Climatic Change (2012) 110:1047–1066
DOI 10.1007/s10584-011-0102-0

The Tuvalu Syndrome

Can geoengineering solve climate's collective action problem?

Adam Millard-Ball

Received: 11 February 2010 / Accepted: 22 April 2011 / Published online: 2 June 2011

Abstract Geoengineering research has historically been inhibited by fears that the perceived availability of a technological fix for climate change, such as the deployment of space-based deflectors, may undermine greenhouse gas abatement efforts. I develop a game theoretic model to show that the credible threat of unilateral geoengineering may instead strengthen global abatement and lead to a self-enforcing climate treaty with full participation. A 'rogue nation' may wish to unilaterally geoengineer if it faces extreme climate damages (as with Tuvalu), or if there are minimal local side effects from geoengineering, such as hydrological cycle disruption or stratospheric ozone depletion. However, the costly global side effects of geoengineering may make it individually rational for other countries to reduce emissions to the level where this rogue nation no longer wishes to unilaterally geoengineer. My results suggest a need to model the impacts of a "selfish geoengineer" intent only on maximizing net domestic benefits, as well as a "benevolent geoengineer" out to restore global mean temperature and minimize global side effects.

1 Introduction

For a scientist or economist concerned about damage from climate change, the implicit taboo against discussing geoengineering as a realistic option to mitigate climate impacts is understandable. The promise of a technological fix for climate change might undermine the political will to reduce emissions. In practice, at least until very recently, this taboo has been effective in limiting both research output and policy discussions on geoengineering (Cicerone 2006; Fleming 2007). Geoengineering has scarcely figured in either international climate negotiations, or the scientific assessments of the Intergovernmental Panel on Climate Change.

A. Millard-Ball (✉)
Emmett Interdisciplinary Program in Environment and Resources, Stanford University,
Yang & Yamazaki Environment and Energy Building-4210, Stanford, CA 94305, USA
e-mail: adammb@stanford.edu

The view of geoengineering as undermining abatement efforts[1] stems from the fear that its low costs and ease of implementation make it an attractive alternative to emissions abatement. First-order estimates of the costs of deploying aerosols or space-based scatters are minimal in comparison to abatement—several billion dollars per year for one of the most promising options, that of injecting aerosol precursors into the lower stratosphere (Robock et al. 2009). Barrett (2008) talks of the "incredible economics of geoengineering" that mitigate CO_2-induced climate damage at the equivalent of pennies per ton of CO_2 reduced.

In practice, however, neither geoengineering nor substantial abatement has been undertaken in practice. While numerous studies (most notably, Stern 2007) suggest that the global damage from climate change far outweighs the cost of abatement, even the modest targets under the Kyoto Protocol are unlikely to be achieved. The reason for this is simple: climate change is a textbook example of a collective action problem. It is individually rational for countries to under-abate as they only capture a small fraction of the global benefits of their efforts. Numerous game theoretic analyses, discussed later in this paper, have shown the virtual impossibility of obtaining a self-enforcing international environmental agreement that comes anywhere close to achieving the efficient level of abatement.

Geoengineering, in contrast, has been described as the inverse of a collective action problem; any individual country could with relative ease undertake unilateral action (Michaelson 1998; Barrett 2008; Victor 2008). In this paper, I extend this line of reasoning to argue that far from posing a threat to abatement efforts, geoengineering may help resolve the collective action impasse. Because the side effects of schemes such as modifying planetary albedo are so great, the credible threat of geoengineering makes it individually rational for nations to reduce emissions to the level that avoids that threat.

I use a simple game theoretic model to demonstrate the following results. First, a credible threat that countries will deploy a geoengineering scheme can increase aggregate abatement to the level that the threat dissipates; the world reduces emissions to a level where geoengineering no longer makes sense. Second, the same credible threat can sustain a self-enforcing climate agreement with full participation and higher abatement than the non-cooperative scenario. I do not claim that these results are inevitable, but rather that they are just as plausible as a scenario under which geoengineering undermines abatement efforts.

I follow Keith (2000) in defining geoengineering as "intentional large-scale manipulation of the environment," but restrict attention to (i) solar radiation management; and (ii) heat transfer, precipitation modification and similar schemes. The first category, solar radiation management, encompasses deployment of space-based deflectors; release of stratospheric aerosols; generation of cloud condensation nuclei;

---

[1] The potential of geoengineering to undermine abatement efforts has often been referred to as "moral hazard" in the geoengineering literature. However, strictly speaking, moral hazard applies to situations where agents do not bear the full consequences of their actions, due to incomplete information or restricted contracts. Insurance is the classic example: insured persons are more likely to partake in risky behavior, but the insurance company cannot observe the risk level. See, for example, Kotowitz (2008). Geoengineering does not involve hidden information; rather, the problem is rather the ease of unilateral geoengineering coupled with the collective action challenge of abatement, as discussed in the following section. Thus, the "moral hazard" terminology is inappropriate. I am grateful to two of the anonymous reviewers for highlighting this point.

and increase in surface albedo through vegetation modification or surface reflectors. The second category includes schemes to transfer heat from one region to another by modifying ocean circulation or towing icebergs; and to change precipitation patterns through large-scale cloud seeding. I exclude carbon cycle geoengineering options that remove and sequester CO_2 from the atmosphere, which are likely to have fewer side effects but to be much more expensive than solar radiation management (Royal Society 2009).

This paper proceeds as follows. The next section briefly discusses the collective action problem in enforcing international environmental agreements. The following section turns to geoengineering, and provides evidence for the two key premises of the paper: that geoengineering has costly side effects, and that a country can capture a disproportionate share of geoengineering benefits for itself while concentrating (by design or as an unintentional side-effect) costs beyond its borders. The following section discusses existing game theoretic models of international environmental agreements, and shows how they can be extended to incorporate geoengineering. I then describe the model and derive analytic results, before applying them to five plausible storylines. Finally, I discuss some of the implications for geoengineering research and climate policy. In particular, I argue for greater research on geoengineering schemes that advance the interests of an individual country, rather than assuming a "benevolent geoengineer" out to maximize global social welfare.

2 The collective action challenge

While the collective action problem in climate change has sparked a voluminous literature, the essential issue is simple to state. Greenhouse gas abatement by a country brings external benefits to other countries, yet these external benefits are not considered by a self-interested, rational nation. Thus, aggregate abatement is suboptimal. In contrast to domestic environmental problems, the standard economic solution of a Pigouvian tax is difficult to implement; there is no supreme world government that can adopt and enforce a carbon tax.

International environmental agreements (IEAs) could help mitigate this underabatement. For example, a treaty under which every nation agreed to abate until its marginal cost equaled the global marginal benefit would yield the efficient outcome. But there is no external enforcer that can hold countries to their treaty commitments; obligations where the costs to a country far outweigh its private benefits are unlikely to be complied with. Hence, the realist observation that IEAs with broad participation are usually shallow, in that treaty commitments diverge little from a nation's non-cooperative strategy. Barrett and Stavins (2003) show that there is a tradeoff between participation and compliance; one can have a "narrow and deep" or "wide and shallow" treaty, but not both.

Some proposals for a new international climate treaty have ignored the participation and compliance issue altogether, in favor of a focus on equity or environmental outcomes (EcoEquity and Christian Aid 2006). Others incorporate explicit political constraints into treaty design (Frankel 2008). Still others have moved away from the assumption of a single agreement with targets and timetables; Finus et al. (2009) suggest that multiple agreements among countries with similar interests may be more effective than a single global agreement. Barrett (2006) calls for agreements that target research and development leading to breakthrough technologies, in the hopes of creating a self-enforcing IEA.

An alternative way to promote full participation and compliance is through negative incentives or "punishments" to defectors. Theoretically, these should be able to invoke full participation and compliance, and this result is shown in several (albeit somewhat restrictive) models (Barrett 2005). The challenge is in identifying a punishment that is sufficiently severe (so that IEA participation and compliance generates a higher payoff than non-participation or non-compliance); credible (it would be rational for the 'enforcing' countries to invoke the punishment in equilibrium); and would either be agreed to by countries ex ante or can be deployed in a way that does not require their consent.

Most punishments in either the Kyoto Protocol or proposed successor treaties fail one or all of these tests. The Kyoto punishment—adding any shortfall plus a penalty to the abatement requirement in subsequent periods—can be endlessly delayed through noncompliance in the second and subsequent periods, or avoided altogether through negotiating a lax second-period emission cap.

Trade sanctions are a more promising enforcement mechanism and have been incorporated into several proposals for a successor treaty to Kyoto (Aldy et al. 2003). In the case of simpler environmental problems such as ozone-depleting chemicals, trade sanctions may provide a credible threat that is sufficient to deter free riding (Barrett 1997). In the case of climate, however, the losses to enforcer countries through a potential trade war may render the punishment non-credible. Even the more limited option of a border tax adjustment—the taxation of "embedded carbon" in imports from non-participants—faces challenges. Barrett and Stavins (2003: 365) suggest it is "straightforward in principle...virtually impossible in practice," due to the difficulties in quantifying embedded carbon and potential violations of WTO rules.

In the remainder of this paper, I show that geoengineering may provide a punishment that is severe, credible and does not require ex-ante consent. This argument rests on two premises. First, geoengineering brings costly side effects, even if the direct costs of deployment are trivial relative to abatement. Second, geoengineers may concentrate net benefits for themselves. This implies that the costs and benefits of geoengineering must be non-uniform, and that the geoengineer can disproportionately capture the benefits while externalizing the damages. I discuss the scientific basis for these premises in the following section.

3 Geoengineering as a credible threat

3.1 Premise 1: geoengineering brings costly side effects

The nascent state of the literature makes it difficult to quantify the impacts of geoengineering, and they vary depending on the chosen technology. However, potential side effects may well be serious. Victor (2008) suggests that "cocktail geoengineering" may be needed with multiple interventions to address multiple climate change impacts and multiple side effects, at the expense of increased cost and complexity. Side effects might include stratospheric ozone depletion from aerosol deployment (Tilmes et al. 2008; Heckendorn et al. 2009); and less precipitation as reduced solar forcing (e.g. from a space-based deflector) reduces evaporation

(Brovkin et al. 2009). There are also risks from a scheme going badly wrong or failing to be maintained; the long tail in the probability distribution of climate damages might well be matched by a long tail in the distribution of geoengineering mayhem. In other words, there may be a low-probability, high-consequence "surprise" lurking in the tail. And further dangerous side effects will probably emerge in due course as researchers start looking for them more aggressively (Victor 2008).

3.2 Premise 2: geoengineers may concentrate net benefits

I contend that an individual country or coalition of nations can deploy geoengineering so that it concentrates the benefits on its own soil, and/or the side effects (or other costs) abroad. This may be by design, or an unavoidable feature of a specific geoengineering technology. In the remainder of this section, I illustrate four broad ways in which this premise can hold. In subsequent sections of this paper, I am agnostic as to which of these situations applies, but I contend that at least one may lead to differential costs from geoengineering, differential benefits, or both.

3.2.1 Targeted geoengineering

The most obvious example of differential net benefits is when a geoengineering technology is selected or implemented in a way to confer the benefits on a limited geographic scale, and impose the costs elsewhere. Examples here might include damming the Bering Strait to redirect ocean currents; iceberg transport to redistribute heat around the globe; or steerable solar shields to reduce solar radiation in specific areas of the planet (Keith 2000). Biogeoengineering through increasing leaf albedo provides another example. This technique may increase soil moisture in some regions such as the United States, while reducing water availability in parts of the subtropics and Australia (Ridgwell et al. 2009). On a smaller scale, cloud seeding could allow the geoengineer to affect the spatial distribution of precipitation. Thus, an upwind country could use cloud seeding (if it works—see Fleming (2010) for accounts of numerous failures) to increase rainfall at the expense of exacerbating drought in downwind countries.[2]

Indeed, military applications have been behind much of the research in geoengineering to date, highlighting the potential of various technologies to yield differential costs and benefits. Schneider (1996: 294) warns that geoengineering could be "an overt or clandestine weapon against economic or political rivals." The Cold War Pentagon was intrigued by the possibility to "release the violence of the atmosphere against an enemy" or to disrupt food supply by "seeding clouds to rob them of moisture before they reached enemy agricultural areas" (Fleming 2007: 54,55). Another prospect is the redirection of hurricanes using satellite-based microwaves. According to Schelling (1996: 307): "I can imagine that fifty years from now when the Philippine Coast Guard cutter moves out to suppress a hurricane it meets a Chinese naval vessel armed with heavier firepower."

---

[2] For a literary analogy, see Fleming's (2010: 31) discussion of the George Griffith novel, *The Great Weather Syndicate*. In the novel, a British engineer sets up a network of mountain stations equipped with machines that break up and dissipate clouds. Using this network, the Syndicate can control global weather patterns and ocean currents, and sell a country the weather that it wants.

3.2.2 Non-symmetric geoengineering damages

Even if geoengineering is not targeted, as in the case of a benevolent geoengineer intent on maintaining global mean temperature, non-symmetric damages from geoengineering may occur unintentionally in one of three ways. First, geoengineering side effects may affect countries in different ways. The scattering of aerosols through the atmosphere might be able to mitigate temperature rises, but at the expense of stratospheric ozone depletion (Tilmes et al. 2008; Heckendorn et al. 2009) which disproportionately affects high-latitude countries in the southern hemisphere, such as Australia. A space-based deflector may also be able to restore global mean temperature, but adversely impact forestry and agriculture in the high latitudes due to reduced solar insolation (Naik et al. 2003).

Second, differences in risk aversion between countries may change the payoff from geoengineering. There are substantial risks from many geoengineering technologies, including potential unforeseen impacts, failure to work as intended, and the possibility of system failure leading to abrupt climate change (Matthews and Caldeira 2007; Blackstock et al. 2009; Royal Society 2009; Fleming 2010). Countries that are risk-averse will therefore derive less expected benefit from a risky geoengineering technology (although these risks from geoengineering need to be weighed against the potential for nasty "surprises" from unmitigated climate change).

Third, geoengineering is likely to compensate for increased radiative forcing in only a patchy manner, generating winners and losers among different countries. Geoengineering from a space-based deflector may create "novel climates" in some parts of the world, which lie outside of the continuum between the pre-industrial climate and unmitigated climate change (Irvine et al. 2010). Brovkin et al. (2009) suggest that regional variations in temperature change could be substantial following stratospheric sulfur injections.[3] Lunt et al. (2008) find that their "sunshade world" has cooler tropics and warmer high latitudes, a result common to other modeling studies of reduced solar forcing (e.g. Matthews and Caldeira 2007). We might also expect a reduction in intensity of the hydrological cycle, with less precipitation and disruptions to the monsoons and El Niño Southern Oscillation (Bala et al. 2008; Lunt et al. 2008; Robock et al. 2008).[4] Jones et al. (2009) find that seeding large-scale marine stratocumulus cloud decks reduces global mean temperature by about 0.6 K, but that regional precipitation impacts vary considerably. There are increases in precipitation in sub-Saharan Africa and India, but reductions of more than 50% in some parts of the Amazon basin. Stratospheric aerosol injection, meanwhile, may also result in "large local changes of precipitation and temperatures" with less precipitation at the equator despite little change in the global mean (Tilmes et al. 2009). The modeling of the impacts of stratospheric aerosols is supported by analysis of the impacts of volcanic eruptions such as Mount Pinatubo, which led to

---

[3] Most modelers, including Brovkin et al., approximate the impacts of solar radiation management schemes through reducing the solar constant until global mean temperature falls to the same level as a world with pre-industrial CO_2 concentrations.

[4] The hydrological result arises because radiative forcing from CO_2 mainly heats the troposphere, while solar forcing mainly heats the surface. In simple terms, compensating for increased CO_2 forcing through a reduction in solar forcing reduces evaporation and in turn precipitation (Bala et al. 2008).

major adverse impacts on precipitation, including drought, particularly in the tropics (Trenberth and Dai 2007; Blackstock et al. 2009).

3.2.3 Non-symmetric climate damages

The third manner in which geoengineering may impose differential costs and benefits follows from the types of climate damage experienced by different countries. Most geoengineering schemes are designed to counter rises in global mean temperature. They may be well-suited to mitigating global sea-level rise and other temperature-related climate impacts, but do little to quell impacts on marine ecosystems from lower ocean pH and aragonite saturation (Matthews et al. 2009). Thus, landlocked countries or those where maritime activities are economically insignificant would mitigate a greater share of their climate damage compared to (say) those dependent on fisheries. A similar argument could be made with respect to changes in precipitation patterns in a high-CO_2 world, which may be more difficult to forestall through modification of planetary albedo or incoming solar radiation. Countries where higher temperatures (or melting ice sheets) are the primary danger might do well from a space-based scatterer; countries where drought is the main challenge, less so.

A similar issue arises if limited geoengineering schemes are implemented to mitigate specific climate impacts. MacCracken (2009) proposes this approach, such as redirecting tropical storms or reducing their intensity through modifying sea surface temperatures in specific areas; or limiting sea level rise through moderating the high-latitude warming that leads to ice-sheet melting. These measures may confer benefits to specific countries, such as low-lying nations or those in the path of tropical storms, but do little to mitigate impacts elsewhere in the world.

Moreover, climate damage is not uniformly distributed across the globe. Some nations such as Russia and Canada stand to gain from a moderate amount of climate change, absent some nasty event far in the tails of the probability distribution. Other nations, such as low-lying island states, would be devastated. The damage from a small increase in global mean temperature is likely negative for Russia; in the case of the Maldives, it approaches infinity.

3.2.4 Intertemporal distribution of benefits

Even assuming that a geoengineering scheme brings uniform benefits across the globe, we might still obtain striking differences in the present value of the benefits and costs between different countries. Suppose that the long-term costs of maintaining a geoengineering scheme in working order and mitigating side effects are substantial compared to the initial costs of deployment. This assertion has ample support in the literature; once geoengineering is deployed, terminating a scheme may lead to abrupt warming (Boucher et al. 2009; Brovkin et al. 2009). At least after an initial period, all countries may need to contribute to mitigation of side effects and system maintenance, not just the nation that initially deployed the geoengineering system. Further suppose that different countries evaluate the present value of a policy option using different discount rates. A fragile democratic government may have a very high discount rate; a hereditary monarch a very low one (Olson 1993). Then, unilateral geoengineering may bring a greater payoff to the country with the high discount rate, as the present value of future maintenance and side-effect mitigation would be less.

4 To geoengineer or not: a game theoretic model

The model in this section adapts the simple non-cooperative game developed by Barrett (1994), and extended in Barrett (2005) and elsewhere, to model participation and compliance in an international environmental agreement (IEA) such as the Kyoto Protocol. Under this game, countries first choose whether or not to participate in an IEA. Participants then determine joint abatement to maximize their collective welfare, acting as a Stackelberg leader. Non-participants then choose their level of abatement, maximizing only their own welfare. The fourth stage, which I add here, involves the decision whether or not to geoengineer. Along with parallel work by Moreno-Cruz (2010), who considers geoengineering in a two-player setting without the possibility of an IEA, the inclusion of geoengineering in game theoretic climate policy models is a new addition to the literature.

There are numerous variants on the game theoretic approach that I adopt here (for reviews, see Barrett 2005; Finus 2008). Some model IEAs as a cooperative game; some model a single shot rather than a repeated game; some model the compliance decision rather than the participation decisions; some allow agreements to be closed rather than open to any nation; and some incorporate the ability to make side payments (Chou and Sylla 2008). Others move beyond a closed-form solution and simulate multiple asymmetric countries, in some cases linking a game theoretic model to an Integrated Assessment Model of climate damages and abatement costs (Carraro 1998; Finus et al. 2009). The essential conclusions, however, are fairly robust to the choice of modeling assumptions. IEAs can increase greenhouse gas abatement, but few countries participate in an agreement and overall abatement falls far short of the socially optimum level.

In general, my assumptions and structure follow those of Barrett (2005), with the addition of the geoengineering stage. I assume N identical countries. The assumption of symmetry is restrictive, but makes the analytics tractable. I relax the symmetry assumption in some of the storylines in the subsequent section. I assume full compliance once a country has decided to join. This may seem restrictive, but Barrett (2005) shows that under some assumptions, participation and compliance are equivalent.

The payoff to each country $i = 1,2,...,N$ is given by:

$$\pi_i = B(Q) - C(q_i) + G(z_i, Q) - D(z_{-i}, Q)$$

$$q_i \geq 0,\ \ Q = \sum_{1}^{N} q_i,\ \ z_i \in \{0, 1\} \tag{1}$$

The first term denotes the benefit to country i from aggregate abatement Q. This benefit function implicitly incorporates adaptation, i.e. any climate damage that is mitigated is net of adaptation. The second term denotes the cost to country i from its own abatement q_i. The third term represents the net benefits to country i of deploying a geoengineering scheme (including any side-effects to itself and the cost of deployment), where z_i is a binary variable that take 1 if geoengineering is deployed by country i, and 0 otherwise. The fourth term represents the impact on country i if at least one other country-i geoengineers and the binary variable z_{-i} takes the value 1. For simplicity, I assume that G is only affected by a country's own decision to geoengineer, and D by the decisions of other countries. In other words, there are no interactions between competing geoengineering schemes (although this could be incorporated at the cost of greater complexity).

The model is very general in that it allows for geoengineering impacts to be identical across countries ($G(1, Q) = -D(1, Q)$), in which case there is no asymmetry in net benefits across countries. The geoengineering damage function D may be negative, i.e., geoengineering brings net benefits for all countries.[5]

A key assumption in this model is the binary nature of geoengineering—a country either geoengineers or does not. Certainly, some technologies offer some choice over the degree of geoengineering, for example in terms of the volume of stratospheric aerosols released. However, the decision to deploy a geoengineering scheme is fundamentally binary, and is difficult to reverse once a scheme is in place. (Compare to abatement, which, as a function of constant decisions by billions of individuals and firms, is clearly continuous.)

I assume that benefits increase in total abatement; costs increase in a country's own abatement; and that net geoengineering benefits G are decreasing in abatement. Formally:

$$\frac{\partial B}{\partial Q} > 0,\ \ \frac{\partial C}{\partial q_i} > 0,\ \ G(0, Q) = 0,\ \ D(0, Q) = 0,\ \ \frac{\partial G(1, Q)}{\partial Q} < 0$$

Note that if $z_i = 0$ for all i, then the model reduces to the Barrett (2005) formulation: $\pi_i = B(Q) - C(q_i)$. I assume that countries are risk neutral in that they maximize expected payoffs, although this does not preclude risk aversion being incorporated implicitly into the abatement benefit or geoengineering damage functions.

The entire game consists of four stages. As I solve for the subgame perfect Nash equilibrium by backward induction, the following subsections derive the solution to each stage in reverse order:

- Stage 1: Countries choose whether or not to participate in IEA
- Stage 2: Countries in IEA choose level of abatement
- Stage 3: Other countries choose level of abatement
- Stage 4: Countries choose whether or not to geoengineer

4.1 Model solution

4.1.1 Stage 4: geoengineering

Each country simultaneously chooses whether or not to deploy a geoengineering scheme, indicated by the binary variable z_i. Thus, each solves:

$$\text{Play } z_i = 1 \text{ if } G(1, Q) > G(0, Q);\ \text{ otherwise, play } z_i = 0$$

---

[5] The model does implicitly assume that there are N different geoengineering technologies or modes of deployment, each of which provides a benefit G to the country that deploys it, and a damage D (which can be negative) to all other countries. This assumption can easily be relaxed by allowing D_i to vary across countries $i = 1...N$ and to equal -G for some i. Alternatively, the assumption can be relaxed by only allowing $M < N$ countries to have access to geoengineering technology. Neither alters the fundamental results discussed below – that geoengineering *can* be a credible threat that increases abatement and promote full participation in an IEA, depending on the relative benefits and damages from geoengineering. However, the conditions would have to hold for all countries depending on their individual values of D_i.

Note that we resolve indifference in favor of "do not geoengineer." By symmetry and by the absence of interactions, if the above condition holds for one country it holds for all countries—if one country finds it advantageous to geoengineer, then so do all countries. If all countries decide to geoengineer, then one randomly selected country succeeds in doing so and is able to deploy its preferred scheme. Thus, the expected payoff for each country from the Stage 4 game is:[6]

$$\pi_i = B(Q) - C(q_i) + \frac{1}{N}G(1, Q) - \frac{N-1}{N}D(1, Q) \text{ if } G(1, Q) > G(0, Q);$$
$$\text{otherwise, } \pi_i = B(Q) - C(q_i) \tag{2}$$

4.1.2 *Stage 3: non-signatory abatement*

Signatories act as Stackelberg leaders, in that they gain a first-mover advantage from committing to a given level of reduction. Thus, with backward induction we solve for non-signatory abatement decisions first, where q_i^n represents the abatement decision of each non-signatory and the solution to (3).

$$\max_{q_i} \pi_i = B(Q) - C(q_i) + \frac{1}{N}G(z_i, Q) - \frac{N-1}{N}D(z_{-i}, Q) \tag{3}$$

4.1.3 *Stage 2: signatory abatement*

Signatories $j = 1,2,...,k$ choose q_j^s to maximize their collective surplus and solve (4).

$$\max_{q_j} \sum_{j=1}^{k} \pi_j = kB(Q) - \sum_{j=1}^{k} C(q_j) + \frac{k}{N}G(z_j, Q) - \frac{kN-k}{N}D(z_{-j}, Q) \tag{4}$$

4.1.4 *Stage 1: treaty participation*

We obtain an equilibrium k^* if the following two conditions hold. The first (Eq. 5) shows that any signatory is better off remaining in the agreement. The second (Eq. 6) shows that any non-signatory is better off outside of the agreement.

$$\pi_s(k^*) \geq \pi_n(k^* - 1) \tag{5}$$

$$\pi_n(k^*) \geq \pi_s(k^* + 1) \tag{6}$$

4.2 Proposition 1. A credible threat of geoengineering can increase abatement levels

Let Q^n denote aggregate abatement in the absence of a geoengineering option (i.e., the outcome from the Barrett (2005) model). Suppose that the geoengineering threat is credible, i.e. countries would geoengineer in the Stage 4 game equilibrium where emissions are Q^n as $G(1, Q^n) > G(0, Q^n) = 0$.

---

[6] If only a subset of $M < N$ countries has access to geoengineering technology, then the payoff under geoengineering is $B(Q) - C(q_i) + \frac{1}{M}G(1, Q) - \frac{M-1}{M}D(1, Q)$ for countries that have access to geoengineering technology, and $B(Q) - C(q_i) - D(1, Q)$ for other countries.

Then Q^g can be equilibrium aggregate abatement in the presence of a geoengineering option, where $G(1, Q^g) = G(0, Q^g)$, i.e. aggregate abatement Q^g is 'just enough' to prevent another country from geoengineering (recall that we resolve indifference in favor of "do not geoengineer").

We know that $Q^g > Q^n$ as by assumption $G(0, Q) = 0$ for any Q and $\delta G/\delta Q < 0$ if $z_i = 1$.Note that while Q^g involves greater abatement, it is unlikely to be at the social optimum (i.e., the collective action problem is only partially solved).

Given total abatement Q^g, would it be in the interests of any non-signatory $i = k + 1 \ldots N$ to reduce abatement from q_i^n to $\tilde{q}_i < q_i^n$? Only if the following condition holds:

$$\begin{aligned} &B(\tilde{Q}) - C(\tilde{q}_i) + \frac{1}{N}G(1, \tilde{Q}) - \frac{N-1}{N}D(1, \tilde{Q}) > B(Q^g) - C(q_i^n) \\ &\tilde{Q} = Q^g - (q_i^n - \tilde{q}_i) \end{aligned} \tag{7}$$

Provided that geoengineering is sufficiently scary, i.e., net damages from geoengineering plus the foregone abatement benefits outweigh the cost savings from reduced abatement, Eq. 7 will not hold. Then, non-signatories will hold emissions at a level to 'just' avoid the deployment of geoengineering. They could even reduce emissions further, if marginal benefits to an individual country exceed marginal costs at Q^g.

An analogous condition to Eq. 7 is required to show that signatories will not reduce abatement at Q^g provided that net damages from geoengineering are sufficiently large, and a further condition to show that k^* is an equilibrium.

Note that Q^n where geoengineering is deployed may also be an equilibrium (although all countries may prefer a Pareto superior equilibrium Q^g which avoids geoengineering). This may arise if $Q^g - Q^n$ is 'large,' in the sense that no single country will reduce its emissions by enough to avoid other countries deploying a geoengineering scheme. Such a reduction might be physically impossible for a single country, or it simply may not be cost effective if marginal abatement costs are increasing in Q.

Also note that we have not said anything about how aggregate abatement Q^g is divided between different countries. Here, there are numerous equilibria with different countries making different contributions; it becomes a bargaining problem in dividing costs between various countries.

4.3 Proposition 2. A credible threat of geoengineering can promote full participation in an IEA

Suppose $k^* = N$ is an equilibrium, i.e. all countries participate in the IEA. Further suppose that the agreement sets abatement levels at "just enough" to prevent geoengineering, and that abatement is divided equally between countries:

$$\begin{aligned} &G(1, Q^g) = G(0, Q^g) \\ &q_j^g = Q^g/N \text{ for } j = 1, 2, \ldots, N \end{aligned} \tag{8}$$

Any reduction ε in the deviating country's abatement will lead to the deployment of a geoengineering scheme. Then no country can gain by deviating, provided that the benefits from deviating are less than the costs imposed by geoengineering. Formally $k^* = N$ is an equilibrium if:

$$C\left(q_j^g\right) - C\left(\tilde{q}_j\right) + \frac{1}{N} G\left(1, \tilde{Q}\right) - \frac{N-1}{N} D\left(1, \tilde{Q}\right) \le B\left(Q^g\right) - B\left(\tilde{Q}\right)$$
$$\forall\, \tilde{q}_j \in \left[0, q_j^g\right] \quad \tilde{Q} = Q^g - \left(q_j^g - \tilde{q}_j\right) \tag{9}$$

We know that deviators will not *increase* abatement as $\delta C/\delta q_j > \delta B/\delta Q$, evaluated at Q^g and $q_j = Q^g/N$.

Intuitively, full participation under this scenario can be sustained by the following mechanism. Suppose that a coalition of $k < N$ countries is formed in Stage 1. Then this coalition will strategically underabate, knowing that non-signatories will abate more in order to avoid the geoengineering scenario. The coalition takes advantage of its position as a Stackelberg leader. Thus, it is advantageous for forward-looking countries to join the IEA in Stage 1, to avoid being left in this position. Signatories will not abate more than non-signatories, as they know that the same aggregate emission reduction will occur; if signatories increase abatement by ε in Stage 2, then non-signatories will reduce abatement by ε in Stage 3 so that $G(1, Q^g) = G(0, Q^g)$. This is analogous to a model where thresholds for catastrophic climate damage can induce countries to cooperate to avoid the threshold (Barrett 2011).

As under Proposition 1, while Q^g involves greater abatement, it is unlikely to be at the social optimum and a partial collective action problem remains.

4.4 Parametric example

The conditions under which the results of this paper hold can be illustrated by assuming specific functional forms for B, C, G and D. I follow Barrett (2005) in assuming linear and quadratic forms for B and C respectively. I assume that the benefits of geoengineering G are declining in abatement, and that damage to other countries from geoengineering D is constant. Specifically:

$$B(Q) = b\,Q,\ C(q_i) = \frac{cq_i^2}{2},\ G(1, Q) = g - Q,$$
$$D(1, Q) = d,\ G(0, Q) = D(0, Q) = 0$$

If $Q^n \ge g$ then geoengineering is not deployed, nor is it a credible threat. The Barrett (2005) results hold, and signatories $j = 1, 2...k$ maximize Eq. 4 and set emissions $q_j^s = k\frac{b}{c}$. Non-signatories $i = k+1,\ k+2...N$ maximize Eq. 3 and set emissions $q_i^n = \frac{b}{c}$. An IEA forms with $k = 3$, as long as $N \ge 3$.

If $Q^n < g$, there are two possibilities. The first is that countries may increase abatement to $Q^g = g$ in order to avoid the deployment of geoengineering. I assume that the symmetric equilibrium is sought through an IEA, where $k = N$, $q_j^s = \frac{g}{N}$ for $j = 1, 2...N$. This equilibrium holds if the condition in Eq. 10 is met, i.e. the payoff from the IEA is greater than the payoff from defecting, reducing abatement to $q_i^n = \frac{b}{c} - \frac{1}{N}$, and accepting that all countries will attempt to geoengineer in Stage 4.

Note that non-signatory abatement is lower than in the “without geoengineering” case by the term $1/N$.[7]

$$bg - \frac{c}{2}\left(\frac{g}{N}\right)^2 \geq bg - b\left(\frac{g}{N} - \frac{b}{c} + \frac{1}{N}\right) - \frac{c}{2}\left(\frac{b}{c} - \frac{1}{N}\right)^2 + \frac{1}{N}\left(\frac{g}{N} - \frac{b}{c} + \frac{1}{N}\right) - d\left(\frac{N-1}{N}\right) \tag{10}$$

Which simplifies to:

$$d \geq \frac{1}{N\,(N-1)}\left(\frac{b^2N^2}{2c} + g\,(1 - b\,N) - \frac{b\,N}{c} - \frac{c}{2}\left(1 - g^2\right) + 1\right)$$

The second possibility is that the condition in Eq. 10 is not met, and countries know that the symmetric equilibrium will not hold. In this case, even if a smaller IEA does form, both signatories and non-signatories will reduce emissions compared to the “without geoengineering” case.[8] Thus, geoengineering is deployed and forward-looking countries reduce abatement efforts.

The parameter values for b, c and N determine the combinations of g and d under which geoengineering is a credible threat, versus a technology that reduces abatement efforts. As is evident from the complexity of Eq. 10, however, there is no simple relationship or comparative statics result, with the exception that the likelihood that geoengineering is a credible threat is increasing in d. Figure 1 plots the indifference curves (i.e., where Eq. 10 holds as an equality) for countries under two different sets of parameter values. The lower region is where $Q^n \geq g$ and geoengineering is neither deployed nor a credible threat. The upper-right region is where d is large enough in relation to g and the other parameter values that geoengineering is a credible threat. In the upper-left region, geoengineering is deployed and abatement is reduced.

4.5 Five storylines

In this section, I use the framework of the basic model to consider five potential storylines. Rather than deriving analytic results, I suggest which combination of functional forms or parameters can yield the given storyline. This permits a wider range of scenarios to be considered, particularly those involving asymmetrical countries.

1. The Tuvalu Syndrome

Suppose that one country, such as Tuvalu or another small island state, is particularly at risk from climate change impacts. Damages to that country from emissions above a certain level will be large, perhaps infinite if the country is rendered uninhabitable due to sea-level rise. Tuvalu may gain access to geoengineering technology from a wealthy philanthropist—Victor’s (2008) Greenfinger—or perhaps purchase sufficient artillery guns on its own to inject aerosol precursors into the stratosphere.

---

[7] The 1/N term arises from differentiating the second half of Eq. 3 with respect to q.
$\frac{1}{N}G(z_i, Q) - \frac{N-1}{N}D(z_{-i}, Q) = \frac{1}{N}(g - Q) - d\frac{N-1}{N}$

[8] See Note 7. The reduction in abatement compared to the “without geoengineering” case is $1/N$ for each non-signatory and k/N for each signatory.

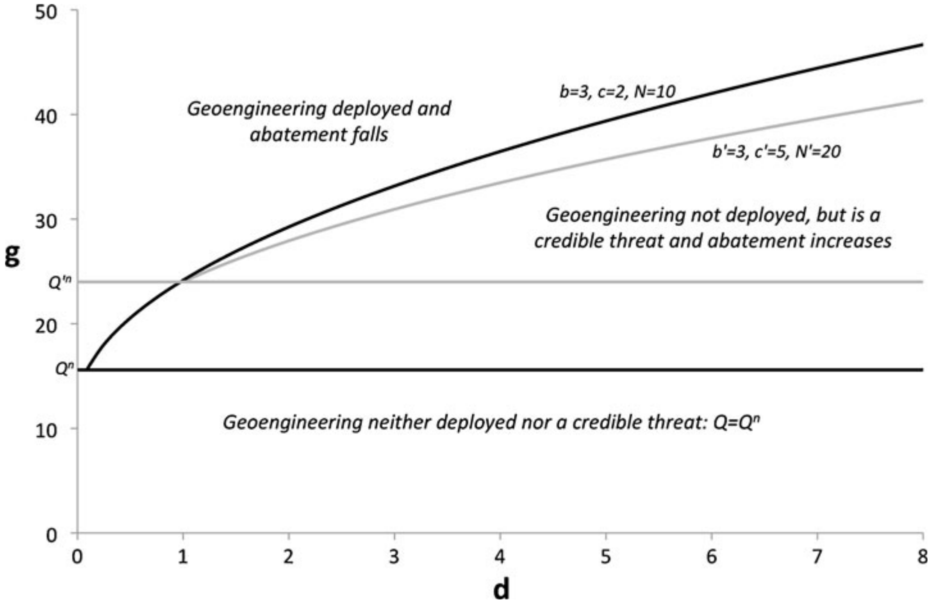

Fig. 1 Parameter spaces under which geoengineering is a credible threat. In the lower region, it is not rational to deploy geoengineering as it brings insufficient benefits. In the upper-left region, geoengineering is deployed as benefits are great and side-effects small. In the upper-right region, side-effects are large and countries increase abatement to avoid the threat of unilateral geoengineering

In the absence of an agreement to substantially reduce global emissions, Tuvalu's best response is to geoengineer, even if the side effects are substantial. This credible threat from a desperate island nation with no other hope of avoiding annihilation means that other countries' best response is to collectively reduce emissions to the level where it is no longer optimal for Tuvalu to geoengineer. As shown in Proposition 2, the result may be an IEA with full participation and compliance (with the possible exception of Tuvalu itself).

Alternatively, one country may respond with armed force to destroy Tuvalu's geoengineering capacity. This option is not considered here. It is certainly plausible, although in democratic societies there may be considerable sympathy for Tuvalu's last-ditch effort to preserve its existence in the face of climate change, making a military response less likely.

2. The Growing Coalition

Tuvalu can be seen as the extreme case of a storyline where countries have different propensities to geoengineer, due to differential impacts from climate change or geoengineering side effects. Suppose that we label countries $i = 1, 2, ...N$ so that $Q_i^g \leq Q_{i+1}^g$ for $i = 1...N-1$, where Q^g is the aggregate level of abatement that leaves a country indifferent as to geoengineering (i.e., $G_i\left(1, Q_i^g\right) = G_i\left(0, Q_i^g\right) = 0$). We can call Q^g the "propensity to geoengineer," as it can be interpreted as the aggregate abatement that is necessary before a country no longer wishes to geoengineer unilaterally.

Suppose that countries $i = 1...D$ never want to geoengineer even at zero abatement, i.e. $G_i(1, 0) < 0$. This might be a coalition of D risk-averse countries, together with those that suffer mild damages from climate change and severe side-effects from geoengineering. This group might also include countries where climate damage primarily occurs through ocean acidification, which would not be impacted by geoengineering. Countries in the European Union; Australia; the U.S.; and fishing-dependent nations such as Iceland are obvious candidates, as well as Russia. (While Russia is likely to benefit from climate change, it may prefer an abatement scenario to an alternative with high CO_2 and geoengineering to restore global mean temperature. Geoengineering impacts such as reduced solar insolation and ozone depletion would disproportionately affect high-latitude countries.)

Suppose that the best response of this coalition is to reduce emissions to Q^g_{D+1}, i.e. the abatement level where one additional country no longer wishes to geoengineer and joins the coalition. The best response of this new coalition may then be to increase abatement to Q^g_{D+2}, and so on until equilibrium abatement is achieved at Q^g_N and the last country is indifferent regarding geoengineering.

3. Selfish geoengineering

Would-be geoengineers can choose from a range of technologies. It is reasonable to posit that a country chooses the technology that maximizes domestic benefits, rather than the socially optimum technology from a global perspective. Suppose that the U.S. deploys leaf albedo biogeoengineering, which may bring net benefits to the U.S. but leave some subtropical countries worse off due to reduced precipitation (Ridgwell et al. 2009). Alternatively, suppose that India launches a fleet of ships to spray sea water and generate cloud condensation nuclei, which increases precipitation in India at the expense of countries in the Amazon basin. Or suppose that China deploys a partial sunshade or stratospheric aerosols that optimize the Chinese climate but disrupt the monsoon cycle.

This “selfish” (or individually rational) geoengineering shifts the level of both $G_i(1, Q)$ and $D_{-i}(1, Q)$ upward for some i, making it less likely that the condition in Eq. 7 will hold. It increases the differential between the benefits gained by a country that is able to develop and deploy a geoengineering scheme, and other nations who are left worse off. For other countries faced with the threat of selfish geoengineering, abatement to the level where geoengineering no longer gives a higher payoff to any country is the best response.

4. Countermeasures

An extension of the previous storyline is one where a country undertakes “selfish geoengineering” but others deploy countermeasures, as suggested by Blackstock et al. (2009). Suppose, for example, that China deploys a steerable solar deflector that disrupts the monsoons and leads to significant damage to India. In turn, India could deploy countermeasures, whether its own geoengineering program (such as sea spray to produce cloud condensation nuclei), or attempting to destroy China’s solar shield. At the extreme, multiple countries may deploy measures and countermeasures in an attempt to achieve their own ideal point in terms of temperature, precipitation, and geoengineering side effects.

Overall, the effect is to increase the severity of side effects $D_{-i}(1, Q)$ from geoengineering, not least from nasty interactions. Other countries, fearing climate chaos from competing geoengineering schemes or rapid forcing from the destruction of a solar deflector, thus have a reduced expected payoff in a high-CO_2 world, making abatement the best response and increasing the gains to an IEA.

5. The Rush to Geoengineer

Another way in which "selfish geoengineering" might play out is through a rush to gain a first-mover advantage from geoengineering. The country that first occupies the inner Lagrange point L1 with a cloud of small spacecraft (as proposed by Angel 2006) could dictate the level of the reduction in solar forcing that maximizes its own benefits. Once in place, it may be difficult for other countries to affect the design of this system, or to deploy their own preferred geoengineering technology such as stratospheric aerosols.

One result could be the "premature" deployment of technology, in that countries deploy a system earlier than they would otherwise prefer, and prior to the detailed testing and modeling that may be needed (Blackstock et al. 2009). The European Union might launch a scheme out of fear that China or the U.S. might deploy their own devices. It might also choose a suboptimal technology (perhaps a solar deflector) that locks in a first-mover advantage, as opposed to the more temporary option of stratospheric aerosols that is more susceptible to being overridden by a solar shield.

The upshot, once again, is to reduce the payoff in a high-CO_2 world, through increasing the damages from geoengineering and moving to the upper-right region of Fig. 1. In turn, this could make abatement the best response and increase the gains to an IEA.

5 Conclusions

We know little about the impacts of climate change, in that nasty surprises may lurk in the tails of the probability distribution. We know far less, however, about the direct impacts and side effects of geoengineering. And we know even less than that about the political economy of geoengineering—who is likely to deploy such a scheme, and how international norms might be developed to govern research and the use of the technology. Instead, the social science literature has tended to adopt a normative approach to how geoengineering could or should be governed (Victor 2008; Lin 2009; Royal Society 2009; Victor et al. 2009; Virgoe 2009).

Until now, analysts have largely fallen into two camps: those cautiously optimistic (geoengineering may in fact be a more efficient alternative to reducing emissions, or can mitigate the risks from climate change); or those fearing that geoengineering may suppress abatement by providing an attractive "technological fix" for the climate. Such fears have also inhibited research output and serious political discussion of geoengineering, at least until very recently. In this paper, I show that such fears may be unfounded. Instead of undermining abatement efforts, it is equally plausible that geoengineering would operate as a credible threat. Under this scenario, geoengineering would not be implemented in equilibrium, but the threat might push countries to abate more than they otherwise would have. Most surprisingly, I show that geoengineering may be able to spur a self-enforcing climate treaty with full participation—not necessarily a treaty that abates to the social optimum, but one that reduces emissions below a non-cooperative equilibrium.

The key to this result is that while geoengineering may bring net benefits to one country, it imposes costs on others, for example through side effects such as loss of ozone and fisheries, or disruption to the hydrological cycle. If there are no side effects from geoengineering, then we have a techno-optimist scenario; the result of this paper does not hold and we are in the upper-left region of Fig. 1. The limited geoengineering research suggests, however, that these side effects may be serious, and moreover may be just the tip of the iceberg, given that we have hardly started to probe the potential consequences of a "sunshade world" or large-scale towing of icebergs. As Victor et al. (2009) observe: "Geoengineers keen to alter their own country's climate might not assess or even care about the dangers their actions could create for climates, ecosystems, and economies elsewhere."

The model developed in this paper by no means demonstrates that geoengineering *will* be able to act as a credible threat that can incentivize abatement. Nor does it discuss the institutional mechanisms by which the Pareto superior equilibrium (all countries abate and none geoengineer) can be achieved. Rather, it shows that this outcome is *possible* depending on the functional forms, i.e. the precise benefits and side effects of geoengineering; abatement costs; and climate damages. At present, we know almost nothing about the impacts of geoengineering, and our knowledge of greenhouse gas abatement costs and climate damages is far from comprehensive. Thus, it would be premature to assume that "geoengineering will save the climate," but equally premature to assume that geoengineering will undermine abatement efforts. (For that matter, it would also be premature to assume that deployment of geoengineering would be riskier than unabated climate change.) The model presented here is very simple, but the result is powerful, and climate science simply does not yet support any precise estimates of parameters or functional forms.

This paper does not examine the barriers to geoengineering or legal liabilities under international law, or other norms that may constrain behavior. Bodansky (1996), for example, suggests that countries would be reluctant to incur the political costs of unilateral action. Nor does it take a position on the ethical merits of geoengineering. Rather, it adopts a realist approach, recognizing that it may be impossible to secure credible commitments from all countries to refrain from unilateral geoengineering. Furthermore, in the same way that nuclear power stations mysteriously pop up close to international borders, it is highly plausible that countries will seek to concentrate geoengineering benefits for themselves and impose the costs on others.

Military action against a state that threatens to geoengineer is certainly an alternative possibility. But geoengineering might be undertaken by a powerful nation such as the United States or China, making it difficult for other countries to respond with armed force. And the likelihood of an armed response may still be insufficient to rule out geoengineering by a small nation, particularly if its survival is at stake. The difficulty of eliminating the threat of geoengineering still serves to increase the expected costs of not abating emissions, and yields a higher payoff from an IEA.

The wider relevance of this paper is threefold. First, it supports the conclusion that others (Schneider 1996; Cicerone 2006; Barrett 2008; Victor 2008) have reached via a different argument—that the implicit taboo against geoengineering research is harmful, and an active research program would be beneficial. In particular, the side effects of various geoengineering schemes have hardly been explored. The technology may be needed as an emergency response, but further research could also identify precisely how geoengineering can be designed to generate differential benefits and costs to enable it to act as a credible threat.

Second, this paper implies that modeling of geoengineering impacts should not only consider a "benevolent geoengineer" out to restore global mean temperature and minimize side-effects, but a "selfish geoengineer" intent only on maximizing net domestic benefits. Ban-Weiss and Caldeira (2010) model a geoengineering scheme that would optimize the global climate. But what would a scheme look like that was optimized for a specific country such as China or the U.S., both in terms of technology choice and impacts elsewhere? What would be the implications of competing geoengineering schemes or geoengineering plus countermeasures?

Third, this paper provides fodder for the study of international environmental agreements, specifically through calling attention to the importance of credible punishment mechanisms in promoting self-enforcing agreements, i.e. those that do not require enforcement from a supreme World Master. Most punishments that have been identified to enforce a climate treaty—trade restrictions, fines or increased targets—are either non-credible (a rational country would not impose the punishment), or require the cooperation of the country being punished. In the same way as English monarchs thought creatively about new institutions that would enable them to credibly commit to uphold property rights (North and Weingast 1989), we might benefit from a greater focus on credible punishments for non-participation in or breach of a climate agreement. And the threat of a foreign power launching a sunshade, turning the sky white through stratospheric aerosols, or damming the Bering Straits, might just be sufficient to spur the world into serious efforts to reduce emissions.

Acknowledgements Thanks to David Victor, Carolyn Snyder, seminar participants at Stanford University and three anonymous reviewers for helpful discussions and comments on an earlier draft. I am grateful to the late and sorely missed Stephen Schneider for encouraging me to pursue this work. I am also grateful for support from a David and Lucille Packard Foundation Stanford Graduate Fellowship, a William C. and Jeanne M. Landreth IPER Fellowship, and a US Department of Transportation Eisenhower Graduate Fellowship.

References

Aldy JE, Barrett S, Stavins RN (2003) Thirteen plus one: a comparison of global climate policy architectures. Clim Policy 3(4):373–397

Angel R (2006) Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). Proc Natl Acad Sci USA 103(46):17184–17189. doi:10.1073/pnas.0608163103

Bala G, Duffy PB, Taylor KE (2008) Impact of geoengineering schemes on the global hydrological cycle. Proc Natl Acad Sci USA 105(22):7664–7669. doi:10.1073/pnas.0711648105

Ban-Weiss GA, Caldeira K (2010) Geoengineering as an optimization problem. Environ Res Lett 5(034009):1–9

Barrett S (1994) Self-enforcing international environmental agreements. Oxf Econ Pap 46:878–894

Barrett S (1997) The strategy of trade sanctions in international environmental agreements. Resour Energy Econ 19(4):345–361

Barrett S (2005) The theory of international environmental agreements. In: Mäler K-G, Vincent JR (eds) Handbook of environmental economics, vol 3. Elsevier, Amsterdam, pp 1458–1516

Barrett S (2006) Climate treaties and "breakthrough" technologies. Am Econ Rev Pap Proc 96(2):22–25

Barrett S (2008) The incredible economics of geoengineering. Environ Resour Econ 39(1):45–54

Barrett S (2011) Climate treaties and approaching catastrophes. Working Paper

Barrett S, Stavins R (2003) Increasing participation and compliance in international climate change agreements. Int Environ Agreem-P 3(4):349–376

Blackstock JJ, Battisti DS, Caldeira K, Eardley DM, Katz JI, Keith DW, Patrinos AAN, Schrag DP, Socolow RH, Koonin SE (2009) Climate Engineering Responses to Climate Emergencies. Novim, Santa Barbara

Bodansky D (1996) May we engineer the climate? Clim Change 33(3):309–321

Boucher O, Lowe JA, Jones CD (2009) Implications of delayed actions in addressing carbon dioxide emission reduction in the context of geo-engineering. Clim Change 92:261–273

Brovkin V, Petoukhov V, Claussen M, Bauer E, Archer D, Jaeger C (2009) Geoengineering climate by stratospheric sulfur injections: earth system vulnerability to technological failure. Clim Change 92(3/4):243–259

Carraro C (1998) Beyond Kyoto: a game theoretic perspective. Prepared for OECD workshop, “Climate Change and Economic Modelling. Background Analysis for the Kyoto Protocol,” Paris

Chou P, Sylla C (2008) The formation of an international environmental agreement as a two-stage exclusive cartel formation game with transferable utilities. Int Environ Agreem-P 8(4):317–341. doi:10.1007/s10784-008-9082-6

Cicerone RJ (2006) Geoengineering: encouraging research and overseeing implementation. Clim Change 77:221–226

EcoEquity and Christian Aid (2006) Greenhouse development rights

Finus M (2008) Game theoretic research on the design of international environmental agreements: insights, critical remarks, and future challenges. International Review of Environmental and Resource Economics 2(1):29–67

Finus M, Saiz ME, Hendrix EMT (2009) An empirical test of new developments in coalition theory for the design of international environmental agreements. Environ Dev Econ 14:117–137. doi:10.1017/s1355770x08004634

Fleming JR (2007) The climate engineers. Wilson Quarterly (Spring 2007): 46–60

Fleming JR (2010) Fixing the Sky. The Checkered History of Weather and Climate Control. Columbia University Press, New York

Frankel J (2008) An elaborated proposal for global climate policy architecture: specific formulas and emission targets for all countries in all decades. Discussion Paper 08–08, Harvard Project on International Climate Agreements, Cambridge

Heckendorn P, Weisenstein D, Fueglistaler S, Luo BP, Rozanov E, Schraner M, Thomason LW, Peter T (2009) The impact of geoengineering aerosols on stratospheric temperature and ozone. Environ Res Lett 4:045108

Irvine PJ, Ridgwell A, Lunt DJ (2010) Assessing the regional disparities in geoengineering impacts. Geophys Res Lett 37(L18702):1–6. doi:10.1029/2010GL044447

Jones A, Haywood J, Boucher O (2009) Climate impacts of geoengineering marine stratocumulus clouds. J Geophys Res 114:D10106. doi:10.1029/2008JD011450

Keith DW (2000) Geoengineering the climate: history and prospect. Annu Rev Energy Environ 25(1):245–284

Kotowitz Y (2008) Moral hazard. In: Durlauf SN, Blume LE (eds), The new Palgrave dictionary of economics online, Palgrave Macmillan

Lin AC (2009) Geoengineering governance. Issues Leg Scholars 8(3):1–24

Lunt DJ, Ridgwell A, Valdes PJ, Seale A (2008) “Sunshade World”: a fully coupled GCM evaluation of the climatic impacts of geoengineering. Geophys Res Lett 35:L12710. doi:10.1029/2008gl033674

MacCracken MC (2009) On the possible use of geoengineering to moderate specific climate change impacts. Environ Res Lett 4:045107. doi:10.1088/1748-9326/4/4/045107

Matthews HD, Caldeira K (2007) Transient climate-carbon simulations of planetary geoengineering. Proc Natl Acad Sci USA 104(24):9949–9954. doi:10.1073/pnas.0700419104

Matthews HD, Cao L, Caldeira K (2009) Sensitivity of ocean acidification to geoengineered climate stabilization. Geophys Res Lett 36:L10706

Michaelson J (1998) Geoengineering: a climate change Manhattan Project. Stanf Environ Law J 17:73–140

Moreno-Cruz J (2010) Mitigation and the geoengineering threat. Working Paper

Naik V, Wuebbles DJ, DeLucia EH, Foley JA (2003) Influence of geoengineered climate on the terrestrial biosphere. Environ Manag 32(3):373–381

North DC, Weingast BR (1989) Constitutions and commitment: the evolution of institutional governing public choice in seventeenth-century England. J Econ Hist 49(4):803–832

Olson M (1993) Dictatorship, democracy, and development. Am Polit Sci Rev 87(3):567–576

Ridgwell A, Singarayer JS, Hetherington AM, Valdes PJ (2009) Tackling regional climate change by leaf albedo bio-geoengineering. Curr Biol 19:146–150

Robock A, Oman L, Stenchikov GL (2008) Regional climate responses to geoengineering with tropical and Arctic SO_2 injections. J Geophys Res 113:D16101. doi:10.1029/2008jd010050

Robock A, Marquardt A, Kravitz B, Stenchikov GL (2009) Benefits, risks, and costs of stratospheric geoengineering. Geophys Res Lett 36:L19703

Royal Society (2009) Geoengineering the climate. Science, governance and uncertainty. The Royal Society, London

Schelling TC (1996) The economic diplomacy of geoengineering. Clim Change 33:303–307

Schneider SH (1996) Geoengineering: could-or should-we do it? Clim Change 33(3):291–302

Stern N (2007) The economics of climate change: the Stern review. Cambridge University Press, Cambridge

Tilmes S, Müller R, Salawitch R (2008) The sensitivity of polar ozone depletion to proposed geoengineering schemes. Science 320(5880):1201–1204. doi:10.1126/science.1153966

Tilmes S, Garcia RR, Kinnison DE, Gettelman A, Rasch PJ (2009) Impact of geoengineered aerosols on the troposphere and stratosphere. J Geophys Res 114:D12305. doi:10.1029/2008JD011420

Trenberth KE, Dai A (2007) Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. Geophys Res Lett 34:L15702

Victor DG (2008) On the regulation of geoengineering. Oxf Rev Econ Policy 24(2):322–336. doi:10.1093/oxrep/grn018

Victor DG, Morgan MG, Apt J, Steinbruner J, Rich K (2009) The geoengineering option. Foreign Aff 88(2):64–76

Virgoe J (2009) International governance of a possible geoengineering intervention to combat climate change. Clim Change 95:103–119