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CLIMATE ENGINEERING: COST BENEFIT AND BEYOND

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Climate Engineering: Cost benefit and beyond

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Abstract

International efforts on abating climate change, focusing on reductions of greenhouse gas emissions, have thus far proved unsuccessful. This motivates exploration of other strategies such as climate engineering. We modify the Dynamic Integrated model of Climate and the Economy (DICE), and use it in a cost-benefit analysis of climate engineering specifically deposition of sulphur in the stratosphere. The model simulations show that climate engineering passes a cost-benefit test. The cost of postponing climate engineering by 20-30 years is relatively low. Going beyond these standard cost-benefit analyses, climate engineering may still fail. Voters may dislike the idea of climate engineering; they do not like the idea of tampering with nature, and their dislike stands independent of outcomes of cost-benefit analyses.

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1 Reconsidering climate change governance

International governance for climate change has so far not been a success. Most of the world's countries have participated in the United Nations' *Framework Convention Climate Change Convention* since 1992. The goal of the climate change convention is to stabilize the amount of greenhouse gases in the atmosphere to avoid dangerous man-made climate change. Almost twenty years after the founding of the climate change convention, and after 15 Conferences of the Parties, including Kyoto 1997 and Copenhagen 2009, the overall concentration of greenhouse gases has increased. The concentration of atmospheric carbon dioxide increased by 5% during the 1995–2005 period, the highest measured decadal increase since recordings began in the 1950s (Intergovernmental Panel on Climate Change, 2007, p 2).

Lack of success in stabilizing greenhouse gases in the atmosphere motivates the exploration of other strategies and approaches to abate climate change. One of these strategies is to engineer a radiation balance in the atmosphere. Pumping sulfur aerosols into the sky reduces the amount of solar radiation entering lower parts of the atmosphere, thus reducing global temperatures. In 1991, Mount Pinatubo, a volcano located in the Philippines, erupted, releasing large amounts of sulfur, thus creating a natural experiment in climate engineering. The eruption led to a global cooling of 0.5 °C the following year (Hansen *et al.*, 1992).

Climate engineering is more likely to implement than emission reduction; the direct cost of climate engineering is relatively low, and a small coalition of countries may partake in it, (Barrett, 2008). These characteristics overcome consensus rules that govern the UN's Climate Change Convention. Within the UN, a handful of countries can block proposals. Proposals agreed upon may be so because they are part of "business as usual." Because climate engineering seems technical and economically feasible, it is more likely to be undertaken.

Another advantage of climate engineering is that it may be put into effect quickly, promoting its use as an emergency tool in the case of rapid climate change.

However, climate engineering may have serious negative consequences. Important environmental risks are drought in Africa and Asia, ozone depletion, very rapid global warming if climate engineering is interrupted, and whitening of the sky (Robock *et al.*, 2009). Although it is possible to foresee some environmental consequences, it will still be impossible to anticipate *all* the consequences of climate engineering, making it a project of uncertainty.

In this paper, we present a cost-benefit analysis of climate engineering. We add climate engineering as a policy variable in the Dynamic Integrated model of Climate and the Economy (DICE); developed by William Nordhaus and his coworkers.[1] The optimal mix of policy instruments realizes by equalizing the marginal benefits and costs of mitigation, adaptation and climate engineering.

Furthermore, we go beyond the standard cost-benefit analyses and discuss climate engineering in a public choice perspective. Even though climate engineering passes a standard cost-benefit test, it may fail as a policy in practice. As there is skepticism towards climate engineering in the scientific community, this may also be true in the public. Voters may dislike the idea climate engineering, independent of the outcome of cost-benefit analyses. Therefore, politicians may find it difficult to advocate climate engineering.

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[1] DICE is an integrated dynamic model, combining an economic growth model rooted in the work of Ramsey (1928) with a global climate model. Nordhaus (1994) developed the original DICE, with further contributions by Nordhaus and Boyer (2000). We use the version documented by Nordhaus (2007), delta version 8, downloaded 03.12.2009.

2 Climate engineering

We define climate engineering as deliberately changing the radiation balance in the atmosphere. The radiation balance is constant if the amount of energy absorbed as sunlight equals the amount emitted back as long-wave radiation. The current net balance of about 240 W/m2 predicts a temperature of -19 C, which equals the observed temperature at 5 km altitude (Le Treut *et al.*, 2007, p 97). The temperature on Earth is higher, and one reason for this is the presence of greenhouse gases in the atmosphere. These gases absorb sunlight, thus causing temperature increases. Climate engineering reduces radiation absorbed in the atmosphere by reflecting more of it back into space. An additional reflection of 4 W/m2 balances the heating caused by doubling of CO2 concentrations (Blackstock et al., 2009, p8).

The reflection of incoming short-wave radiation can be changed by using different technologies such as: i) increasing ocean reflection by producing micro-bubbles, ii) increasing land surface reflectivity by crop modification, iii) cloud whitening, and iv) adding sulfur to the stratosphere, which we focus on here. For more details, see Blackstock *et al.* (2009, p9).

In this paper, we limit the policy of climate engineering to the emission of sulfur into the stratosphere. Emitting sulfur into the stratosphere reflects solar radiation back into space before it can contribute to warming the atmosphere.[2] Volcanic eruptions have acted as natural experiments by emitting large quantities of sulfur into the stratosphere. Mount Pinatubo erupted in 1991, leading to a global cooling of about 0.5 °C the following year (Hansen *et al.*, 1992). The eruption of Tambora in Indonesia in 1815 was the prime contributor to the following “year without summer,” in which the temperature from July-August on the Iberian Peninsula was 2-3 degrees lower than average for those months (Trigo *et al.*, 2009).

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[2] For a recent review of climate engineering using stratospheric sulfate aerosol, see Rasch *et al.* (2008).

To cool down a planet, Budyko (1977) proposed using airplanes to burn sulfur during flight in the stratosphere to reflect sunlight. According to Rasch *et al.* (2008, p. 4008), the idea of deliberately changing Earth's climate goes back to the 1830s, when J.P. Espy suggested lighting a large fire to change the intensity and frequency of rain. One hundred years later, in 1955, John von Neumann discussed deliberately changing the radiation balance in order to change the climate. According to von Neumann, the investment cost of changing the radiation balance is low, but "(t)he main difficulty lies in predicting in detail the effects of such drastic intervention." However, he was optimistic on behalf of science, as "(o)ur knowledge of the dynamics and controlling process of the atmosphere are rapidly approaching a level that would permit such predictions" (Neumann 1955,1981, p 41).

Several studies have followed up on Budyko's suggestions of cooling the planet by emission of sulfur into the atmosphere. In the USA, the National Academy of Sciences (1992) analyzed climate engineering in their report on policy implications of greenhouse warming. Of major concern, were the following three questions: *i)* Does it appear feasible that engineered systems could actually mitigate the effects of greenhouse gases? *ii)* Is it technically feasible at a reasonable cost? *iii)* Do the proposed systems have effects, besides the sought-after effects, that might be adverse, and can these be accepted or dealt with? They answered yes to *i)* and *ii)* and requested further scrutiny regarding *iii)*.

IPCC's latest assessment report was less inclined to answer yes to these questions (Barker *et al*., 2007). Climate engineering tends to be speculative; many of its environmental side effects are uncertain, and it is without a clear institutional framework for implementation. In Great Britain, the Royal Society made an extensive report on climate engineering, requesting more research with focus on the technological feasibility, cost-effectiveness and environmental side effects (Shepherd *et al*. 2009).

Rasch *et al.* (2008, p. 4033) conclude in their overview of climate engineering using stratospheric sulfate aerosols that this “[…] technique might be used in a planetary emergency to mitigate some of the effects of a projected global warming. […] However, many uncertainties remain in understanding the influence of climate engineering on the climate system […]. More work is required to understand the costs, benefits and risk involved, and to reconcile the legal political and ethical issues of climate engineering.”

Crutzen (2006, p 217) concludes his editorial essay about climate engineering with a call for active scientific research on the topic. He also stresses that most preferable would be “[…] if emissions of the greenhouse gases could be reduced so much that the stratospheric sulphur release experiment would not need to take place.”

3 Implementing climate engineering in DICE

DICE integrates an economic growth model, rooted in the work of Ramsey (1928), with climate. The basic tradeoff is consumption now and consumption in the future.[3] Increased consumption now reduces investment and precludes some future production possibilities. This shrinkage reduces future consumption. Output is determined by a Cobb-Douglas production function with labor, capital, and greenhouse gases energy as inputs. These greenhouse gases enter the atmosphere and upper and lower oceans and, over time, affect the radiation balance and, therefore, temperature. Increases in temperature again reduce production possibilities and, therefore, reduce future consumption.

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[3] Consumption, measured in dollars in DICE, includes food, cloth, housing, health services, schooling, etc. Investment and capital, also measured in dollars, include equipment, education, research, etc.

We include climate engineering in the DICE model by modifying the radiation balance equations and by adding a cost element. For more details about the DICE model and how we modified it, see Appendix A. Based on studies of the volcanic eruption of Mount Pinatubo in 1991, the effect of the sulfur injection on radiation concentration ranged from 0.75 Wm^{-2}/TgS (Crutzen, 2006) to 2.5 Wm^{-2}/TgS (Rasch *et al.*, 2008). We computed an average of these: 1.67 Wm^{-2}/TgS = ϖ in the equation (A 20) in the appendix.

The policy-relevant range of sulfur injection in the atmosphere is 1–5 Tg S, according to Crutzen (2006) and references herein.[4] A load of 5 Tg S will outweigh the warming caused by a doubling of current CO2 concentrations. Compared with the overall concentration of sulfur in the atmosphere, 1–5 Tg S is small, perhaps 2% (Rasch *et al.*, 2008, p. 4032). Annual sulfur emissions due to human activities ranged from 0.8 Tg S in 1850 to a peak of 73 Tg S in 1987 (Stern 2005). Current non-volcanically deposition of sulfur in the stratosphere is 0.1 Tg S (Rasch *et al.*, 2008, p. 4011), and accordingly, 1-5 Tg S are relative large numbers. However, after the eruption Mount Pinatubo in 1991, the concentration of sulfur in the tropical stratosphere peaked at 10 Tg S and declined to 6 Tg S within 6 months (Crutzen 2006).

Cost of climate engineering

The cost of climate engineering includes the cost of depositing sulfur in the atmosphere, of changing the environments, and the economic and social consequences of changing the environment. These costs are highly uncertain and this uncertainty is in itself a cost.

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[4] 1 Tg S = 10^{12} grams of sulfur = 1 million tons sulfur.

The cost of depositing sulfur in the atmosphere depends on the residency period of the deposited sulfur. In the stratosphere, sulfur particles have a residency period of one to two years, compared with a couple of weeks in the troposphere. A longer residency period reduces the required amount of sulfur significantly. In addition, sulfur injected into the stratosphere disperses evenly, and therefore influences radiative forcing over a larger area. The size of the sulfur particles, as well as the chemical forms of which they are part, also effect the cost. Large particles, such as those from volcanic eruptions, are less effective in scattering incoming solar radiation and, in addition, absorb some outgoing energy (Rasch *et al.*, 2008). However, the technologies for delivery are immature and cost estimates are, therefore, highly uncertain.

The cost of deposition of 1 Tg S is stipulated to be in the range of 225–30,000 million USD depending on the technology used (Robock *et al.* 2009). This range corresponds to 0.0004–0.045% of the world’s total production of sulfur in 2005, as calibrated in DICE. Robock *et al.* describe some deposition technologies: *i)* Planes burning sulfur through their fuel system or having a separate dispersal system, *ii)* shells filled with sulfur and shot into the stratosphere where they burst, *iii)* balloons filled with sulfur, which explode at the correct altitude, and *iv)* hoses connected to tall towers.

The cost of climate engineering includes environmental impacts and social and economic consequences of environmental changes. Environmental damage includes effects such as drought in Africa and Asia and ozone depletion. There may also be some positive effects: agricultural productivity may increase in some regions, and some regions may experience a better climate. Furthermore, these consequences are uncertain and this uncertainty is a cost in itself. All human decisions are similar; we make decisions every day under conditions of uncertainty. These decisions are made in a trial and error process; decisions are adjusted through these processes. However, there are marked differences; the project climate engineering is larger and adjustment is harder to achieve.

The technology of sulphur deposition in stratosphere is immature and environmental consequences are mostly unknown. Our research strategy for dealing with these uncertainties is to use a broad range of cost functions with a specified upper limit. This upper limit is calibrated so as to render the net benefit of climate engineering negative within the logical framework of the DICE model. With cost functions above this upper level, it is never optimal - as calculated in the DICE model - to use climate engineering.

We model the overall cost of climate engineering as a share of worlds GDP, in the same way DICE represents the cost of climate change.[5] The cost share is:

$$D_t = \frac{1}{1 + \alpha_1 G_t + \alpha_2 G_t^2},$$

where G_t is the increased concentration of sulfur in the stratosphere in period t and (α_1, α_2) are parameters. This reduces output Q_t as follows:

$$Q_t^{Net} = D_t Q_t^{Gross}.$$

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[5] This cost function is similar to the cost of climate change in DICE; a share of the world's gross production, equations (A4)* and (A6) in the appendix and Nordhaus and Boyer (2000, chapter 4). The cost includes the impact on agricultural, health, time use and catastrophic output. The catastrophic impact is a certainty equivalent based on a panel of experts' best estimates of probabilities of a drop in worlds GDP similar to that of the Great Depression for specific temperature increases. In the current version of DICE, the parameterized cost of climate change is 1,7 percent of worlds GDP for 2.5 Celsius increase and 9,0 percent for a 6.0 Celsius increase.

We use three different parameter sets (α_1, α_2) of the cost function, reported in Table 1. Costs of climate engineering are higher the more we engage in it.

(Insert Table 1 here)

4 Cost-benefit analysis

The fundamental trade-off in our cost-benefit analysis is current consumption and consumption in the future. Increased consumption today reduces investment in man-made capital and increases emissions of greenhouse gases. Less investment and higher concentrations of greenhouse gases in the atmosphere come with a cost; production possibilities shrink in the future and in that way reduce consumption in the future. Investments in climate engineering and emission reduction reduce current consumption, but increase consumption in the future and near future, respectively, as production possibilities increase.

We present results from three policies: “emission control,” “climate engineering,” and “both emission control and climate engineering” compared with “business as usual.” Adaptations to climate change adjust optimally in all policies including business as usual. The net economic benefit of a policy is the present value of the differences in consumption in business as usual and consumption of the policy, discounted by the business at the usual interest rate. For more details, see the appendix.

Our point of departure is that emission reduction is hard to realize and that climate engineering is an alternative policy. The net economic benefits of climate engineering range from 1.5 to 17.8 trillion US dollars depending on the assumption of cost of climate engineering. The net benefit is particularly high considering the low cost of climate engineering due to the high benefit in terms of reduced climate change damage. The temperature increases above the pre-industrial level is below 2 degrees Celsius for lower and medium costs of climate engineering (see Figure 1).

Postponement gives us time, through research and field experiments, to learn more about the consequences of climate engineering, and we can act in accordance to this information. Postponing climate engineering by 30-50 years reduces the total net benefit by less than 10 percent. Postponing climate engineering to 2050 reduces the net economic benefit by 1,5 percent using high cost of climate engineering and 6,5 and 9,5 percent using for medium and low cost of climate engineering, respectively.

Combining climate engineering and emission control increases the net benefit even further to 4.3 – 18.0 trillion US dollars, depending on parameters in the cost of the climate engineering function. As expected, these increases in net benefits are higher due to the higher cost of climate engineering. The use of sulphur decreases by adding emission reduction as a policy instrument. If climate engineering costs are low, the increase in the net benefits is relatively small and the annual use of sulphur remains almost the same. For high-cost parameters, the net gain increases from 1,5 to 4,3 trillion US dollars, and the use of sulphur decreases to 0,4 Tg S. Increasing the forcing efficiency, the coefficient ϖ in equation (A20) in the appendix, increases as expected the net benefit of climate engineering; calculations are not shown here.

(Table 2 and Figure 1 about here)

Cost-benefit analyses of climate engineering pass the cost-benefit test even for - what we label here as – the high cost of climate engineering. If the costs of climate engineering are low or medium, the benefit is considerably higher than costs. These results hinge on our assumptions. In DICE, both the economy and climate policies are assumed to work efficiently. In the economy, markets allocate labour and capital in an efficient way. Abatement policies are implemented efficiently, either as worldwide taxes on greenhouse gases or as functioning permit markets for greenhouse gases. In the next section, we go beyond cost-benefit analysis results and discuss implementation of climate engineering.

5 Beyond cost-benefit analysis

In his paper "Incredible economics of geoengineering," Scott Barrett argues the future implementation of climate engineering seems more likely than not,

> "[partly] because the incentives for countries to experiment with geoengineering, especially should climate change prove abrupt or catastrophic, are very strong. It is also because the incentives for countries to reduce their emissions are weaker. Geoengineering and emission reductions are substitutes." Barrett (2008, pp 45-46)

Even in the face of such strong incentives climate engineering may still be difficult to implement. A majority of the electorate may be negative about climate engineering; they do not like the idea of tampering with nature, and their dislike stands independent of outcomes of cost-benefit analyses. In these circumstances, politicians will find it difficult to pursue climate engineering. Even if a majority of voters agrees on implementing climate engineering, it may still be too costly to implement if a minority of voters *strongly* disagree. This effect can explain why most democracies have super-majority rules for important questions (Buchanan and Tullock 1963). In a similar way, countries may find it difficult to implement climate engineering if other nations *strongly* oppose. Although there is no formal rule that precludes a country from pursuing climate engineering, the political cost of implementing it when other countries *strongly* oppose may be too high.

Voters may oppose climate engineering in the same way as scientists do. Climate engineering is controversial in the scientific community. Thomas Schelling wrote in 1996 that in any discussion ten years ago about climate engineering, "part of the audience thought it crazy and most of the rest thought it dangerous" (Schelling 1996, p. 303). Ten years later, scientists opposed the publication of Paul Crutzen's editorial essay (2006) on climate engineering "even after peer review and revisions, for various and sincere reasons that are not wholly scientific" (Cicerone 2006, p 221). These controversies in the scientific communities mirror, we believe, similar controversies among voters. Their beliefs and standpoints influence the possibilities of realizing climate engineering.

During a public debate project, participants were skeptical about the deposition of sulfur in the stratosphere (NERC 2010). The 87 participants, randomly drawn and between the ages of 18 and 72, had a debate on climate engineering. The participants were more supportive of planting trees than of the deposition of sulfur in the atmosphere; 93 percent "strongly / tend to support" aforestation compared to 21 percent for deposition of sulfur particles in the stratosphere (NERC 2010, p 24). Differences in supportiveness between planting trees and deposition of sulfur in the stratosphere are explained by what the participants taught natural. Planting trees were natural. Deposition of sulfur in stratosphere is not natural; "scientists do not have the right to interfere deliberately without knowing the full consequences" (NERC 2010, p 31).

In general, an ethical principle, such as “not tampering with nature,” may be an effective rule even though humans cannot understand and rationalize it. Ethical principles and Rules for behaviors reflect collective experiences that “have passed the slow test of time” (North 1993, p 5). Such principles and rules may be efficient, but there is no guarantee that they are. As time passes and new challenges arise, such as climate change, ethical principles may change.

Arguments against “not tampering with nature” include those that say humans intentionally interfere with nature in many areas; for example in the agricultural sector. Man cultivates soil to make it more fertile, resulting in poisons being deposited into rivers, along with pesticide and fertilizer runoff. Man breeds cattle, leading to higher emissions of methane, a powerful greenhouse gas. Agricultural and climate engineering, however, differs in time and scale. Agriculture develops through an adaptive process involving farmers, buyers and local communities over thousands of years. Local environmental consequences internalize in trial-and-error processes. Climate engineering is, in this comparison, a large-scale project in which humans have less experience. One wrong step may result in dramatically irreversible consequences. These differences between agricultural and climate engineering may explain people’s acceptance of agricultural interference in nature while being skeptical towards climate engineering.

In a similar way, participants in the NERC’s public debate project stress the difference between doing something deliberately and doing it accidentally. The participants meant that it is wrong to experiment with depositing sulfur in the stratosphere. On the other hand, burning coal and oil, and thus causing increases in greenhouse gases in the atmosphere, was a necessity not considered as an experiment, NERC (2010, p 55).

Another standpoint in the scientific community is that climate engineering may be the first step on a slippery slope that leads to global climate management (Virgoe 2009). John von Neumann (1955), anticipating that climate management could improve agricultural productivity, also warns about the slippery slope:

> "(U)seful and harmful techniques lie everywhere so close together that it is never possible to separate lions from the lambs. This is known to all who have laboriously tried to separate secret "classified" science or technology (military) from the open kind; success is never more – nor intended to be more – than transient, lasting perhaps half a decade. Similarly, a separation into useful and harmful subjects in any technological sphere would probably diffuse into nothing in a decade… After global climate control becomes possible, perhaps all our present involvements will seem simple. We should not deceive ourselves: once such possibilities become actual, they will be exploited. It will, therefore, be necessary to develop suitable new political forms and procedures."

This slippery slope was also prominent in the public debate project reported in NERC (2010); interference with natural systems, such as climate engineering, might legitimize interference in nature later (NRCE p. 34).

Climate engineering, combined with natural variation in climate over space and time, causes regional differences in climate impact over time. Climate engineering may benefit a specific region – at least a majority of people in this region may believe it will do so. In other regions, people may believe that consequences of climate engineering are severe. These regional differences are open to political challenges both in field experiments and in the eventual implementation of climate engineering. Morrow *et al.* (2009) compare climate engineering testing with that of nuclear weapon testing near populated areas and of subjecting poor rural African-Americans to medical experiments. Scholars realizing these potential regional conflicts have called for international governance of climate engineering (Barrett 2008 and Lin 2009).

6 Conclusion

Climate engineering passes a standard cost-benefit test given the range of functions for the cost of engineering, but the uncertainty remains. The cost of postponing climate engineering is relatively low; this provides us time to resolve some of the uncertainties related to climate engineering.

Although climate engineering passes standard cost-benefit tests, the political machine has not yet approved it. A majority of the electorate may be negative about climate engineering; they do not like the idea of tampering with nature, and their dislike stands independent of the outcomes of cost-benefit analyses. In these circumstances, politicians will find it difficult to pursue climate engineering, in societies with regular and fair elections as well as in societies with authoritarian regimes.

Both emission reduction and climate engineering require international governance. Elinor Ostrom remarks that an important lesson from her intensive study of governance of local public goods “is that simply recommending a single government unit to solve global collective action problems—because of global impacts—needs to be seriously rethought and the important role of smaller-scale effects recognized” (Ostrom, 2009, p. 34).

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Appendix Equations and Variables —Modified DICE

New and modified equations are marked by asterisks.

(A1) $W = \sum_{t=0}^{T} u[c(t), L(t)]R(t)$

(A2) $R(t) = (1+\rho)^{-t}$

(A3) $u[c(t), L(t)] = L(t)[c(t)^{1-\alpha} /(1-\alpha)]$

(A4)* $\mathrm{Q(t)} = [1-\mathrm{D(t)}][1-\Omega(\mathrm{t})][1-\Lambda(\mathrm{t})]\mathrm{A(t)K(t)}^{\gamma}\,\mathrm{L(t)}^{1-\gamma}$

(A5)* $\mathrm{D(t)} = 1-(1/[1+\vartheta_1 \mathrm{G(t)} + \vartheta_2 \mathrm{G(t)}^2])$

(A6) $\Omega(\mathrm{t}) = 1-(1/[1+\psi_1 \mathrm{T_{AT}(t)} + \psi_2 \mathrm{T_{AT}(t)}^2])$

(A7) $\Lambda(t) = \pi(t)\theta_1(t)\mu(t)^{\theta_2}$

(A8) $\mathrm{Q(t)} = \mathrm{C(t)} + \mathrm{I(t)}$

(A9) $c(t) = C(t)/L(t)$

(A10) $K(t) = I(t) + (1-\delta_K)K(t-1)$

(A11) $E_{Ind}(t) = \sigma(t)[1-\mu(t)]A(t)K(t)^{\gamma}\,L(t)^{1-\gamma}$

(A12) $CCum \le \sum_{t=0}^{T} E_{Ind}(t)$

(A13) $E(t) = E_{Ind}(t) + E_{Land}(t)$

(A14) $M_{AT}(t) = E(t) + \phi_{11}M_{AT}(t-1) + \phi_{21}M_{UP}(t-1)$

(A15) $M_{UP}(t) = \phi_{12}M_{AT}(t-1) + \phi_{22}M_{UP}(t-1) + \phi_{32}M_{LO}(t-1)$

(A19) $M_{LO}(t) = \phi_{23}M_{UP}(t-1) + \phi_{33}M_{LO}(t-1)$

(A20)* $F(t) = \eta\{\log_2[M_{AT}(t)/M_{AT}(1750)]\} + F_{EX}(t) - \varpi G(t)$

(A21) $T_{AT}(t) = T_{AT}(t-1) + \xi_1\{F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{LO}(t-1)]\}$

(A22) $T_{LO}(t) = T_{LO}(t-1) + \xi_4[T_{AT}(t-1) - T_{LO}(t-1)]$

(A23) $\pi(t) = \varphi(t)^{1-\theta_2}$

Variable definitions and units

New variables are marked by asterisks.

$A(t)$	total factor productivity (productivity units)
$c(t)$	capita consumption of goods and services (2005 U.S. dollars per person)
$C(t)$	consumption of goods and services (trillions of 2005 U.S. dollars)
$E_{Land}(t)$	emissions of carbon from land use (billions of metric tons of carbon per period)
$E_{Ind}(t)$	industrial carbon emissions (billions of metric tons of carbon per period)
$E(t)$	total carbon emissions (billions of metric tons of carbon per period)
$*G(t)$	increase in level of sulphur in stratosphere due to climate engineering (Tg S)
$F(t)$	total radiative forcing (watts per square meter from 1900)
$F_{EX}(t)$	exogenous radiative forcing (watts per square meter from 1900)
$I(t)$	investment (trillions of 2005 U.S. dollars)

$K(t)$	capital stock (trillions of 2005 U.S. dollars)
$L(t)$	population and labour inputs (millions)
$M_i(t)$	mass of carbon in reservoir for atmosphere (i=AT), upper oceans (i=UP), and lower oceans (i=LO) billions of metric tons of carbon, beginning of period
$Q(t)$	net output of goods and services, net of abatement and damages (trillions of 2005 U.S. dollars)
t	time (decades from 2001–2010, 2011–2020, . . .)
$T_{AT}(t), T_{LO}(t)$	global mean surface temperature and temperature of lower oceans (°C increase from 1900)
$u[c(t), L(t)]$	utility function (utility per period)
W	objective function in present value of utility (utility units)
$\Lambda(t)$	abatement costs as fraction of world output)
$\mu(t)$	emissions-control rate (fraction of uncontrolled emissions)
$\Omega(t)$	cost of climate change as a fraction of worlds output
$*D(t)$	cost of climate engineering as a fraction of world output
$\varphi(t)$	participation rate (fraction of emissions included in policy)
$\pi(t)$	participation cost markup (abatement cost with incomplete participation as fraction of abatement cost with complete participation)
$\sigma(t)$	ratio of uncontrolled industrial emissions to output (metric tons of carbon per output in 2005 prices)

Parameters

New parameters are marked by asterisks.

α	elasticity of marginal utility of consumption (pure number)
$CCum$	maximum consumption of fossil fuels (billions of metric tons of carbon)
γ	elasticity of output with respect to capita (pure number)
δ_K	rate of depreciation of capital (per period)
$R(t)$	social time preference discount factor (per time period)
T	length of estimate period for model (60 periods_600 years)
η	temperature-forcing parameter (°C per watts per meter squared)
ϕ_{ij}	parameters of the carbon cycle (flows per period)
ψ_{ij}	parameters of damage function due to temperature increase
$*\vartheta_{ij}$	parameters of damage function due to climate engineering
$*\varpi$	efficiency of sulphur in reducing forcing (watts per meter squared per Tg S)
ρ	pure rate of social time preference (per year)
$\theta_1(t), \theta_2$	parameters of the abatement-cost function
ξ_{ij}	parameters of climate equations (flows per period) i=AT,UP, and LO and j= AT,UP, and LO

Cost-benefit calculations

The net economic benefit of a policy is the present value of the difference in consumption in business as usual (bau) and the policy discounted by the interest rate of business as usual:

$$\sum_{t=1}^{T}(C_t^{policy} - C_t^{bau})\beta_t$$

where the discount rates are determined recursively $\beta_t \equiv \beta_{t-1}(1+r_t)^{-10}$ and $\beta_1 = 1$. The real interest rate, r_t, is derived from the Ramsey-equation $r_t = \rho_t + \alpha g_t$, where g_t is the growth rate of per capita consumption and ρ_t is determined by solving $(1+\rho_t) = (1+\rho)^{10}$.

The net economic benefit is split into benefit, cost of climate engineering and abatement cost. By using equations (A4)* and (A8) and by defining $Y_t^j = A_t^j \left(K_t^j\right)^{\gamma}\left(L_t^j\right)^{1-\gamma}$ for j=bau and policy, the difference in the consumption pattern of policy and business as usual is

$$\begin{aligned}
& C_t^{policy} - C_t^{bau} \\
& = (Q_t^{policy} - Q_t^{bau}) - (I_t^{policy} - I_t^{bau}) \\
& = [(1-D_t^{policy})(1-\Omega_t^{policy})(1-\Lambda_t^{policy})Y_t^{policy} - (1-D_t^{bau})(1-\Omega_t^{bau})(1-\Lambda_t^{bau})Y_t^{bau}] - (I_t^{policy} - I_t^{bau}) \\
& \\
& \approx (\Omega_t^{bau}Y_t^{bau} - \Omega_t^{policy}Y_t^{policy} + (Y_t^{policy} - Y_t^{bau}) - (I_t^{policy} - I_t^{bau}) \\
& \quad + (D_t^{bau}Y_t^{bau} - D_t^{policy}Y_t^{policy}) \\
& \quad + (\Lambda_t^{bau}Y_t^{bau} - \Lambda_t^{policy}Y_t^{policy})
\end{aligned}$$

The first line on the right-hand-side of the approximation sign is the benefit including reduction in damage of climate change; the second line, the cost of climate engineering; and the last line is the abatement cost. The approximation is linear in the parameters $(\Lambda_t, D_t, \Omega_t)$.

Tables

Table 1 Cost of climate engineering as percentage of total world's GDP.

Cost of climate engineering (%)	Climate engineering (Tg S)	
	1	5
Low	0,1	1
Medium	0,5	5
High	1	10
Upper limit	2,4	40.0

Note: Upper limit is calculated from the "climate engineering" policy.

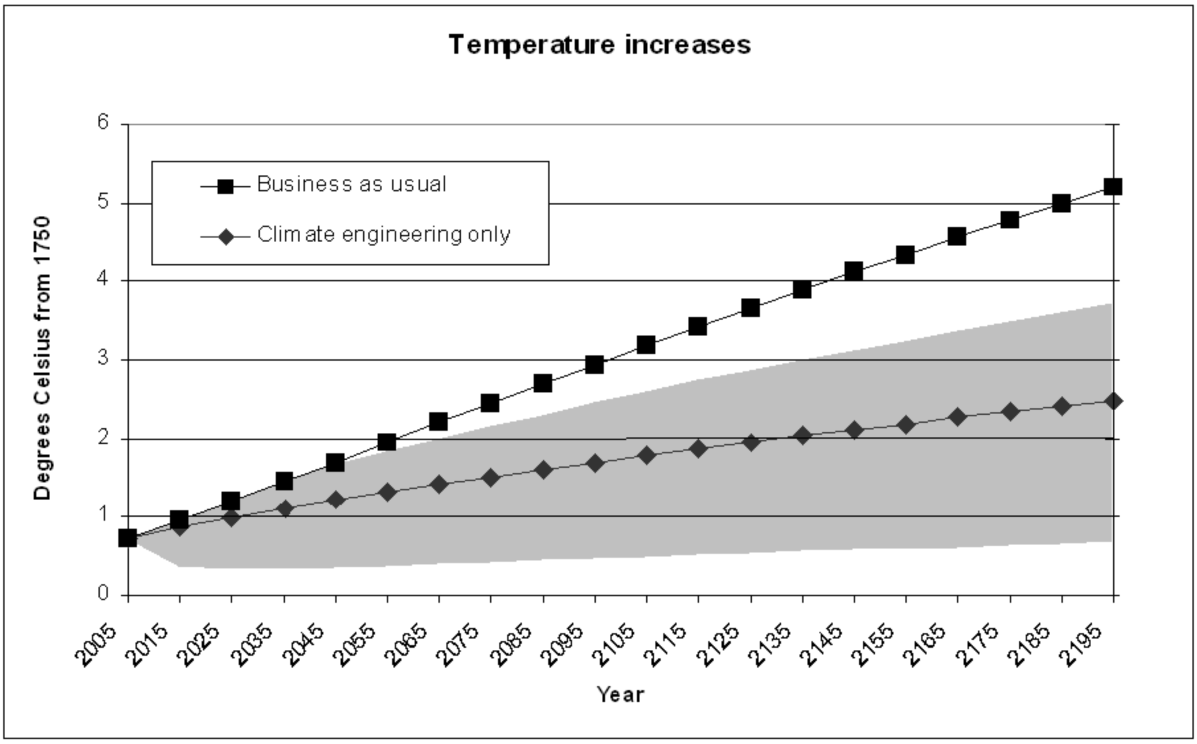
Table 2 Present value of net benefits and costs for policies "climate engineering," "climate engineering and emission control," and "emission control only" compared to business as usual. All measured in trillion USD (2005).

Policy	Net economic benefits	Benefits	Costs of climate engineering	Abatement costs	Annual use of sulfur (Tg S)
Climate engineering					
Low	17,8	22,4	4,9	na	2,7
Medium	5,9	13,7	8,0		1,4
High	1,5	5,5	4,0		0,7
Climate engineering and emission control					
Low	18,0	22,5	4,7	0,1	2,5
Medium	7,4	14,7	6,5	1,0	1,2
High	4,3	8,3	2,3	1,8	0,4
Emission control only	3,7	5,9	na	2,3	na

Notes: i) Low, medium, and high refer to cost of climate engineering. ii) Last column is mean annual use of sulfur for the first 200 years.

Figures

Figure 1 Temperature increases from pre-industrial time for “business as usual” and “climate engineering only.” Lower and upper borders of shadow areas are low and high costs, respectively, of climate engineering.



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