AT}(t-1) + \phi_{21} M_{UP}(t-1) - AC(t-1) \quad (2)$$

$E(t-1)$ 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*. $AC(t-1)$ is the mass of carbon permanently removed from the atmosphere during period *t* – 1 via AC, which we assume occurs concurrently with emissions. Again, this amount is not restricted to be constant, but we will focus on this case.

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, the

2 Assuming 2.2 GtC per 1 ppm.

temperature of the atmosphere in the previous period, and the temperature of the lower oceans, T_{LO}, in the previous period. Specially,

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

ξ_2 is the climate feedback parameter, which is equal to the radiative forcing for a doubling of CO_2 concentrations, η, divided by the temperature increase for a doubling of CO_2, which DICE assumes is 3°C. ξ_2 is therefore equal to 1.27 (3.8/3.0). In equilibrium, Equation (3) implies that the impact of a change in radiative forcing is $\Delta T = \xi_2^{-1}\Delta F \approx (1.27)^{-1}\Delta F \approx 0.79\Delta F$. Similarly, the negative radiative forcing at the troposphere required to offset a temperature increase of 3°C is $\Delta F \approx 1.27 \cdot 3 = 3.8\ \mathrm{W\ m^{-2}}$. 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. We also note that DICE's use of a two stratum climate model does not account for vertical differences in radiative forcing, which may be important (NRC, 2005). We do not, however, believe these limitations limit the usefulness of DICE within the present context or undermine our argument that climate engineering merits additional research.

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

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

where ψ_1 and ψ_2 are chosen to fit the literature regarding climate impacts. 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, and possibly AC. We do not alter DICE's damage function and therefore may underestimate the benefit of rapid cooling or the cost of rapid warming.

3.3 Solar Radiation Management

We analyze three generic SRM strategies that entail deploying either 1 W m^{-2}, 2 W m^{-2}, or 3 W m^{-2} of negative forcing beginning in 2025 and continuing through 2605. We refer to these as SRM 1, SRM 2, and SRM 3, respectively. As mentioned in §3.1, we consider three different emission controls environments: no controls, optimal controls, and limiting temperature change to 2°C.

Figure 1: No Controls temperature changes (°C) with the deployment of SRM.

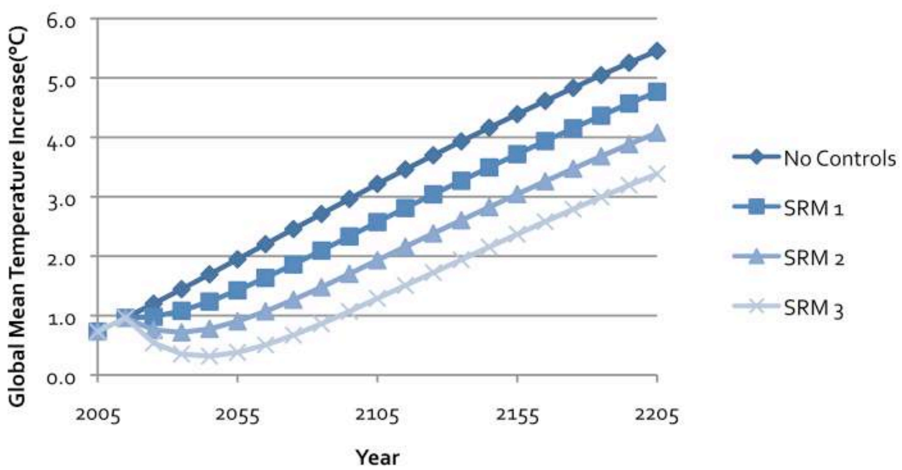


Figure 2: Difference in temperature relative to no controls (top) and the equivalent equilibrium radiative forcing (bottom).

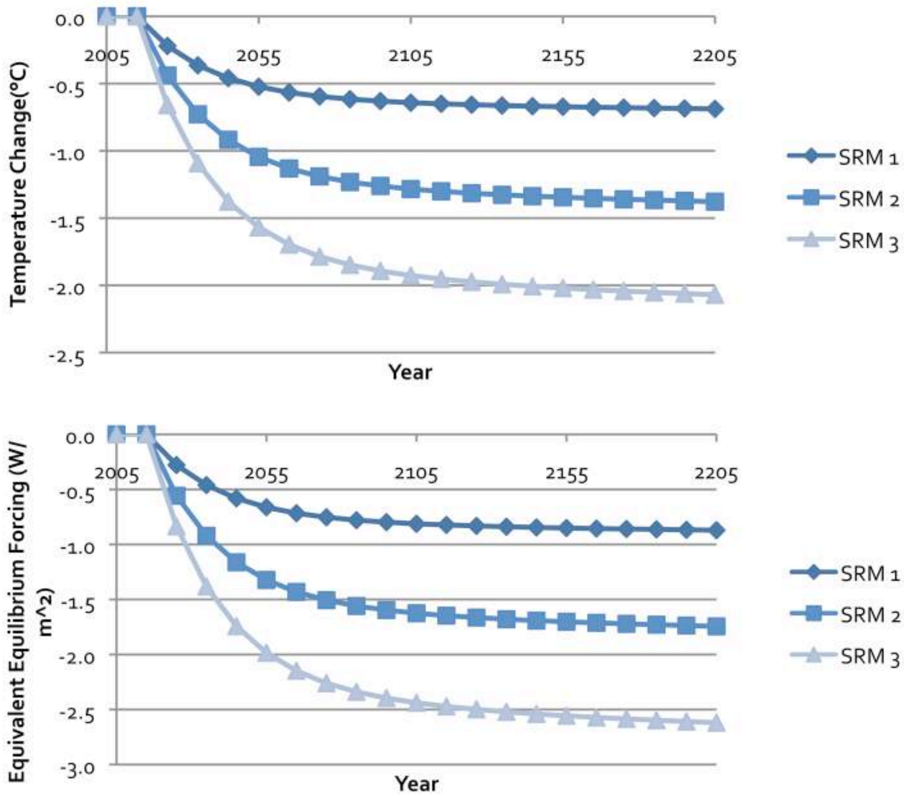


Table 1: Benefit of SRM under No Controls with 2025 Start ($ are trillions of US $2005).

SRM Strategy	PV of Climate Damages	Benefit of SRM	Cost Reduction
SRM 0 (No Controls)	$21.7	$0	0%
SRM 1	$14.2	$7.5	34%
SRM 2	$8.6	$13.1	60%
SRM 3	$4.9	$16.8	78%

No Controls

We begin by analyzing the use of SRM under an assumption of no reductions in GHG emissions, referred to as No Controls (NC). Running the DICE model without any climate engineering produces a 200-year present value of climate damages of $21.7 trillion (all dollar amounts are in 2005 US $), compared to a 600-year present value of $22.6 trillion reported by Nordhaus (2008).

The impact of deploying SRM on temperature is shown in Figure 1. Increasing the quantity of SRM shifts temperature increases into the future. In fact, each W m^{-2} of SRM shifts the higher temperatures due to elevated GHG concentrations out about 30 years. Thus, if society sought to avoid the amount of harm that would be caused by reaching a given temperature level, deploying 3 W m^{-2} of SRM would buy almost 100 years of time in which to develop the less costly low-carbon energy sources needed to reach that goal.

The top panel of Figure 2 displays the change in temperature relative to NC that is accomplished by each SRM strategy. SRM 1, for example, approaches -0.79°C, which is expected from the equilibrium relationship $\Delta T = \xi_2^{-1}\Delta F \approx 0.79\Delta F$. The bottom panel displays the equilibrium negative radiative forcing that is equivalent to the temperature decreases in the top panel. We see that, for example, a constant 3 W m^{-2} of SRM will not produce negative forcing equivalent to an equilibrium forcing of -3 W m^{-2}. This result obtains because of lags in the climate system (e.g., see Equation) and the fact that the climate is being forced away from equilibrium through continued carbon loading under the NC scenario.

The damages imposed by climate change are lessened because of the reduction in temperature increases. The present value (PV) of climate damages is reduced from $21.7 trillion to $14.2 trillion through the deployment of 1 W m^{-2} of SRM. Thus, the benefit of 1 W m^{-2} of SRM is $7.5 trillion, which is a cost reduction of about 34%. To place SRM 1 in perspective, 1 W m^{-2} is about 0.3% of the incoming solar radiation of 341 W m^{-2} (Kiehl and Trenberth, 1997; Trenberth et al., 2009). Table 1 summarizes the benefit of each SRM strategy. For example, 3 W m^{-2} of SRM reduces climate damages by almost $17 trillion or 78%. Clearly, SRM hold the potential to significantly reduce climate damages.

We notice that the marginal benefit of SRM is decreasing. For example, SRM 2 does not have twice the benefit of SRM 1. This occurs because of the quadratic nature of the DICE damage function, Equation (4); as temperature is reduced, the next incremental change has less of an impact on damages. Further, the benefits estimated here exceed the value for CE presented by Nordhaus (1994). This result stems from the fact that the PV of climate damages reported at that time were $9 trillion (2005 $), compared to $21.7 trillion (2005 $) reported in Nordhaus (2008).[3]

A possible concern with the use of SRM under a NC scenario, identified §2.3, is that the atmosphere would continue to be loaded with CO_2 and that temperatures may increase rapidly if SRM were ended (Wigley, 2006). As can be seen in top panel of Figure 2, in the year 2105 SRM 1, SRM 2, and SRM 3 would offset approximately 0.6°C, 1.3°C, and 1.9°C, respectively.

Optimal Controls

We next analyze the use of SRM under a scenario of optimal emissions as determined by DICE, which we refer to as Optimal Controls (OC). In this case, DICE determines the optimal level of abatement via emissions reductions. Therefore, in this case, we are investigating the combined use of climate engineering and (optimal) abatement. The 200-year PV of climate damages under OC is $16.2 trillion. The PV of the abatement costs is $2.0, bringing the total cost of climate change, under optimal emissions, to $18.2 trillion, compared to a 600-year present value of $19.5 trillion reported by Nordhaus (2008).

The impact of deploying SRM on temperature is shown in Figure 3. Under SRM 1, temperatures peak in the year 2205. Under SRM 2 and SRM 3 temperatures increases peak at 2.7°C in 2215 and 2.4°C in 2235 (not shown), respectively. In this case, each W m^{-2} of SRM shifts increased temperatures out about 35 years. We see that, the combined use of climate engineering and optimal abatement is nearly able to hold the temperature change to 2°C.

3 Please see Nordhaus (2008, p. 112) for a discussion of differences between DICE-1999 and DICE-2007

Figure 4 displays optimal emissions control rates (top) and carbon taxes (bottom) as a function of SRM level.[4] We see that the use of SRM on the levels we are considering here will not replace emissions reductions or carbon taxes. However, each W m^{-2}of SRM delays a given emissions reductions level or carbon tax by about 25 years. Thus, 3 W m^{-2} of SRM would forestall the level of emission reductions produced by DICE by about 75 years. We should also note that optimal emission control rates are affected in the years before SRM is deployed. For example, as shown in the top panel of Figure 4, emissions control rates differ in 2015, even though SRM is not deployed until 2025. This occurs because DICE has perfect foresight and "knows" that SRM will be deployed in the future. This feature, common in modeling, may, of course, simulate actual social decision making rather poorly.

As was the case with NC, the reduction in temperature reduces the damage imposed by climate change. The PV of climate damages and abatement costs is reduced from $18.2 trillion to $11.9 trillion through the deployment of 1 W m^{-2} of SRM—a benefit of $6.3 trillion or about a 35% cost reduction. This benefit is about $1 trillion less than the case of NC because emission reductions are also avoiding damages in the optimal scenario. Table 2 summarizes the benefit of each SRM strategy. We see again that SRM can significantly reduce climate damages. For example, 3 W m^{-2} of SRM reduces climate damages and abatement costs by $14 trillion or 77%. In percentage terms, the benefits are almost evenly split between reductions in climate damages and reductions in abatement costs. For example, SRM 3 reduces climate damages by 77% and abatement costs by 78%.

Figure 3: Optimal Controls temperature changes (°C) with the deployment of SRM.

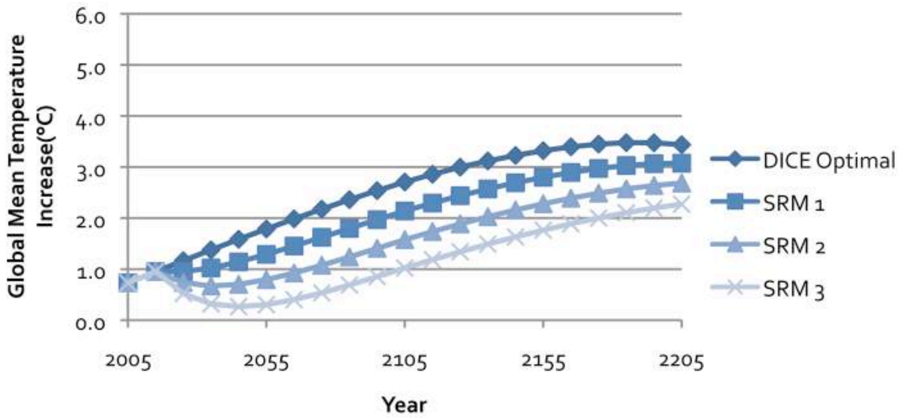
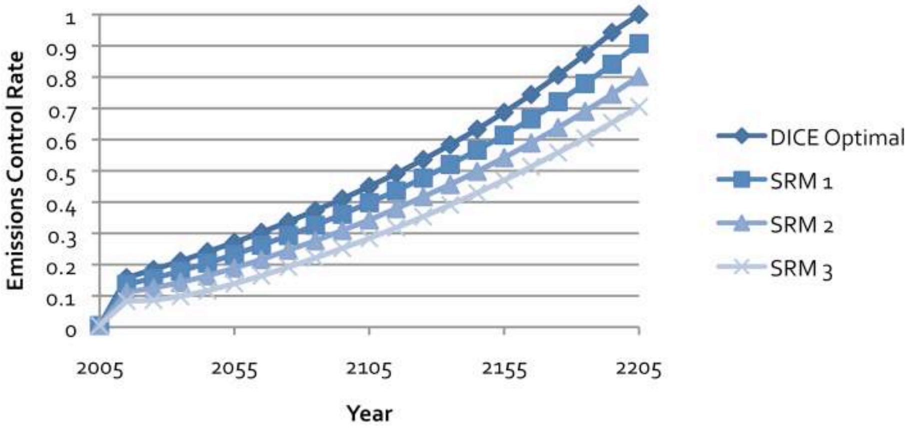


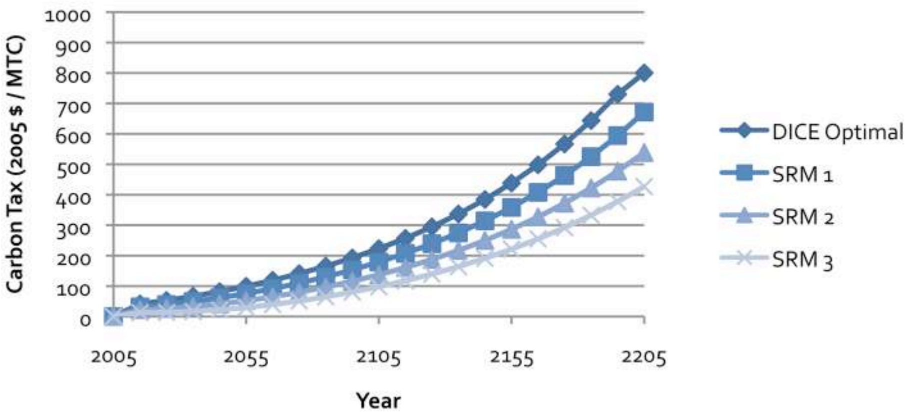
Table 2: Benefit of SRM under Optimal Controls with 2025 Start ($ are trillions of US $2005).

SRM Strategy	PV of Climate Damages	PV of Abatement Costs	PV of Climate Damages and Abatement Costs	Benefit of SRM	Cost Reduction
SRM 0	$16.2	$2.0	$18.2	$0	0%
SRM 1	$10.5	$1.4	$11.9	$6.3	35%
SRM 2	$6.3	$0.9	$7.2	$11.0	60%
SRM 3	$3.7	$0.5	$4.2	$14.0	77%

4 Divide by 3.66 to place the carbon taxes in terms of $ per MT of CO_2.

Figure 4: Optimal emissions control rates (left) and carbon taxes (right) with the use of SRM.





A concern expressed regarding the use of SRM is the continued carbon loading of the atmosphere. To get a rough sense for this risk we analyze the CO_2 concentrations when SRM is employed compared to the situation when it was not employed. For example, the 2105 CO_2 concentration under SRM 3 with optimal abatement is 631 ppm, compared to 581 ppm in the OC case without SRM—a difference of 50 ppm or a ratio of 1.086. Thus, the "latent forcing" due solely to the increase in carbon loading is 0.36°C ($3.8 \cdot 0.79 \cdot \log_2(1.086)$). This should be compared to the SRM 3 temperature decrease in the year 2105, which is 1.7°C (see Figure 3).

Thus, we see that under OC the primary risk in ending an SRM program stems from stopping the negative forcing of the SRM itself, rather than from its secondary effect on CO_2 emissions. Conversely, the 2205 CO_2 concentration under No Controls is 1189 ppm, which is 488 ppm greater than OC with SRM 1. These differences are shown relative to OC and NC for SRM 1, SRM 2, and SRM 3 in Figure 5. In the year 2105 the increased loading due to the availability of SRM is between 15 and 50 ppm, relative to optimal controls. This loading is not as pronounced as the case where one assumes SRM completely displaces GHG reductions (e.g., Goes *et al.*, 2009). Such an assumption regarding SRM deployment is a modeling choice, rather than an inherent feature of the technology. Furthermore, it is an assumption that does not correspond to the manner in which we and others (e.g., Wigley, 2006) have suggested SRM might be used.

Delayed Start

The reasons that society might wish to delay the use of SRM have been discussed in §2.2. As noted there, both Crutzen (2006) and Wigley (2006) argue that the ozone risk, while warranting further study, may not be significant. However, delay would dispel whatever fears might exist on these grounds, and it would also greatly dampen the risks that SRM might do net harm to high-latitude nations. Both of these effects would lower the transaction costs of deploying SRM. Society might then wish to wait until the middle of this century before beginning SRM. The benefit of starting a SRM program in 2055 instead of 2015 is \$3.9, \$7.1, and \$9.5 trillion for SRM 1, SRM 2, and SRM 3, respectively. The impact on temperature in this case is shown in Figure 6. Comparing Figure 6 and Figure 3 we see that while delay lowers benefits, it has no discernible effect on maximum temperature changes.

Table 3 details the impact of a delayed start on the PV of climate damages and abetment costs. Comparing Table 2 and Table 3 we see that the delay primarily increases the PV of climate damages.

Figure 5: Difference in SRM CO_2 Concentrations Compared to Optimal Controls and No Controls.

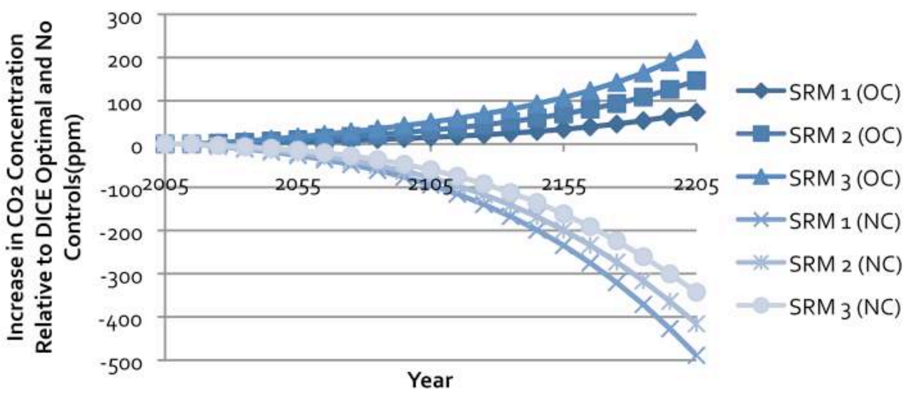


Figure 6: Optimal Controls temperature changes (°C) with the year 2055 deployment of SRM.

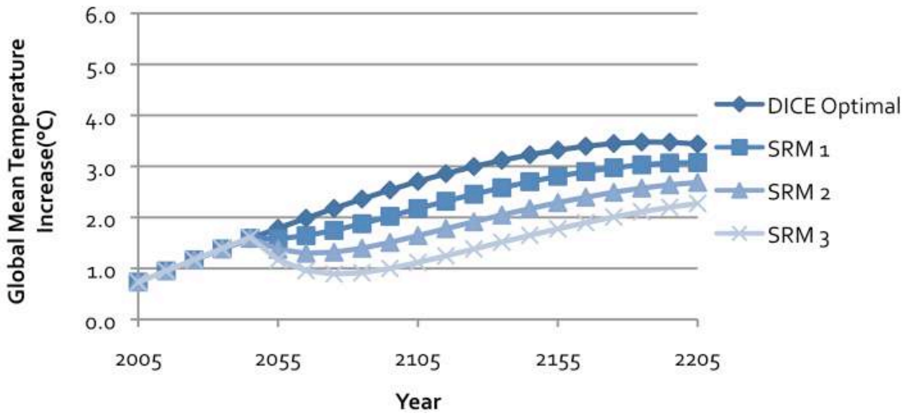


Table 3: Benefit of SRM under Optimal Controls with 2055 Start ($ are trillions of US $2005)

SRM Strategy	PV of Climate Damages	PV of Abatement Costs	PV of Climate Damages and Abatement Costs	Benefit of SRM	Cost Reduction
SRM 0	$16.2	$2.0	$18.2	$0	0%
SRM 1	$12.7	$1.6	$14.3	$3.9	22%
SRM 2	$10.0	$1.1	$11.1	$7.1	39%
SRM 3	$8.0	$0.7	$8.7	$9.5	52%

Temperature Constraints

We now consider the case of using SRM to lessen the cost of meeting temperature constraints. Specifically, we assume that society chooses to constrain the increase in global mean temperature to no more than 2°C, noting that many governments have embraced this target. Constrained by this target, the optimal GHG control policy would result in a 200-year present value of climate damages of $11.9 trillion. The present value of the abatement costs would be $10.9 trillion. Thus, the total cost of climate change would be $22.8 trillion, compared to a 600-year present value of $24.4 trillion reported by Nordhaus (2008). We see that limiting temperature change to be no more than 2°C would cause a loss of $4.6 trillion when compared to OC and would be $1.1 trillion *worse* than NC, *i.e.* it would be worse than doing nothing at all. Compared to OC, limiting the increase in temperature reduces damages by $4.3 trillion, but incurs $8.9 trillion more in abatement costs. Compared to NC, this strategy reduces climate damage by $9.8 trillion, but requires $10.9 trillion in abatement.

The impact of deploying SRM on temperature in this case is shown in Figure 7. Without SRM, the 2°C constraint is reached in 2095. With 1 W m^{-2}, 2 W m^{-2}, or 3 W m^{-2} or SRM the temperature constraint is reached in 2125 (+30 years), 2165 (+70 years), and 2205 (+110 years), respectively. Again, SRM could give society more time to make the technological change required to limit the harm from a global temperature increase.

Figure 8 displays optimal emissions control rates (top) and carbon taxes (bottom) as a function of SRM level.[5] SRM significantly alters the timing of required emissions controls and carbon taxes. For example, in order to meet a 2°C temperature constraint, an emissions reduction of 20% would have to be in force by 2015. Under SRM 3 this level of emissions reductions would not be required for another 70 years. Likewise, a carbon tax exceeding $100 per MTC (2005 $) would not be necessary until 2105.

The PV of climate damages and abatement costs is reduced from $22.8 trillion to $13.0 trillion through the deployment of 1 W m^{-2} of SRM—a benefit of $9.8 trillion or about 43%. This benefit is over $3.5 trillion more than the OC case (benefit of $6.3 trillion); SRM is worth more under a temperature constraint because it lessens the need to perform costly abatement

5 The unstable behavior of these graphs occurs once the temperature constraint has been reached and DICE alternates between relaxing emissions constraints only to have to impose them again as temperature rises.

in the near term. Table 4 summarizes the benefit of each SRM strategy. The benefits of SRM in this case are quite significant, with the largest percentage gains coming from reduced abatement costs. For example, while SRM 1 reduces the PV of damages and abatement costs by 43%, it reduces the PV of abatement by 63% (from $10.9 to $4.0). It is also noteworthy that a 2°C temperature constraint with 1 W m^{-2} of SRM is more than $5 trillion better than DICE's OC ($18.2 trillion) and over $1 trillion *better* than No Controls with 1 W m^{-2} of SRM ($14.2 trillion). This later result is surprising given that, without SRM, a 2°C constraint is worse than doing nothing. This result is obtained because SRM holds temperatures in check, avoiding climate damages, while society builds the capital and technology necessary to achieve emissions reductions at lower cost. The policy lesson, of course, is that SRM can lower the costs of pursuing non-optimal GHG control strategies, not that non-optimal strategies are harmless. SRM with a 2°C constraint is still worse than SRM with OC.

Low Discount Rate (*The Stern Review*)

In order to match the assumptions made by the *Stern Review*, Nordhaus (2008) sets the time preference to 0% and the consumption elasticity to 1.0. These assumptions imply a real rate of return of about 2%. We adopt this case as our low discount rate scenario. It is important to note, however, that these assumptions do not match empirical returns on capital and therefore the benefit of investments in the real economy.

The low discounting greatly amplifies future damages and the *Stern Review* assumptions result in an emissions reduction of 50% and a carbon tax of over $300 per MTC beginning in 2015. In order to compare these strong abatement measures, resulting from a low discount rate, to our other scenarios we, following Nordhaus, find the present value using our previous 5.5% real rate.[6] The 200-year present value of climate damages is $9.2 trillion, about $7 trillion less than OC. However, the PV of the *Stern Review's* abatement costs is $22.1 trillion, about $20 trillion more than OC.

Employing 1 W m^{-2} of SRM reduces the PV of climate damages and abatement costs to $19 trillion ($6.3 trillion in climate damages and $12.7 trillion in abatement costs), which is a benefit of over $12 trillion. Surprisingly, the PV of the *Stern Review* policy with 1 W m^{-2} of SRM is very close to that of DICE Optimal Controls. Clearly, SRM holds the potential to mitigate damage to the environment induced by global warming and damage to the economy as the result of poor policy. Table 5 summarizes the benefit of each SRM scenario.

Table 4: Benefit of SRM under 2°C Constraint with 2025 Start ($ are trillions of US $2005).

SRM Strategy	PV of Climate Damages	PV of Abatement Costs	PV of Climate Damages and Abatement Costs	Benefit of SRM	Cost Reduction
SRM 0	$11.9	$10.9	$22.8	$0	0%
SRM 1	$9.0	$4.0	$13.0	$9.8	43%
SRM 2	$6.0	$1.5	$7.5	$15.3	67%
SRM 3	$3.6	$0.6	$4.2	$18.6	81%

6 This is, of course, not internally consistent with DICE. However, the present values calculated using 5.5% can be thought of as how much capital would be required to finance the *Stern Review's* recommendations in the real economy.

Figure 7: Temperature changes (°C) with the deployment of SRM under a 2°C temperature constraint.

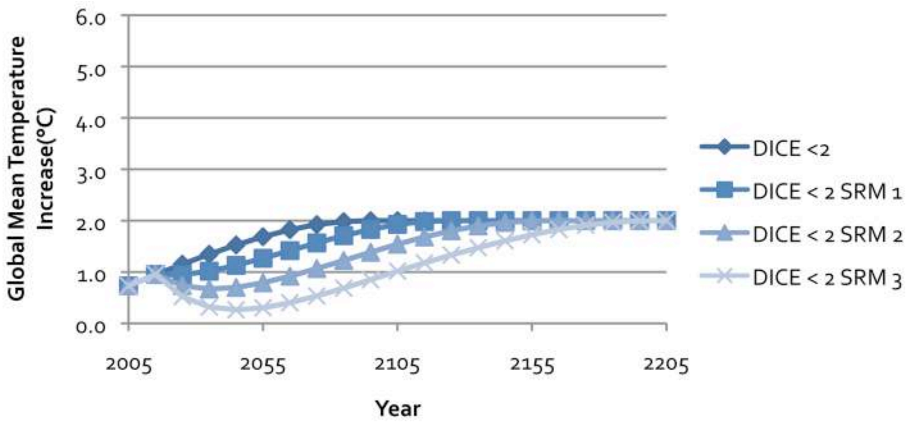
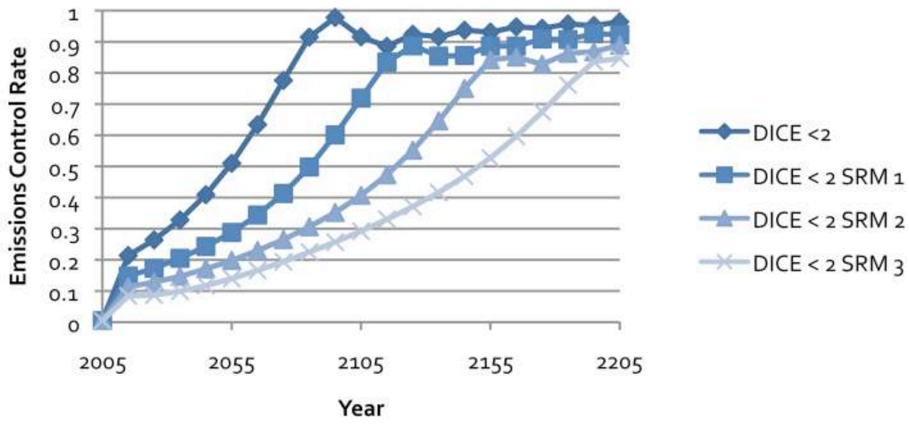


Figure 8: Optimal emissions control rates (top) and carbon taxes (bottom) under a 2°C constraint.



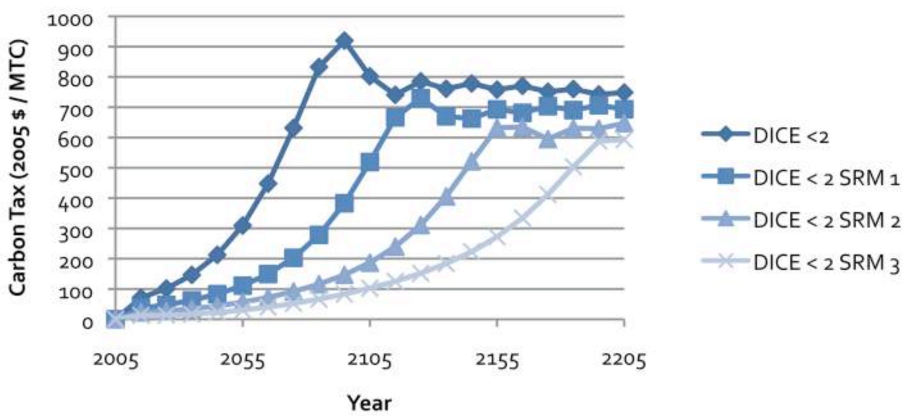


Table 5: Benefit of SRM under Low Discount Rate Scenario with 2025 Start ($ are trillions of US $2005).

SRM Strategy	PV of Climate Damages	PV of Abatement Costs	PV of Climate Damages and Abatement Costs	Benefit of SRM	Cost Reduction
SRM 0	$9.2	$22.1	$31.2	$0	0%
SRM 1	$6.3	$12.7	$19.0	$12.2	39%
SRM 2	$4.0	$7.1	$11.1	$20.1	64%
SRM 3	$2.6	$3.8	$6.4	$24.8	79%

3.4 Air Capture

As mentioned in §1.5, air capture technologies do not appear as promising as solar radiation management from a technical or a cost perspective. For this reason, we are focused primarily on SRM. However, it is useful to contrast the potential net benefits of SRM and AC.

As a point of comparison, we begin by determining the level of AC that would have the same *economic benefit* as SRM 1. As described in §3.2, we modify DICE's carbon-cycle model to allow for the permanent removal of CO_2 from the atmosphere. After multiple DICE runs, we find that capturing and sequestering 5.5 GtC of CO_2 per year has approximately the same benefit as one W $m^{-2}$of SRM. We will refer to this air capture scenario as AC 5.5. Specifically, the benefit of AC 5.5 is $5.5 trillion, compared to $6.3 trillion for SRM 1. To place this number in perspective, current global CO_2 emissions are around 8.5 GtC per year. Thus, AC 5.5 is equivalent to removing and sequestering almost 65% of current emissions. In other words, when considering only the impact on temperature, capturing and sequestering almost 65% of global annual CO_2 emissions has about the same economic benefit of reducing the solar flux by 0.3%.

As discussed in §1.5, Keith *et al*. (2006) have estimated that the cost of AC using current technology is $500 MTC^{-1} and might be driven below $200 MTC^{-1} over the next century. They caution however that these estimates could be off by a "factor of three." Pielke, Jr., (2009) notes that at $500 MTC^{-1} AC costs about $1 *trillion per ppm*. Pielke, Jr., (2009) goes on to cite Klaus Lackner as estimating the current cost to be $360 MTC^{-1} and that eventually it might fall to $100 MTC^{-1}. At $500 MTC^{-1} AC 5.5 would cost $2.75 trillion *per year*. The 200-year present value of this cost is almost $30 trillion, yielding a B/C ratio of 0.20. At a cost of $100 MTC^{-1} the present cost of AC 5.5 is $5.6 trillion, approximately equal to its benefit. This example reveals the tremendous cost challenge faced by AC technologies. As we show in §4, SRM might be able to achieve this same benefit for less than $0.5 trillion.

Given the benefit-cost framework of this Copenhagen Consensus study, we will not consider even higher levels of AC. However, as another point of reference, consider the scenario suggested by Pielke, Jr., (2009) of the capturing and sequestering all US auto emissions, which total 0.48 GtC annually. We round this and consider an AC 0.5 strategy. As a reminder, the optimal controls 200-year PV of climate damages and abatement costs is $18.2 trillion. Under AC 0.5 with optimal controls, the PV of climate damages and abatement costs is reduced to $17.7 trillion—a benefit of $0.5 trillion or savings of about 3%. Pielke, Jr., (2009) estimates that it would cost $0.240

trillion per year (at \$500 MTC^{-1}) to capture and store 0.48 GtC annually. Thus, costs would exceed the complete 200-year benefit of AC 0.50 in only two years.

These results should not be surprising given current cost estimates and AC's benefit profile. The impact of deploying AC on temperature is shown in Figure 9. As was the case with SRM, AC does delay temperature increases. However, the patterns of performance are quite different. We have added SRM 1 and SRM 3 to Figure 9 as a reference. AC's impact is delayed because of lags in the climate system. We see that SRM 1 outperforms AC 5.5 until 2085 (+70 years) and AC 0.5 through at least 2205 (+200 years). SRM 3 outperforms all three air capture scenarios over the next 200 years. In addition, the levels of AC we consider here are unable to hold temperatures changes below 2°C and AC 0.5 offers almost no temperature benefit relative to OC, hence its near zero economic benefit.

Figure 10 displays optimal emissions control rates (top) and carbon taxes (bottom) as a function of AC level. Importantly, we see that the use of AC has almost no effect on the optimal emissions control rate or the carbon tax - especially in the short term, because of AC's delayed effect. None of the AC scenarios considered can match the impact that even SRM 1 has on these policy variables.

This provides another lens through which to view AC's cost challenges. As discussed above, AC costs are on the order of \$500 MTC^{-1} and might fall to 100 MTC^{-1} over a century. These costs exceed the optimal carbon tax (or the social cost of carbon) for at least the next 50 to 150 years. For example, under DICE OC a \$100 MTC^{-1} carbon tax is not achieved until 2055 and a \$500 MTC^{-1} is not reached until 2165 (see Figure 10).

Table 6 summarizes the benefit of each AC strategy. We see that AC has almost no ability to reduce the present value of abatement costs and makes only a moderate reduction in climate damages.

AC does have the benefit of removing CO_2 from the atmosphere, which is potentially less risky than SRM—assuming the CO_2 remains safely sequestered. For example, the 2205 CO_2 concentration under AC 0.5 with optimal abatement is 610 ppm, compared to 627 ppm in the OC case without AC—a reduction of 17 ppm. The 2205 reduction for AC 5.5 is 155 ppm. Figure 11 displays the CO_2 concentrations differences (relative to optimal controls) for each AC and SRM scenario.

Figure 9: Optimal Controls temperature changes (°C) with the deployment of AC.

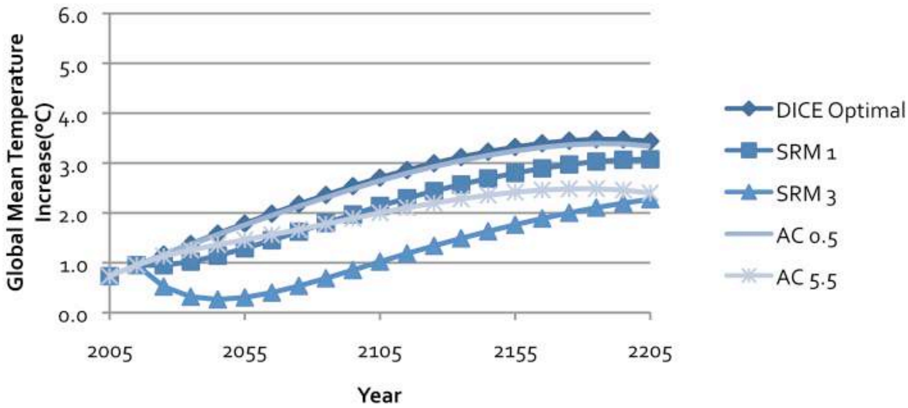
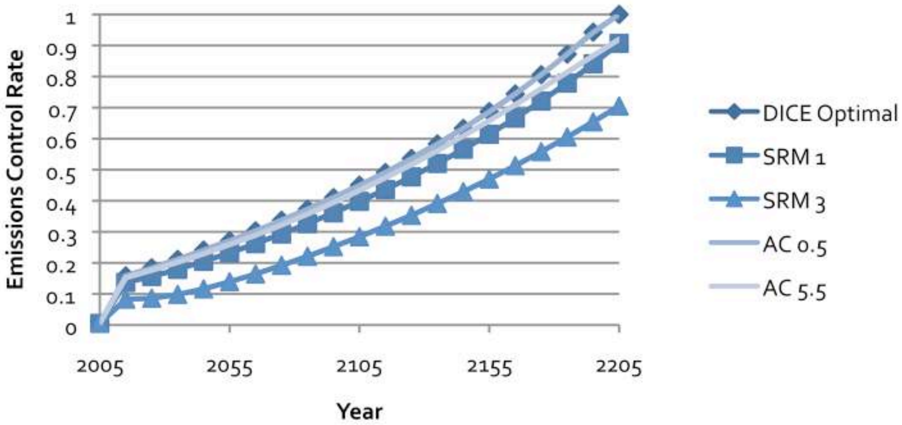


Figure 10: Optimal emissions control rates (top) and carbon taxes (bottom) with the use of AC.



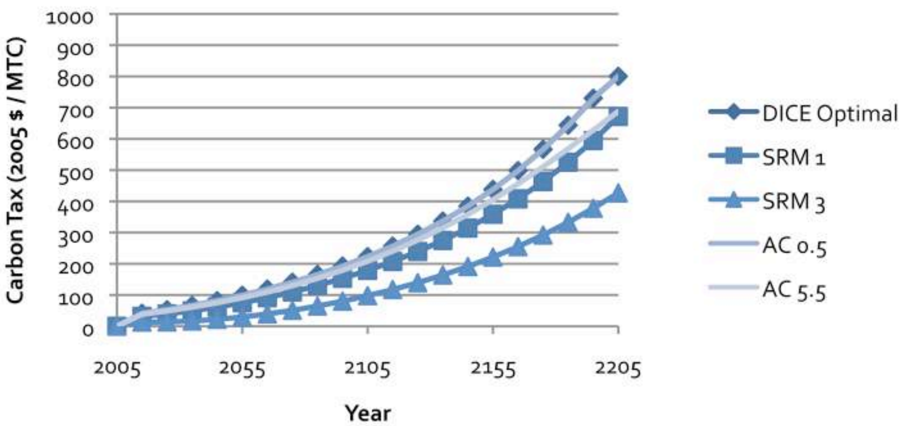


Figure 11: Difference in AC and SRM CO_2 Concentrations Compared to Optimal Controls.

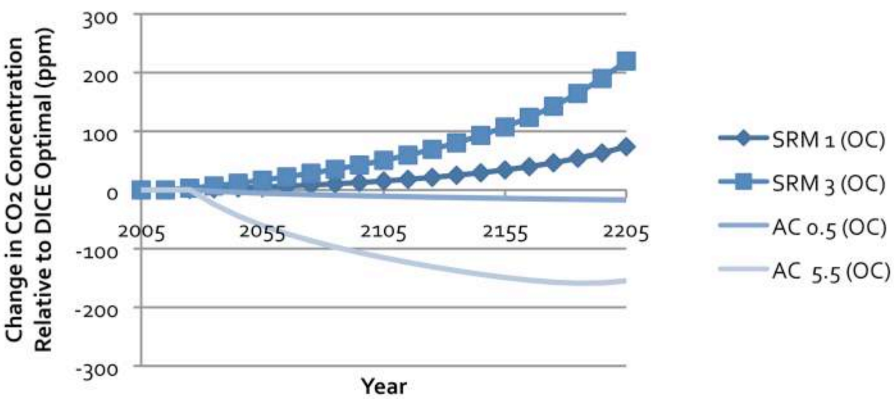


Table 6: Benefit of AC under Optimal Controls ($ are trillions of US $2005).

SRM Strategy	PV of Climate Damages	PV of Abatement Costs	PV of Climate Damages and Abatement Costs	Benefit of AC	Cost Reduction
AC 0	$16.2	$2.0	$18.2	$0	0%
AC 0.5	$15.7	$2.0	$17.7	$0.5	3%
AC 5.5	$10.9	$1.8	$12.7	$5.5	25%

Table 7: Summary of SRM Benefits of SRM ($ are trillions of US $2005).

SRM Strategy	No Controls	Temp < 2°C	Optimal Controls		
			2025 Start Market Discount Rate (5.5%)	2055 Start Market Discount Rate (5.5%)	Low Discount Rate (2.0%)
SRM 1	$7.5	$9.8	$6.3	$3.9	$12.2
SRM 2	$13.1	$15.3	$11.0	$7.1	$20.1
SRM 3	$16.8	$18.6	$14.0	$9.5	$24.8

3.5 Summary of Benefits

As detailed in the previous four sections, the ability of SRM to reduce climate damages and abatement costs appears to be dramatic. For example, a single W m^{-2}of SRM:

- Is worth over $6 trillion under Optimal Controls.
- Can turn an emissions control strategy of limiting temperatures to +2°C, which is worse than doing nothing, into a strategy better than that of DICE's Optimal Controls.
- Can blunt the economic damage caused by policies such as those of the *Stern Review*.
- Has an economic benefit, when considering the impact of temperature changes, equivalent to capturing and sequestering over 65% of the world's annual CO_2 emissions.

Table 7 summarizes the benefits of SRM.

We now turn to the task of estimating the costs the different SRM strategies.

4 CLIMATE ENGINEERING DIRECT COST ESTIMATES

The incoming solar radiation at the top of the atmosphere (TOA) is 341 W m^{-2} (Trenberth et al., 2009). Of this, 102 W m^{-2} is reflected back to space corresponding to an average planetary albedo α_p of .299 (102/342). The change in planetary albedo needed to achieve a particular change in radiative forcing ΔF is

$$\Delta\alpha_p = \frac{-\Delta F}{341} \quad (5)$$

Thus, if one wanted to reduce the radiative forcing by 1 W m^{-2}, 2 W m^{-2}, or 3 W m^{-2} the planetary albedo would need to be increased by .003, .006, and .009, respectively.

In this section we consider three SRM strategies that operate at three distinctly different positions relative to the Earth's surface. The first is the enhancement of marine stratiform cloud albedo. The second is the injection of aerosols into the stratosphere. Finally, the third is a sunshade placed in orbit at the Lagrangian-1 point between the Earth and the Sun. While the direct cost estimates we describe are speculative, we will show that they are so small that it is almost certain that SRM's *direct* benefit-cost ratio is greater than unity.

4.1 Marine Cloud Whitening

Lenton and Vaughan (2009) develop a simple methodology to approximate the change in atmospheric albedo required to bring about a desired change in planetary albedo. The specifics of which depend upon where reflection takes place in the atmosphere. They approximate marine stratiform cloud albedo enhancement by assuming all reflection takes place just above the Earth's surface, after all atmospheric absorption. We follow Lenton and Vaughn's method, but instead of basing our estimates of global energy fluxes on the work of Kiehl and Trenberth (1997) we use the updated estimates of Trenberth et al. (2009). We note in passing that Kiehl and Trenberth (1997) estimated that the TOA flux was 342 W m^{-2}, whereas the 2009 estimate (Trenberth *et al*., 2009) was 341 W m^{-2}. This 1 W m^{-2} difference parallels our SRM 1 strategy. We estimate that the required change in atmospheric albedo, when reflection occurs after absorption, $\Delta\alpha_a$, is

$$\Delta\alpha_a = 1.482\Delta\alpha_p = 1.482\frac{-\Delta F}{341} \quad . \tag{6}$$

Thus, decreasing radiative forcing by 1 W m^{-2} would require an increase in atmospheric albedo of .004. To determine the required increase in low-level marine stratiform cloud albedo, we must divide by the fraction of the Earth that is covered by such clouds. Latham *et al*. (2008) estimate the increase in marine stratiform cloud albedo, $\Delta\alpha_c$, is

$$\Delta\alpha_c = \frac{\Delta\alpha_a}{.175\,f} = 1.482\frac{-\Delta F}{.175\cdot f\cdot 341} \approx \frac{-\Delta F}{40\cdot f}, \tag{7}$$

where .175 is the fraction of the Earth covered by marine stratiform clouds and *f* is the fraction of these clouds that are seeded. Further, Latham *et al*. estimate the volume of seawater (m^3 s^{-1}) that must be injected to achieve a particular increase in cloud albedo. Table 8 details the required increase in cloud albedo and the required rate of injection as a function of desired forcing.

Table 8: Required Injection Rate for Marine Stratiform Cloud Albedo Enhancement

Negative Forcing (W m^{-2})	Required Change in Planetary Albedo, $\Delta\alpha_p$	Minimum Fraction of Clouds that Must be Seeded	Required Change in Cloud Albedo, $\Delta\alpha_c$			Required Injection Rate (m^3 s^{-1})		
			f = .25	*f* = .50	*f* = 1	*f* = .25	*f* = .50	*f* = 1
1	.003	.14	.099 (14-33%)	.050 (7-17%)	.025 (4-8%)	12.7	8.6	7.2
2	.006	.29	NA	.099 (14-33%)	.050 (7-17%)	NA	25.4	17.3
3	.009	.43	NA	.149 (21-50%)	.074 (11-25%)	NA	57.9	31.3

The minimum fraction of clouds that must be seeded is based on Latham et al.'s estimate that the number of droplets within the clouds can be increased by at most ten times (Latham et al., 2008). The cells marked "NA" are thus technologically infeasible. The numbers in parenthesis are the percentage increases in cloud albedo based on a natural marine stratiform cloud albedo of between .3 and .7 (Salter *et al*., 2008; Lenton and Vaughan, 2009). For example, an increase in cloud albedo of .099 (2 W m^{-2}, f = .50) represents an increase of 14% to 33%, which seems technologically feasible (Lenton and Vaughan, 2009). An injection of 25 m^3 s^{-1} equates to 0.785 km^3 (0.188 mi^3) per year, or about 4.9 billion barrels per year, which is about 17% of world oil consumption.

Salter *et a*l. (2008) investigate a range of wind-powered vessel designs and nominally consider a design able to inject 0.03 m^3 s^{-1}. Thus, it would take 288 vessels to offset 1 W m^{-2} if 50% of the available clouds are seeded (8.6/0.03). Salter et al. also estimate, based on vessel displacement and power requirements that each vessel would cost between £1 million and £2 million. We take the higher estimate and assume the vessels will cost about $US 3 million each.[7] We further assume, conservatively, that this fleet must be replaced every 10 years. Thus, the 10-year cost to offset 1 W m^{-2} (SRM 1) with 50% seeding would be about $860 million. The 200-year PVs of this recurring cost, beginning in 2025, using DICE's endogenous discount rate, is $0.90 billion. Given that the benefit of SRM 1 under Optimal Controls is $6.3 trillion, the direct benefit-cost ratio is over 7000 to 1 ($6.3/$0.00090). The benefit-cost ratios for each SRM strategy and each control environment are given in Table 9, assuming that 50% of available clouds are seeded.

In the case of a 2055 start, the costs and benefits do not begin for 40 more years. The PV of SRM 1 cost is $0.27 billion, yielding a B/C ratio of approximately 14,500 ($3.9/$0.00027). The fact that the B/C ratio is larger for the delayed start may be surprising given that the net befits are smaller. This result is of course a limitation of ranking based on the ratio between benefits and costs, instead of the difference between benefits and costs.

Benefit-cost ratios are also quite high in the low discount rate scenario. For example, the benefit of SRM 1 in this case was $12.3 trillion. The cost is $0.90 billion, yielding a B/C ratio of almost 14,000. Limiting temperature changes to 2°C also yields large B/C ratios. Clearly, the more one deviates from optimal emission reduction strategies the greater the value that should be placed on SRM.

Clearly, these B/C ratios are quite large. Part of the reason for this is that intervention takes place close to the Earth's surface, requiring less energy for deployment than either a sunshade or stratospheric aerosols, In addition, as Latham et al. (2008) point out, nature provides the energy to increase the droplet size by 4 to 5 orders of magnitude from that which enters the bottom of the cloud bottom compared to its size at the cloud top. These results strongly suggest that marine stratiform cloud albedo enhancement should be investigated more fully.

7 Based on an exchange rate of $1.5 per £1. Given the uncertainty in this estimate and its small magnitude, we assume these are in 2005 $.

Table 9: Benefit-Cost Ratios for Marine Stratiform Cloud Albedo Enhancement (50% Seeding)

SRM Strategy	Annual Injected Volume (km^3)	Number of Vessels Required	PV of Costs (trillions 2005 $)		Benefit-Cost Ratios				
							Optimal Controls		
			2025 Start	2055 Start	No Controls	Temp < 2°C	2025 Start Market Discount Rate (5.5%)	2055 Start Market Discount Rate (5.5%)	2025 Start Low Discount Rate (2.0%)
SRM 1	0.27	284	0.0009	0.0003	8,531	11,227	7,188	14,580	13,925
SRM 2	0.80	830	0.0026	0.0008	5,101	5,988	4,283	9,055	7,859
SRM 3	1.83	1881	0.0058	0.0018	2,889	3,191	2,413	5,365	4,265

4.2 Stratospheric Aerosol Injection

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 trillion grams = 1 billion kilograms = 1 million metric tons of sulfur). Rasch *et al*. (2008) use a coupled atmospheric model to better understand the role that aerosol particle size plays 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. Unfortunately, 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, the SRM 1 strategy requires an injection equivalent to approximately 1% of the sulfur 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 for our SRM 1 strategy.

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} (1.1 times that of S) and 64.07 g mol^{-1} (2.0 times that mass of S), respectively. The use of SO_2 would require about twice the capital as H_2S and we therefore assume the use of H_2S as a precursor. We note however that hydrogen sulfide is both toxic and flammable. In sum, in order to offset 1 W m^{-2} we would need to inject about 0.57 Tg H_2S per year.

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 cost of naval artillery and balloons were about the same, while 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 airplanes. 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, in this section, we estimate direct costs based on the use of naval artillery.

The NAS assumed that each artillery shell could carry a payload of 500 kg. Therefore, our SRM 1 strategy would require 1.1 million shells per year, or the continuous firing of about 2 shells per minute. The cost of this system was estimated to be \$40 per kg (2005 \$), or \$40 billion per Tg, to place aerosols in the stratosphere. Approximately \$35 of this cost (89%) is the variable cost of the ammunition and the personnel. The remaining \$5 is the capitalized cost of the equipment, which was assumed to have a 40-year lifetime. The yearly cost for SRM 1 would then be \$22.8 billion (0.57×40). The 200-year PV of this yearly cost, beginning in 2025, is \$230 billion, yielding a B/C ratio under Optimal Controls of 27 to 1 (\$6.3/\$0.23). The B/C ratios for each SRM strategy and emissions scenario are given in Table 10.

The direct B/C ratios for stratospheric aerosols appear to be quite attractive. The use of planes instead of artillery might further improve this performance. Likewise, Teller *et al*. (2003) have suggested the development of engineered particles could reduce the cost of our SRM 3 strategy to about \$1 billion per year, which is about an order a magnitude less that our current cost estimates. If true, this would result in B/C ratios on the order of 1000 to 1.

Table 10: Stratospheric Aerosol Benefit-Cost Ratios (Naval Rifles)

SRM Strategy	Annual Injected Mass ($Tg\ H_2S$)	Shell Firing Frequency (shells min^{-1})	PV of Costs (trillions '05 \$)		Benefit-Cost Ratios				
							Optimal Controls		
			2025 Start	2055 Start	No Controls	Temp < 2°C	2025 Start Market Discount Rate (5.5%)	2055 Start Market Discount Rate (5.5%)	2025 Start Low Discount Rate (2.0%)
SRM 1	0.57	2.2	0.23	0.07	32	43	27	56	53
SRM 2	1.13	4.3	0.46	0.14	29	34	24	51	44
SRM 3	1.70	6.5	0.68	0.21	25	27	21	46	36

4.3 Space Sunshade

Angel (2006) analyzes reducing the solar flux through the deployment of a large sunshade, composed of trillions of tiny (~1 g) autonomous spacecraft ("flyers"). These flyers would be placed in a 1-year period orbit slightly beyond the Lagrange-1 point (L1), which is approximately 1.5 million km from Earth. Angel optimizes his design in terms of mass, reflexivity, and distance from the Sun. As discussed below, the sheer scale of this project boggles the mind.

In order to offset 1 W m^{-2} the solar flux would need to be decreased by 1.46 W m^{-2}, taking into account the planetary albedo of .299 (1/(1-.299)). This is a 0.43% decrease in the solar flux and based on Angel's calculations, would require a total flyer cross section of 1.1 million km^2. Based on an individual flyer cross-section of 0.28 m^2 we find that 3.9 trillion flyers would be required with a total mass of 4.7 million MT. Based on the current design, each launch would include 800,000 flyers and therefore approximately 5 million launches would be required to put the SRM 1 screen in place. In is enlightening to put this number into perspective. If 800,000 flyers were launched every five minutes it would take almost 50 years to put the sunshade in place.[8] If we wished to have the sunshade in place within one year, we would need to launch about every 6 seconds, which Angel estimates could be achieved with multiple launchers.

Angel roughly estimates that the cost of the sunshade program to offset 4.23 W m^{-2} would be on the order of $5 trillion. This is broken out as follows: electromagnetic launchers ($0.6 trillion), flyers ($1 trillion), launches/fuel ($1 trillion), and development and operations ($2.4 trillion). Of this $5 trillion, 60% is ($3 trillion) is fixed cost. These estimates are really not estimates at all, but rather cost targets. For example, when Angel considers the cost lifting 20 million MT (what is required to offset 4.23 W m^{-2}) into high-Earth orbit, he writes "… for the sake of argument if we allow $1 trillion for the task, a transportation cost of $50 kg^{-1} of payload would be needed [$1 trillion / 20 billion kg]." In fact, as Angel notes, the current cost to achieve high-Earth orbit is $20,000 kg^{-1}, in which case launch costs alone would be $395 trillion. Similarly, in the case of manufacturing costs, Angel writes "An aggressive target would be the same $50 per kilogram as for launch, for $1 trillion total." The scale required to produce trillions of (tiny) spacecraft is unprecedented. The only spacecraft that have been manufactured in any "mass" quantity are the Iridium satellites, which Angel cites as costing $7000 kg^{-1}, in which case manufacturing costs for the sunshade would be around $135 trillion.

Angel's aggressive targets are based on assumptions regarding returns to scale, but the scale of this project is so far beyond anything that has every been attempted in the space industry, that we are uncomfortable using Angel's targets. Unfortunately, development of our own cost estimates is outside the scope of our current effort and we will have to leave this as an issue for further study.

4.4 Benefit-Cost Ratio Summary

Both stratospheric aerosol injection and cloud albedo enhancement have attractive *direct* B/C ratios. In the interest of space, Table 11 summarizes the B/C ratios for each SRM technology under optimal controls only, for the market discount rate and low discount rate scenarios. B/C ratios decline with increasing amounts of SRM. This is related to the quadratic nature of DICE's damage equation. Policy regimes that result in significant emissions reductions in the short term (e.g., low discount rate, temperature constraint) result in higher B/C ratios because SRM helps to delay these costly interventions.

8 In fact, just keeping up with the 2 ppm yr^{-1} increase in CO_2 under No Controls would require about 138,000 launches per year, or one launch every four minutes.

Table 11: Summary of Benefit-Cost Ratios for SRM (Market and Low Discount Rate Cases)

SRM Strategy	2025 Start Market Discount Rate (5.5%)		2055 Start Market Discount Rate (5.5%)		2025 Start Low Discount Rate (2.0%)	
	Stratospheric Aerosol	Cloud Albedo	Stratospheric Aerosol	Cloud Albedo	Stratospheric Aerosol	Cloud Albedo
SRM 1	27	7,188	56	14,580	53	13,925
SRM 2	24	4,283	51	9,055	44	7,859
SRM 3	21	2,413	46	5,365	36	4,265

5 SOME POSSIBLE OBJECTIONS AND RESPONSES

An earlier version of this paper received helpful comments from Dr. Anne Smith and Professor Roger Pielke, Jr. These comments raised valuable points that deserve explicit treatment. Space constraints, however, limit us to an 800-word response within the body of this paper rather than a rejoinder. Thus, before concluding, we address some of the main points raised by these valuable critiques.

5.1 Anne Smith

The main thrust of Dr. Smith's comments stresses the potential worth of applying a value of information (VOI) analysis to the issues discussed in this paper. This suggestion is valid and we would urge that later study of this type be undertaken.

At the same time, we note that the VOI calculation requires additional assumptions and analyses such as: the direct damages that may be caused by SRM, the increase in climate damages due to more rapid warming if SRM is halted, the mitigation strategy that should be selected given that R&D on SRM is pursued, the reliability of an R&D program, etc. Dr. Smith has done an admirable job at providing these additional assumptions, and she suggests that more accurate estimates could be obtained from the DICE model. Unfortunately, doing so is outside the scope of these comments and also, as we discuss below, it is, in some cases, beyond DICE's capabilities. We regard this as an excellent area of future research.

5.2 Roger Pielke, Jr.

Professor Pielke, Jr. has highlighted several important issues. He raises four objections.

A Contradiction in the use of BCA

Dr. Pielke's sees a contradiction in our noting that the *direct* benefit-cost ratios for SRM are large, but not arguing for immediate deployment. We see no such contradiction. As we argue throughout this paper, while the potential net benefits of SRM are large, indirect costs might still change the calculus. Only research can address this question. Our recommendation for research does not stem from a "skepticism" in our analysis, but rather from a recognition of our discussion that unknown and potentially large uncertainties remain.

The Inability to Accurately Anticipate Costs or Benefits

First, we begin by noting that the basis of the Copenhagen Consensus was to "present empirically based cost-benefit estimates." Thus, Professor Pielke's criticisms of our use of benefit-cost analysis are outside the framework to which we all agreed.

Second, Professor Pielke, while expressing doubts about the utility of BCA, believes that our paper did not actually employ it. He writes that that there are "no policy recommendations [in our paper] that result directly from the cost-benefit analysis." We disagree. The case for studying SRM, to begin with, rests on the evidence that in order to achieve net benefits, greenhouse gas (GHG) control policies must be structured to accept substantial amounts of damage from climate change. Furthermore, our paper uses BCA in winnowing the technologies worthy of R&D and setting priorities among them.

Third, Professor Pielke "disagrees that cost-benefit analysis tells us anything meaningful about how much should be invested in research or what the potential payoffs might be." Why then does he recommend research into climate engineering? He bases his recommendation for research into *climate engineering* because it "has considerable value to advancing fundamental understandings of the global earth system." This reasoning applies to climate research in general. Why then call it "climate engineering" research?

Finally, Professor Pielke cites the work of Goes *et al*. (2009). He avers that "the same (or a very similar)" model could produce different results. In fact, these authors used a modified version of DICE that differed quite substantially from our own. They also assumed a fundamentally different implementation of SRM. The differences in modeling and scenarios make the results difficult to compare. Further, Goes *et al*. acknowledge that future learning might raise SRM's net benefits and expand the range of conditions in which substituting SRM for GHG control would pass a cost benefit test. This observation seems to endorse precisely the kind of R&D proposed in our paper.

Reliance of a Demonstrably Incorrect Conceptual Model of How Climate Engineering Influences the Climate System

Professor Pielke's notes that the science underlying SRM is not well understood and doubts that DICE depicts it accurately. From this note of doubt, Professor Pielke wishes to segue to the conclusion that cost-benefit analysis is at least useless and possibly misleading. However, as Dr. Smith argues, attempting to understand the benefits of climate engineering, while the science is still evolving, is useful. Such an effort can help to highlight what is not known, identify critical assumptions, and focus future research. We share her views.

Climate Engineering as a Technological Fix

Professor Pielke cites Sarewitz and Nelson (2008), as do we. Sarewitz and Nelson state three rules that, in their judgment, define where technological solutions to social problems are likely to work and where they are not. Professor Pielke, however, claims that the Sarewitz Nelson rules argue against research on SRM, a claim that Sarewitz and Nelson do not make. In fact, Nelson's previous work makes clear that the sort of BCA that we use to show SRM's superiority to AC is an important and valid part of the R&D selection process (Nelson and Winter 1977).

Further, Dr. Pielke's effort in this respect seems to us to stretch the Sarewitz-Nelson argument beyond its reasonable limits. Thus, rule one is merely that the solution should embody a clear cause and effect relationship. SRM does embody such a relationship. Much, although not all, of the damage caused by climate change arises from warming. SRM is designed to lessen warming. Rule two calls for clear metrics of success. SRM will either reduce warming or it will not. Rule three suggests that odds of success are better the smaller are the required advances in science and technology. In fact, the volcanic record and existing evidence of marine-cloud formation suggest that well-established scientific knowledge underlies both stratospheric aerosols and marine cloud whitening. True, SRM will require new knowledge of climate science. At the same time, AC faces the challenge of finding processes that can accomplish it at a cost that society is willing to pay and with less risk than they are willing to bear. Neither is certain.

6 CONCLUSION

6.1 Limitations of the Results

Any assessment of SRM and AC will be limited by the current state of knowledge, the rudimentary nature of the concepts, and the lack of prior R&D efforts. As noted in §1.1, this analysis relies on numbers found in the existing literature and existing climate change models. These inputs to our analysis are admittedly speculative; many questions surround their validity, and many gaps exist in them. This paper has also stressed the potential importance of transaction costs and "political market failures". Finally, 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. How will SRM impact regional precipitation patterns and ozone levels? To what extent can SRM be scaled to the levels considered here? What is the best method for aerosol injection? Are there other side effects that could invalidate the use of SRM? These are just a few of the questions that a well-designed research program should be designed to answer.

6.2 Principal Implications for Climate Policy

This analysis, then, can claim to be only an early and partial look at the potential benefits and costs of CE. Even so, the large scale of the estimated direct net benefits associated with the stratospheric aerosol and marine cloud whitening approaches are impressive. One might draw several preliminary conclusions from our results. These include:

- The direct B/C ratio for stratospheric aerosol injection is on the order of 25 to 1, while the B/C ratio for marine cloud whitening is around 5000 to 1. Net benefits are clearly large relative to plausible costs of an ambitions R&D effort. Problems could indeed surface in the course of future research. Indirect cost issues are much more likely to preclude or severely limit the use of SRM than are direct costs. Much of the R&D effort, therefore, should seek to narrow the uncertainties that surround these issues. Nonetheless, the results of this initial benefit-cost analysis place the burden of proof squarely on the shoulders of those who would prevent such research or would place *ex ante* arbitrary restrictions on its progress.

- The space sunshade appears to be an exception to this conclusion. This conjecture rests on the sunshade's far less promising B/C ratio, the extremely high economic risks entailed by its massive fixed costs, and its large scale and high technological risk.

- The greater the degree to which the global GHG control regime falls short of optimal in the policy tools that it employs, the targets it sets, or the gaps in its participation, the greater the potential value of SRM. However, SRM yields large net benefits even with an optimal control regime.

- Transaction costs and failures of the policy market are likely to affect SRM just as they do all other climate policy options. These costs could greatly affect its benefits and costs. The deferred deployment scenario for SRM, as described in §3.3, offers an example of the possible impact on benefits. At least in this example, net benefits fall, but remain large. In some areas, the political transaction costs of SRM may exceed those of other options. In other areas its costs may be lower. For example, some reasons exist for hoping that SRM may be a less tempting target for pork barrel politics than are some other responses to climate change.

- Insofar as possible, the transaction costs and the effects of political market failures should be recognized as likely to affect CE, as well as all other options for dealing with climate change. Even when the effects cannot be quantified *ex ante*, they should be explored as thoroughly as possible in qualitative terms. BCA should attempt to assess these costs consistently across all climate policy options.

- SRM is more promising than AC, but the latter, despite its current high costs, merits a secondary R&D effort. It offers a particularly low risk strategy with appealing institutional features that resemble those of SRM.

- Future research efforts should be more heavily focused on SRM. Such research should seek to remove uncertainty regarding possible side effects that SRM may cause and the associated risks. It should also address the technical and political feasibility of aerosol injection and marine cloud whitening, and explore the degree to which these approaches can be scaled, their deployment and operational costs, and their impact on other climate change policies. Some research should also be directed towards development of engineered particles. Such particles may improve the cost and environmental profile of aerosol injection. Finally, research funding should be allocated for benefit-cost studies so as to improving our results. This would include: the quantification of uncertainty, side effects, and the ability of CE to reduce the risk of abrupt climate change, as well as quantification of the indirect costs discussed above.

While our analysis is preliminary, we believe it makes a strong case that the potential net benefits of SRM are large; the question is whether or not the indirect costs will change the calculus. Only research can answer this question.

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COPENHAGEN CONSENSUS ON CLIMATE

The science is clear. Human-caused global warming is a problem that we must confront.

But which response to global warming will be best for the planet? The Copenhagen Consensus Center believes that it is vital to hold a global discussion on this topic.

The world turned to scientists to tell us about the problem of global warming. Now, we need to ensure that we have a solid scientific foundation when we choose global warming's solution. That is why the Copenhagen Consensus Center has commissioned research papers from specialist climate economists, outlining the costs and benefits of each way to respond to global warming.

It is the Copenhagen Consensus Center's view that the best solution to global warming will be the one that achieves the most 'good' for the lowest cost. To identify this solution and to further advance debate, the Copenhagen Consensus Center has assembled an Expert Panel of five world-class economists – including three recipients of the Nobel Prize –to deliberate on which solution to climate change would be most effective.

It is the Copenhagen Consensus Center's hope that this research will help provide a foundation for an informed debate about the best way to respond to this threat.

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