GEOENGINEERING'S ROLE IN CLIMATE CHANGE POLICY

Scott Barrett*

Johns Hopkins University
School of Advanced International Studies

6 March, 2009

This paper is about geoengineering—a concept that has attracted consternation and fascination in perhaps equal measure. The questions I address are: What role *should* geoengineering play in climate change policy? and What role is geoengineering *likely* to play in climate change policy? I pose the first question from the perspective of the world as a whole. I pose the second from the perspective of individual countries, each entitled to act as it pleases, though each also constrained by the knowledge that its behavior will affect others, and possibly cause others to change *their* behavior. In answering both questions, I examine geoengineering not in isolation but as one of several possible interventions.

The definition of geoengineering is currently unsettled. In this paper I take it to mean *actions taken deliberately to alter the temperature without changing the atmospheric concentration of greenhouse gases*. Other writers have taken a broader perspective. Geologic or ocean storage of carbon dioxide (CO_2) is sometimes considered a form of geoengineering. So is the removal of CO_2 directly from the atmosphere by tree planting, ocean fertilization, increasing ocean alkalinity, and industrial processes. I discuss all of these possibilities in this paper, but my focus is on the technologies that can compensate for the effect of higher greenhouse gas concentrations on temperature. More formally, the temperature is determined by the amount of incoming shortwave radiation and outgoing longwave radiation. Actions to limit concentrations seek to increase the amount of longwave radiation emitted by the Earth. Geoengineering options, as defined here, limit the amount of shortwave radiation absorbed by the Earth.

There are four basic ways to do this—by increasing the amount of solar radiation reflected from space, from the stratosphere, from low-level clouds that blanket the skies over parts of the ocean, and from the Earth's surface.

The idea of doing any of these things may seem preposterous, if not reckless and hubristic. As I shall explain, however, geoengineering has much to offer as well as much to fear. Indeed, it could turn out to be an option that we may someday be glad to *use*.

Whatever one's initial reaction to the idea might be, we need to understand all of the possible ways in which we can address the challenge of climate change, and how

---

* I am grateful to Lee Lane for many stimulating discussions on geoengineering over a number of years, and for his thoughtful comments on an earlier version of this paper.

geoengineering fits into this set of options. One thing that we cannot do is to close our eyes and pretend that the option does not exist.

Climate change: an overview

Climate change is more than an environmental issue. It is also a development challenge, an ethical matter, and a problem for risk management. More than anything, it is a collective action problem. It is a collective action problem because climate change is determined by the concentration of greenhouse gases in the atmosphere, which depends on the aggregate level of (net) emissions, not the emissions of individual countries. Because of this, each country gets only a small share of the total benefit of its own emission reductions, while benefiting from the cuts made by others. By its very nature, climate change mitigation is vulnerable to free riding.

This basic free riding problem is made worse by other features of climate change:

First, the costs of reducing emissions very substantially will be huge. Emissions can be reduced significantly at low cost, but to stabilize concentrations, emissions must be reduced dramatically (eventually, net emissions must fall to zero), and this will be very costly. Indeed, it is because of this that free riding is such a great problem for climate change. The cost of substituting away from CFCs was relatively inexpensive, which helps to explain why the Montreal Protocol was able to overcome free rider incentives (Barrett, 2007).

Second, the costs of cutting emissions will fall on industry, especially trade-sensitive, energy-intensive industry, shifting comparative advantage in these sectors towards countries that do *not* cut their emissions. To business, cutting emissions unilaterally threatens a loss in "competitiveness." To environmentalists, it implies "trade leakage"—an increase in the emissions of countries that do not adopt a climate policy, in response to a reduction in the emissions of those countries that do adopt a climate policy. Trade leakage is essentially a penalty imposed on the countries that do the "right" thing. Frustratingly, it is also a reward handed to the countries that do the "wrong" thing.

Third, there are very long lags between the date at which emissions are reduced and the period of time during which these reductions produce benefits. Even if atmospheric concentrations were frozen at today's level, and net emissions were therefore reduced to zero, globally and instantaneously, the temperature would continue to warm 0.3°-0.9°C through this century (IPCC 2007: Table SPM.3). The cost of reducing a ton of emissions is incurred now. The benefits unfold over a very long period of time. Emission reductions are thus like an investment. To evaluate the economics of any investment, it is necessary to discount future benefits, so that these future values can be expressed in terms (present values) that are comparable with current costs. The economics of mitigation are highly sensitive to the rate of discount.

Discounting is one ingredient in a framework that should help us to decide what to do about climate change. One plausible ethical perspective is that we should choose what to do about climate change from behind a veil of ignorance. By that I mean we should decide what to do without knowing the generation to which we belong. From this vantage point, would we want to discount the future? Possibly not. But suppose future generations will be better off. Then we may want to discount the future, so that the less well off early generations do not suffer greatly for the sake of the more fortunate future generations. Suppose instead that we believe the future will be worse off. Then we may want earlier generations to shoulder more of the burden—implying a lower and possibly negative discount rate. One reason future generations may be worse off is because of climate change. Should climate change truly threaten future prosperity, the ethical perspective adopted here would ask the current generation to make a sacrifice for the future. The appropriate discount rate is thus endogenous to the climate scenario, and sensitive to our ethical perspective.

Finally, it can help to think of there being two kinds of climate change. "Gradual" climate change refers to a slow unfolding of climate change over an interval of time, such as the rest of this century. "Abrupt" climate change implies rapid shifts that may occur at any date, but with a probability that cannot be deduced from historical experience—an example being disintegration of the West Antarctic Ice Sheet. It is also important to look further into the future. Most analyses of climate change stop in 2100. We are not accustomed to making decisions that require us to peer that far in to the future. But with climate change the effects are so slow to build and so long lasting that we need to peer much, much farther into the future. In the very distant future, even gradual climate change will produce only losers. Moreover, the likelihood of abrupt climate change will increase, especially should we fail now to take action to limit atmospheric concentrations. So, even from the perspective of gradual climate change, it seems clear that the world should eventually stabilize atmospheric concentrations. Concern about abrupt climate change should make us want to do more. How much more? That is a problem of decision-making under uncertainty. For climate change, the uncertainties are profound. We are pushing a system into a place it has never been before. We can't be sure what we will find when we get there.

Climate change: what have we done about it thus far?

What has the world done so far about climate change? The short answer is: "Not much."

In 1988, at a quasi-political conference held in Toronto, participants concluded that global CO_2 emissions should be reduced 20 percent from the 1988 level by 2005. Through 2004, however, and despite two climate treaties having entered into force, global emissions increased 32 percent.[1] A gap this big (50 percent), opening up over a period of just two decades, hints at the magnitude of the collective action challenge.

The Toronto target is important not only because it was the first target ever proposed but because it was a global target. As noted before, only global emissions matter. The problem with global targets, however, is that everyone is responsible for meeting them—

---

[1] See the Carbon Dioxide Information Analysis Center for data on global emissions.

meaning, of course, that no one is responsible for meeting them. That is why they have had no effect so far.

What about individual targets? After the Toronto meeting, Austria, Denmark, Italy, and Luxembourg all pledged to meet the Toronto target individually (by reducing their individual emissions 20 percent from the 1988 level by 2005). In the end, however, none did so.[2] These failures are further expressions of free riding behavior.

In February 2007, the European Union unilaterally set the goal of reducing emissions 20 percent from the 1990 level by 2020, and by 30 percent should the United States and other industrialized countries agree to the same target.[3] The reason for making their reductions contingent upon other countries' reductions is to create an *incentive* for other countries to reduce their emissions. But will its offer change the behaviour of these other states? History is not encouraging.[4] Over 10 years ago, EU officials travelled to Kyoto proposing to cut their emissions 15 percent if the other OECD countries did so. That offer was rejected, and Europe eventually agreed to reduce its emissions by just 8 percent. In 1992, the European Community proposed a mix of measures, including a carbon/energy tax, to stabilize EC emissions at the 1990 level. Like the EU's recent proposal, the EC's tax was made contingent on other OECD countries adopting the same tax. And just as in the other instances, their offer was rejected and the EC dropped the tax. These are all further illustrations of free riding behavior.

Kyoto is the most ambitious attempt so far in getting countries to reduce their emissions, but it has had little if any effect. The United States did not participate in Kyoto. Canada ratified Kyoto, but will not comply. Russia ratified Kyoto and will comply, but that is only because the emission constraints for Russia are so generous that they will not bite. China also ratified Kyoto and will comply, but Kyoto does not require that China be subject to any emission limit. Many other countries, such as Japan and New Zealand, face a serious compliance gap. The situation for Europe is mixed. Spain has the largest gap of any country. Denmark is well off its individual target. However, Kyoto treats Europe as a "bubble," meaning that these countries are not bound to meet their individual limits so long as the original 15 members of the European Union meet their collective limit. Overall, Europe has been helped by Kyoto's choice of a base year (1990), which makes reducing emissions relatively easy for some countries (such as the United Kingdom and Germany). Of course, the European Union has established its Emissions Trading Scheme—the most ambitious of its kind ever. But this scheme covers less than half of emissions and has been beset by various problems. (Most recently, market price for emission reductions has fallen dramatically, due partly to underlying weakness in the

---

[2] The targets are summarized in International Energy Agency (1992).

[3] In 2005, EU-27 emissions were almost 8 percent below the 1990 level; see European Environment Agency, *Annual European Community Greenhouse Gas Inventory 1990-2005 and Inventory Report 2007*, Technical Report No. 7, 2007.

[4] As well, to call for identical percentage cuts in emissions from the same base year is to ignore differences among countries. The EU-27 includes countries in economic transition. The emissions of these countries are already substantially below the 1990 level for reasons of restructuring. For other OECD countries to meet the same target would not reflect "equal sacrifice." This is the "comparability" problem, discussed later in this paper.

economy.) Australia recently ratified the Kyoto Protocol, but after taking land use, land-use change, and forestry activities into account, Australia is within its Kyoto limit; Australia will have to do very little to comply.

The main point I want to stress here is that, for all the efforts made over the last two decades since the Toronto conference, global emissions have kept on rising, as have atmospheric concentrations. Indeed, growth in atmospheric concentrations has been accelerating in recent years (Canadell et al., 2007). It is really because of our failure to address climate change fundamentally that we must now contemplate the possible use of geoengineering (Crutzen, 2006).

Intriguingly, the growth rate in atmospheric concentrations declined after a "natural" geoengineering experiment. In 1991, the eruption of Mount Pinatubo threw a plume of particles into the atmosphere. One consequence of this was to increase diffuse radiation. This in turn stimulated photosynthesis, which enhanced the terrestrial carbon sink. The effect was to cause a "temporary decline in the growth rate of atmospheric carbon dioxide after the eruption" (Gu et al., 2003: 2035). These same particles also reflected sunlight away from the Earth, causing global mean temperature to fall. It is this second effect that hints at the possibility of geoengineering to offset the warming effect of increasing concentrations.

Actions we can take

What *should* we do about climate change? We need to do five basic things.

First, we need to reduce global emissions of greenhouse gases. We can do some of this at relatively low cost using existing technologies, by means of conservation, fuel switching, and substitution of non-fossil fuel energy for fossil fuels. We can do more of this, also using existing technologies, but only at higher cost (in welfare terms)—we can always shut off our coal-fired power plants! To reduce emissions dramatically and at an acceptable cost will require a climate-technology revolution.

Second, to discover and develop new technologies, we must undertake more R&D. In some cases, we have a pretty good sense of the technologies we need. It seems very clear, for example, that carbon capture and storage will have to play a substantial role in reducing emissions. We already know how to capture carbon, but we don't know how to do this efficiently at the scale of a large power plant. So far, this has not been done anywhere. We also need to understand the full implications, including the risks, of geologic storage. In other cases, R&D will be at a much more basic stage—an example being nuclear fusion research. We need a broad portfolio of R&D effort.

Third, some climate change seems inevitable; so, no matter how effective we are in reducing emissions, we will need to adapt. Adaptation can be undertaken in anticipation of future climate change—an example being R&D into seed varieties that perform better under climate stress. It can also be undertaken in reaction to climate change—an example here being spatial redistribution of agriculture.

Fourth, we need to remove CO_2 from the air. Planting trees is one way of doing this. Fertilizing the oceans may be another, although only a few areas of the ocean are iron-limited, and the environmental consequences of this approach are unknown. Another way to increase ocean uptake of CO_2 is to change the ocean's alkalinity by adding lime or bicarbonate to the ocean. Increasing ocean alkalinity could reduce atmospheric concentrations of CO_2 even as it reduced ocean acidification. The feasibility, environmental impacts, and costs of this approach are unknown, but its role in stabilizing concentrations will in any event be limited because the rate of uptake of CO_2 by the oceans is slow. A third possibility is to remove CO_2 from the air directly, anyplace on Earth, by means of an industrial process that puts air into contact with a chemical "sorbent," such as an alkaline liquid, with the captured CO_2 being stored underground. This technology is still at an early stage of development, and it has advantages and disadvantages. One advantage is that the capture facilities can be located anywhere. In contrast to power plant carbon capture, they need not be located near population areas. Another advantage is that they can potentially be scaled to any level. Industrial air capture is a true "backstop technology." The great disadvantage of this technology is cost. Mainly because CO_2 is less concentrated in the air than in a power plant's stack gases, industrial air capture is more expensive than power plant capture and storage.

Finally—and here I return to the main subject of this paper—we need to contemplate the use of geoengineering to counteract the effect of rising concentrations of greenhouse gases.

Relationships among these actions

How are these different options related? In particular, how do the various options compare to reducing emissions?

R&D spent on technologies that can reduce emissions is a *complement* to emission reductions. R&D will open up new ways to reduce emissions. It will also lower the costs of reducing emissions. The more R&D we do, the more we will want to reduce emissions; and the more we want to reduce emissions, the greater will be the returns to R&D.

Of course, R&D spent on adaptation, air capture, or geoengineering is a complement to these activities.

Adaptation, air capture, and geoengineering are *substitutes* for emission reductions.

Adaptation lowers the damages from climate change. It therefore lowers the returns to reducing emissions. Adaptation is clearly an *imperfect* substitute for emission reductions. A dike may save land from rising sea levels, but limiting atmospheric concentrations would avoid the need for a dike—and save shoreline that is not worth protecting by dike building.

Air capture is more nearly a perfect substitute; like emission reductions, it alters the concentration of greenhouse gases in the atmosphere. However, industrial air capture is less constrained than emission reductions. It could be scaled to reduce concentrations, and not only to limit their rise. It could also be scaled to reduce concentrations relatively quickly.

Geoengineering, like adaptation, is an imperfect substitute for emission reductions. It is expected to reduce climate change damages, but it will do so by means of a different mechanism than emission reductions. Importantly, geoengineering will do nothing to address ocean acidification.

Risk and uncertainty

Climate change is uncertain. Even if we were sure that dangerous climate change could be avoided by limiting temperature increase to no more than 2° C—a goal endorsed by the European Union—we are not sure what we need to do to meet this temperature change target. We can only meet it with some probability. To increase the chances of meeting it, we have to reduce emissions by more. Since reducing emissions is costly, we have a familiar tradeoff between money and risk.

We also face a risk-risk tradeoff. For while climate change poses a risk, so do some of the actions we may take to limit climate change. Two technologies seem likely to play an important role in any effort to limit concentrations this century – nuclear power and carbon capture and storage. Nuclear waste remains highly radioactive for thousands of years. The best means for storing nuclear waste long-term is well known. It involves storage deep underground. Because of the risks of storage, however, no country has so far constructed such a facility. An allied problem is nuclear proliferation. If nuclear power is to help us to address climate change, it will need to expand in developing countries. This will increase the number of states with an opportunity to acquire enrichment capability. Underground storage of CO_2 in geological formations also poses risks. Sudden releases are possible, and may pose health and environmental risks (by displacing oxygen in the neighborhood of the release). More gradual releases are also possible, and may contaminate groundwater and soils. Of course, such releases would also allow CO_2 to escape into the atmosphere. The capacity of the deep ocean to store CO_2 is greater still, but the oceans are not a truly permanent solution, and deep ocean storage would also change ocean chemistry at the injection site and, over time, as the ocean waters mixed, throughout the world's oceans. The ecological consequences of large-scale, deep ocean storage are unknown.

As I shall explain later, geoengineering poses substantial risks as well. The point I wish to make here is that our other options also involve risks. As we contemplate what we should do about climate change, these risk-risk tradeoffs need to be considered. Sweden's decision to end its ban on new nuclear power stations hints that the risks of climate change may be increasing relative to the risks of mitigation by this option—and, therefore, that countries might also contemplate using geoengineering as the risks of climate change increase even more.

Because the risks of various interventions are different (not perfectly correlated), we should, even now, be thinking about a portfolio of actions or possible actions. We shouldn't only reduce emissions. Even if we did so dramatically, we would not eliminate climate change risk, and doing so dramatically, as just mentioned, would introduce other risks in addition to involving great cost. Adaptation offers some protection from climate change risk. It should be done in association with emission reductions. Similarly, R&D undertaken now will create more options for the future—options we may want to have should climate change prove more harmful than expected.

Overview of the geoengineering options

As noted in the introduction, there are four main geoengineering options. These are summarized in Table 1.

The first approach would erect a parasol in space at the so-called Earth-sun inner Lagrange point (L1), large enough to shade all sun-exposed parts of the Earth 24 hours a day, 365 days a year. Its main advantage is that it would have a nearly uniform effect. Another possible advantage is that it would leave the Earth's chemistry unaltered (of course, this approach, like all the other geoengineering options discussed here, will not help address ocean acidification). Its main disadvantages are engineering complexity and cost.

To compensate for the effects of a doubling in CO_2 concentrations, the sunshade would need to be 3.4 million square kilometers in size if placed 1.5 million kilometers from the Earth (9.4 million square kilometers in size if placed 3 million kilometers from the Earth; see Angel, 2006: 17185). Rather than build a single shade or a cloud of tiny scattering particles, the most advanced proposal would amass "a cloud of spacecraft holding their orbits by active station-keeping" (Angel, 2006: 17184). Each "flyer" would be less than a meter in diameter and weigh just over one gram. In total, many trillions of flyers, with a total mass of about 20 million tons, would be needed to do the job (Angel, 2006: 17186). To put the payload into space would require 20 million launches. Once placed in the desired orbit, the discs would need to be controlled so as to provide the desired screening, and coordinated so as not to collide into one another. They would operate for a few decades, at which point they would need to be replaced. Where will the dead discs go? Some will return to Earth, posing a danger to Earth-orbiting space craft. A "small fraction might take up eccentric orbits and eventually reach the Earth intact" (Angel, 2006: 17188-17189). Based on some generous assumptions, the cost of erecting the sunscreen would cost several trillion dollars. Over time, of course, the flyers would need to be replenished.

This is just to compensate for a doubling in CO_2 concentrations. If concentrations are not held to a doubling, then to maintain the same temperature, more flyers will have to be launched. Lenton and Vaughan (2009: 2576) calculate that doing this would require 135,000 launches per year, each carrying 800,000 space flyers.

TABLE 1
Summary of Geoengineering Options

Option	Description	Scale	Advantages	Disadvantages
Sunshades placed at the inner Lagrange point (Angel, 2006).	Place trillions of small discs a million miles above the Earth in an orbit aligned with the sun to reduce the amount of incoming radiation.	Calculations show that this could be scaled to offset the effect of a 2 × CO_2 increase in concentrations, and very possibly more than that.	Entire planet would be cooled; shades would have a lifetime of many decades; only incoming solar radiation would be changed; orbit could be changed to alter effect.	Requires enormous mass; would need to maintain orbit; under probably optimistic assumptions, upfront cost to offset 2 × CO_2 about $5 trillion.
Injecting sulfate aerosols or manufactured particles in the stratosphere (Caldeira and Wood, 2008; Rasch et al., 2008)	Inject particles in the stratosphere above the equator.	Calculations show that this could be scaled to offset the effect of a 2 × CO_2 increase in concentrations, and very possibly more than that.	Inexpensive: offsetting 2 × CO_2 might cost $25-$50 billion per year or even less. Essentially involves increasing the mass of a substance that is already found in the atmosphere. For more, see Table 2.	See Table 2.
Increasing the reflectivity of low-level marine clouds (Latham et al., 2008).	Self-propelled and powered, unmanned ship throws ocean spray into the clouds, thus whitening the clouds.	Fleet of 1,500 vessels could offset the effect of a 2 × CO_2 increase in concentrations (but see Lenton and Vaughan, 2009).	According to the engineers who propose this approach, the cost of offsetting 2 × CO_2 would be around $4 billion/year.	According to Lenton and Vaughan (2009: 2589), the effects would be "regional and patchy."
Increasing the reflectivity of the Earth's surface (Lenton and Vaughan, 2009).	Painting roofs white; covering desert areas with white polyethylene; growing or engineering more reflective (shiny) plants.	Could not, by itself, offset the effect of a 2 × CO_2 increase in concentrations.	White roofs would reduce cooling needs for buildings and reduce heat island effect in urban areas.	Enhancing desert albedo has the largest effect, but this option would change temperature mainly in the desert regions. Will destroy desert ecosystems.

The second proposal, though hardly "down to Earth," is certainly simpler. It involves projecting sunlight-deflecting, sulfate or engineered particles into the stratosphere. The purpose would be to mimic a volcanic eruption, like that of Mount Pinatubo, which is known to have had a cooling effect. Sulfates are already resident in the stratosphere. To offset the warming associated with a doubling in CO_2 concentrations, the amount of sulfates in the stratosphere would have to increase 15-30 times—a large multiple, but a very small increase relative to the amount of sulfur in the troposphere (Rasch et al., 2008).

There are a number of ways to deliver sulfates to the stratosphere: by artillery shells, rockets, high-flying jets, or even hoses tethered to balloons. To maximize the time that the sulfate particles stay in the air, and to create a uniform cooling effect, the particles should be released near the equator. They would be transported to, and eventually rain out over, the poles. If the intention were to cool the Arctic only, particles could be scattered in the higher latitudes of the northern hemisphere (Caldeira and Wood, 2008).

The economics of this form of geoengineering are incredible (Barrett, 2008). Upon reviewing the options in depth, the National Academy of Sciences Panel on the Policy Implications of Greenhouse Warming (1992: 452, 454) calculated that adding stratospheric aerosol dust to the stratosphere would cost just pennies per ton of CO_2 mitigated. Crutzen (2006) thinks the costs would be perhaps $25-$50 billion per year to offset the effects of a doubling in CO_2 concentrations, but other estimates are lower (Barrett, 2008). It seems clear that, relative to stabilizing concentrations, this form of geoengineering is so cheap that cost will not be a major consideration in whether it is ever used (Keith, 2000: 263).

More important are likely to be the disadvantages. In addition to not addressing ocean acidification, stratospheric aerosols could destroy ozone. It is also possible that the cooling effect may not preserve the existing spatial distribution of climate. Finally, and as with all the other geoengineering experiments, we cannot rule out the possibility that this technology will have other effects, including harmful effects, as yet unimagined. The particles would not remain in the stratosphere as long as the space flyers (perhaps a year or two as opposed to several decades), and so would have to be replenished more often. An advantage of this feature, however, is that this geoengineering experiment could be turned off relatively quickly should its effects prove harmful overall.

The third proposal involves an intervention much closer to Earth—seeding low altitude stratus clouds over the oceans with seawater spray. The added salt would whiten the blanket of clouds already present and so increase their reflectivity (their "albedo").

The sea spray could be produced by unmanned, ocean-going vessels, propelled by vertical spinning cylinders that act like sails, with the movement of the ships creating the power needed to produce the spray. Satellites could measure the reflectivity of the clouds, allowing the amount of spray to be varied to maintain the desired level of solar deflection. Preliminary calculations suggest that a fleet of 1,500 vessels could offset the warming effect of a doubling in CO_2 concentrations. According to the designers of this concept, the fleet of vessels needed to offset the effects of a doubling in CO_2 concentrations would cost around $4 billion (Salter et al., 2008).

A recent analysis by Lenton and Vaughan (2009: 2589) finds that this approach would be less effective than suggested by Latham et al. (2008). It would thus also be more costly than suggested above, and harder to scale up than sunshades or stratospheric particles. Another feature of cloud seeding is that its effects would be patchier. One possible advantage of this approach, however, is that the sea spray would remain in the clouds for only a few days. It would be very easy to shut off this geoengineering experiment.

The final suggestion is to change the albedo of the Earth's surface—by painting roofs and other surfaces white, by covering desert regions with a film of polyethylene, or by planting and possibly bioengineering shinier trees, plants, shrubs, and grasses. The effect of these changes on temperature is relatively small compared to the other options discussed here (Lenton and Vaughan, 2009). More importantly, the effects would be patchy. This means that attempts to use this technology to lower global mean temperature "could lead to excessive regional cooling" (Lenton and Vaughan, 2009: 2593).

Intriguingly, however, this technology might be used specifically to *produce* a local cooling effect. Sulfate particles in the troposphere also result in local cooling. However, these particles are harmful to human health, and have been falling for that reason, causing global mean temperature to rise; see Crutzen (2006). The possibility of using geoengineering to alter local temperature would totally transform the analysis of this technology. If a problem with planetary scale geoengineering is that every country will be affected, whether they contribute to the effort or approve of it, a problem with local engineering is that countries can insulate themselves from the effects felt by other countries. Local geoengineering would be more akin to adaptation.

To sum up, there exist a number of proposals for geoengineering reductions in shortwave radiation to counteract the increase in longwave radiation due to rising atmospheric concentrations of greenhouse gases. Putting sunshades in space would be a formidable technical challenge. It would also be very costly. It seems an implausible choice. Some combination of cloud seeding and enhanced surface albedo is more plausible and affordable but would be patchy and could not be scaled up to any desired level. Stratospheric aerosol injection is technically feasible, would have a more uniform effect, and can be scaled up to almost any desired level. It is also inexpensive. It seems the most likely option, and for that reason I have summarized its pros and cons in Table 2. However, I want to emphasize that further investigation is needed to understand the relative merits of all these options—and others that have yet to be considered. It would be premature at this stage to pick a "geoengineering winner."

Further research can also improve upon the proposals made thus far. For example, preliminary research suggests that particles could be engineered to have a more efficient scattering effect, reducing the mass of particles that would need to be added to the stratosphere (Teller et al., 1997; Keith, 2000). Other ways may also be found to reduce the consequences of sunlight scattering for ozone depletion (Crutzen, 2006).

TABLE 2
Pros and Cons of Stratospheric Aerosol Injection

PROS	CONS
Would affect temperature within months.	Would be a large-scale experiment. May have effects that have yet to be contemplated, in addition to those that are already known though also uncertain.
Is expected to have a fairly uniform effect on temperature.	May not preserve today's distribution of climate; some areas may suffer a worse climate.
Can be scaled to nearly any desired level.	Would not address ocean acidification.
Particles would last a year or two in the stratosphere; the experiment could be shut off relatively quickly.	Must continue to inject particles indefinitely in order to sustain cooling effect.
May increase net primary productivity of biomass. The effect of higher concentrations of CO_2 on growth would likely overwhelm the negative effect of reduced sunlight (Govindasamy et al., 2002).	Will likely reduce precipitation (Trenberth and Dai, 2007).
	Less sun for solar power.
Inexpensive in financial terms relative to reducing emissions.	Will deplete stratospheric ozone (Crutzen, 2006; Tilmes et al., 2008).
Decoupled from the energy system.	Will add sulfur to the atmosphere and could contribute to acid rain, though the total additional loading would be small and could be offset by reductions in emissions to the troposphere (Rasch et al., 2008).
Can be done unilaterally or by a coalition of the willing.	Who decides whether, under what circumstances, and on what scale it should be attempted?
The sky would be less blue (more white) during the day, more vibrant (red) during sunrise and sunset. A gain or a loss?	

Geoengineering in the risk portfolio

How might geoengineering be used? There are four main options.

First, we might prohibit the use of geoengineering altogether. We might even prohibit experimentation into geoengineering. One justification for this extreme position is the fear that geoengineering may impose unacceptable risks (see especially Robock, 2008). However, and as I explained previously, the alternatives to geoengineering also pose serious risks. Why should geoengineering risks be treated differently than the others?

Another reason in support of this proposal is that, if it were known that geoengineering could be used, less effort would go into reducing emissions. However, we must then ask if the promise not to use geoengineering, ever, would be *credible*. Suppose we observe the beginnings of "runaway" climate change. Due to lags in the system, emission reductions could not, at this point, prevent catastrophe. Would it really be credible not to use geoengineering under such circumstances? Indeed, the worst possible scenario might be that someday we find ourselves in a situation in which we want to use geoengineering to avert a catastrophe, but lack the knowledge of how to make geoengineering work, and to work with a minimum of adverse side effects.

Second, we might use geoengineering as the first line response to climate change, meaning that we would not bother to reduce emissions, to undertake R&D into new technologies, or to make investments that would lower the damages from future climate change. This would be to put all of our eggs, so to speak, in the geoengineering basket. From the perspective of risk, this is an ill-advised proposal. Suppose we discover that geoengineering does not work, or works at the expense of unwanted side effects. Suppose, in particular, that we discover these things several decades into a geoengineering program. At this point, we could still adapt; we could start to reduce emissions; and we could also scale up air capture. But we would have lost the opportunity to reduce emissions (and, therefore, atmospheric concentrations) more cheaply at a much earlier stage.

Robock (2008: 17) has expressed a different concern—that, were geoengineering to be shut off many years into the future due to a "technological, societal, or political crisis," the continued buildup of greenhouse gases in the atmosphere will mean an abrupt shift and "rapid climate warming, which would produce much more stress on society and ecosystems than gradual global warming." It is certainly true that shutting off geoengineering many decades into a geoengineering-only policy would have this effect. But it is precisely for this reason that this scenario seems unlikely. Since the consequences of discontinuing the use of geoengineering would be severe, the incentives to continue using it will be very powerful. I believe the environmental risks of geoengineering are the more important.

Third, we might use geoengineering in combination with emission reductions to prevent significant temperature change while we also work to reduce emissions. According to this proposal, we should start to use geoengineering soon. Wigley (2006) has modeled this scenario, and finds that it has advantages. Indeed, he finds that "geoengineering, when combined with mitigation, could even lead to the stabilization of global mean temperature at near present levels and reduce future sea-level rise to a rate much less than that observed over the 20th century: aspects of future change that are virtually impossible to achieve through mitigation alone." One major reason for using geoengineering in combination with emission reductions is that geoengineering will not address the allied problem of ocean acidification. It is also possible that there may be long-term risks of geoengineering not yet foreseen.

Fourth, we might hold geoengineering in reserve, to use only in the case in which signs of "abrupt and catastrophic" climate change first emerge. This seems to be the position of Paul Crutzen (2006: 216), who writes that "the albedo enhancement scheme should only be deployed when there are proven net advantages and in particular when rapid climate warming is developing…." We would undertake R&D now, but would not deploy geoengineering until a later date—if ever. As noted by Stephen Schneider (2008: 17), "R&D is needed and should be an early part of the climate policy investment sequencing, even if deployment is the last resort." The option of delaying deployment can be contemplated as compared with the third option because geoengineering can affect the climate very rapidly—in months rather than decades. One risk in this approach, however, is that we can't be sure that geoengineering will be able to avert every kind of abrupt and catastrophic climate change.

Combinations of the less extreme alternatives are also possible. Iklé and Wood (2008: 23) conclude:

> "We should continue to pursue all reasonable measures for reducing emissions of greenhouse gases so that longer-term atmospheric levels of these gases are kept within tolerable bounds. And we should more vigorously explore geoengineering options for climate stabilization in the near term and for use in the event of a global warming emergency situation."

One strong result that emerges from this discussion is that the case for geoengineering R&D is very strong. What kind of R&D? In an article entitled "20 Reasons Why Geoengineering May be a Bad Idea," Alan Robock (2008: 17-18), hardly an advocate for geoengineering, concludes that there is a case for limited research:

> "The reasons why geoengineering may be a bad idea are manifold, though a moderate investment in *theoretical* geoengineering research might help scientists to determine whether or not it *is* a bad idea. Still, it's a slippery slope: I wouldn't advocate actual small-scale stratospheric experiments unless comprehensive climate modeling results could first show that we could avoid at least all of the potential consequences we *know* about."

Is it right to draw a red line under theoretical research, to forbid experimentation? I would only point out that we are currently carrying out a planetary experiment that we know will have adverse consequences, and that we fear may have catastrophic consequences, at least in the longer term, for a high enough level of atmospheric concentrations. So, why should we undertake small-scale experiments into geoengineering only if we are confident that we can avoid *all* of the potential consequences we know about? A theme of this paper is that we confront risk-risk tradeoffs, and we should deal with these in a consistent manner.

The geopolitics of geoengineering

An important aspect of geoengineering is that it can be undertaken by a single country, or by a coalition of the willing. This makes it entirely unlike emission reductions. As explained previously, emission reductions are extremely vulnerable to free riding. Geoenginering is not.

How might matters play out? We do not know, but we can make educated guesses, and I think we should try to do this because the consequences of using or not using geoengineering will be profound, and every country will be affected by the decisions that are made. I have so far explained how we should think about geoengineering from the perspective of the world as a whole. In this section I focus on how individual countries will look at this technology. This perspective is essential because individual countries are capable of deploying the technology, and yet they may have little incentive to take into account how other countries will be affected by their decisions.

Geoengineering, unilateralism, and "gradual" climate change

So, what are the incentives for a country to undertake geoengineering?[5] Let us do a simple back-of-the-envelope calculation. According to Cline (2007), India's agricultural potential could fall 30 percent for a 3°C mean global temperature increase by around 2080. Currently, agriculture makes up around 20 percent of India's GDP.[6] In 2007, India's GDP was about $1,171 billion.[7] This implies that agriculture yields India an income of around $230 billion. Assuming that, were it not for climate change, this value would remain constant over time, climate change in 2080 would cost India about $70 billion. Based on estimates given previously, geoengineering could avoid this loss for much less money. Of course, there are many other factors to consider, but it is pretty clear that some country, or group of countries, may be tempted to use geoengineering in the future.

---

[5] David Victor (2008) has suggested that geoengineering might be attempted by an individual—a "Greenfinger" (so-named after James Bond's antagonist, Goldfinger). I find this scenario implausible—no government, and certainly not all of the world's governments, would allow an individual to alter the Earth's climate. The world's reaction to the plan by Planktos, a California-based company, to experiment with "ocean fertilization" near the Galapagos Islands hints at how countries are likely to respond to a planetary scale intervention. Due to opposition from a number of governments, including the U.S. government, Planktos canceled its plans.

[6] Data collected from the World Bank.

[7] Data collected from the World Bank.

To reinforce this point, note that about 70 percent of India's 1.1 billion people live in rural areas.[8] Is it realistic to expect that a democracy will not act to help a majority, when doing so is feasible and not very costly? The internal pressure for action would be very strong.

Note as well that India has already sent a spacecraft to the moon. It is currently planning a manned mission to the moon. It is certainly within India's technical capability to deploy a geoengineering project.

It is also within its political capability. As I am writing this paper in February 2009, a joint German-Indian research team is undertaking a related experiment on "ocean fertilization" in the South Atlantic, despite protests by environmentalists. India, it should also be remembered, developed nuclear weapons outside of the Nuclear Nonproliferation Treaty, and tested those weapons over the objections of other countries. External pressure for restraint may not deter India from using geoengineering, should India believe that its national interests are at stake.

I am not saying that it is inevitable that India would want to deploy geoengineering. I am only saying that, under plausible assumptions, the possibility needs to be considered.

Domestic politics will help to shape decisions. The ocean fertilization experiment just mentioned is being undertaken over the objections of the German Environment Ministry. Geoengineering is thus likely to create internal as well as international tensions. In some countries, domestic politics will be more of a constraining influence than in other countries.

I have focused here on India only to illustrate a general point. For a variety of reasons, India may not want to use geoengineering. And many other countries (and groups of countries) are capable of deploying this technology, including Brazil, China, Europe, Japan, Russia, and the United States. Perhaps one of these countries is more likely than India to have an incentive to use it.

The effect of gradual climate change on agriculture is uncertain. Cline's analysis finds that the United States will gain from climate change over this century (I shall return to the implications of this later). Other evidence points to possibly steep losses. In a recent working paper, Schlenker and Roberts (2008) uncover strong evidence of a threshold effect in U.S. agriculture. Yields of individual crops rise for temperature increases below the threshold (29°C for corn), but fall dramatically for temperature increases above the threshold. Schlenker and Roberts find that yields of individual crops (rather than the aggregates examined by Cline) in the U.S. may fall 30-80 percent by the end of this century. If this study is right, the United States may be the first country to want to use geoengineering (or use it in concert with India). Indeed, if nonlinear effects turn out to be the norm, some or all of the other geoengineering-capable countries may also want to use it. (I shall also return to the implications of "minilateral" geoengineering later in this paper.)

---

[8] Data collected from the World Bank.

Would it matter which country ventured to use geoengineering first? India might be perceived as being more of a victim of climate change, the U.S. more responsible for causing human-induced climate change. The Framework Convention on Climate Change, to which both countries and nearly every other country is a party, says that "developed countries [need] to take immediate action.... as a first step towards comprehensive response...." India might argue that developed countries failed to fulfil this duty. It might also claim that it lacked any alternative means of protection. India might conceivably assert a need to use geoengineering for reasons of "self-defense." It would be harder for the U.S. to make such a claim.

Ultimately, however, *any* state that is capable of using geoengineering might seek to use it, should it feel that its national interests are threatened by climate change.

Winners and losers

Whether such a state *would* use geoengineering depends very much on how it expects other countries will respond. Of supreme importance is whether other countries believe that they would be *harmed* by geoengineering.

As reaffirmed by the Framework Convention, states have a "responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction" (the customary "no harm" principle). Of course, this same language has been interpreted as implying that states have a duty to reduce their emissions of greenhouse gases. But there is a difference between the two situations. First, any state might plausibly argue that it cannot be held to be individually responsible for harming other states when human-induced climate change is caused by aggregate, cumulative emissions. If geoengineering were undertaken unilaterally, by contrast, the state deploying the technology would plainly be individually responsible for its consequences (though it may be disputed whether the harm suffered by any state were *caused* by geoengineering). Second, climate change is an *unintended* consequence of the emission of greenhouse gases, whereas the *purpose* of geoengineering *is* to alter the climate.

"Gradual" climate change is almost certain to produce winners and losers. The use of geoengineering to reduce the effects of gradual climate change will thus also produce winners and losers. Cline (2007), for example, finds that, due to gradual climate change, agricultural capacity in China, Russia, and the United States would likely increase 6 to 8 percent by around 2080. Under this scenario, if India were to deploy geoengineering to avert a local catastrophe, other countries would almost certainly complain. Of course, India might argue that its avoidance of a loss should count more than another country's stolen gain (and ethical reasoning may support this claim), but the point is that some countries may lose should geoengineering be deployed, and they may seek to respond. They might, for example, launch a countervailing geoengineering effort to *warm* the Earth (if one country were entitled to use geoengineering, why shouldn't any country be so entitled?). Alternatively, they might seek to "disable" a geoengineering effort by military means. This last possibility is especially worrying, given that many of the states mentioned as being affected, positively or negatively, by geoengineering possess nuclear weapons. Precisely for this reason, however, I think it is unlikely that a military strike will be carried out. It does, however, seem likely that, so long as climate change has asymmetric effects on countries, geoengineering will create or amplify global tensions.[9]

Geoengineering wars?

Are "geoengineering wars" likely? Although geoengineering will, under the circumstances outlined above, stimulate conflict, states also have incentives to avoid conflict. Geoengineering wars are not inevitable. Indeed, they may not even be likely.

The scenario discussed here involves a clash in rights—the right of one or more states to use geoengineering to avoid climate change losses versus the right of other states not to be harmed by geoengineering. Clashes of this kind are common in international affairs. International water disputes, for example, are of a similar nature (though of course these disputes play out on a different scale). An upstream state may assert its right to divert the waters of a shared river for its own purposes, while the downstream state will claim its right to an uninterrupted flow of this water. Resolution of such disputes invariably demands mutual concessions. Typically, the parties will seek an "equitable" solution, meaning a sharing of rights (Barrett, 2005). The nature of the bargain that is struck will depend on the context, including the characteristics of the parties. For example, if the upstream state is poor and the downstream state rich, the latter state may need to pay the upstream state not to divert its waters. By contrast, if the upstream state is rich and the downstream state poor, the former may need to compensate the latter. Perhaps, then, India will refrain from using geoengineering, or scale back its plans, in exchange for other countries offering to help India improve the productivity of its agriculture (taking the climate as given). By contrast, if the U.S. were inclined to use geoengineering first, it seems more likely that it would be required to finance investments in other countries, to blunt the negative impacts of its use of geoengineering on these countries.

The offer of assistance to states like India is arguably warranted today, even if the possibility of geoengineering did not exist. For the assistance would help India to *adapt* to climate change, and the rich countries have already acknowledged, in the Framework Convention, their duty to "assist the developing country Parties that are particularly vulnerable to the adverse effects of climate change in meeting costs of adaptation to those adverse effects." However, geoengineering turns the tables on this exchange. The credible threat by India to use geoengineering creates an *incentive* for other countries to offer adaptation assistance, so as to discourage India's use of geoengineering. By contrast, should the U.S. want to be the first country to use geoengineering, it may need to offer assistance to the countries that expect to be harmed by its use geoengineering, in exchange for their acquiescence.

---

[9] Schelling (2006) also sees geoengineering as a possible source of tension, though the example he gives is of intervening in the control of hurricanes.

My analysis here is relying on the fact that geoengineering and adaptation are substitutes. We can extend this logic just a little to note that, while India might gain adaptation assistance by its credible threat to use geoengineering, the U.S would likely want to invest in adaptation at home, to avoid paying for the privilege of using geoengineering.

"Minilateral" geoengineering

Although I have emphasized unilateral geoengineering to this point, I consider such a scenario to be very unlikely. The conditions that would make geoengineering attractive to one state will also make it attractive to some other states. A more plausible scenario is one in which some states support, and others oppose, its use. Generally speaking, the greater is the size of the coalition supporting its use relative to the opposing coalition, the greater will be the chances that the technology will be used.

In a scenario in which India would find it attractive to deploy geoengineering, it seems likely that some if not many countries in the low latitudes will cheer. According to Cline (2007), agriculture in equatorial Africa will decline more than 50 percent by 2080, should global mean temperature increase 3°C. The countries in this region are incapable of deploying geoengineering themselves, but would probably welcome India's efforts to do so.

As noted before, India may not be the only powerful state that is tempted to use geoengineering. Cline's analysis indicates that agriculture in Australia, Brazil, Iran, and South Africa will also decline under a scenario of gradual climate change. This may seem an unlikely alliance, but a number of states could find it in their joint interests to form a coalition of the willing, and to launch a collective geoengineering effort, helping equatorial Africa in the bargain. The legitimacy of an effort to use geoengineering will be strengthened as more countries approve of the decision.

However, because some very powerful states—including China, Europe, Japan, Russia, and the United States—might lose should geoengineering be used, it is not obvious that geoengineering will be used. For reasons explained previously, the powerful states that will lose from geoengineering might seek to deter its use, either by threatening to undermine the effort in some way or by offering assistance to those states intent on using geoengineering. Equatorial Africa, with little bargaining power, could be left out of this deal.

To sum up, the "geoengineering game" will be played principally by the more powerful states. The weak states will be affected, for better or worse, but they will have little influence on how the game is played.

Geoengineering and "abrupt and catastrophic" climate change

The situation changes when we peer farther into the future. Over longer periods of time, even gradual climate change will be harmful all around—melting of the Greenland Ice Sheet, for example, would increase sea level by about seven meters over perhaps seven centuries. It is hard to see how any country could gain from this degree of sea level rise, even it occurred gradually.

Abrupt climate change is a greater worry. Warming is expected to be especially strong in the Arctic region. Should this warming trigger massive releases of carbon dioxide and methane, a positive feedback will be unleashed. No country will gain from such a climate shock. A collapse of the West Antarctic Ice Sheet, though perhaps unlikely, would also have very serious consequences. No country will gain from this kind of change either.

It thus seems likely that the interests of states as regards geoengineering will tend to converge over time. Tensions that loom large in a world of gradual climate change will evaporate in the longer run and will disappear very quickly should the prospect of abrupt, catastrophic climate change appear imminent. Robock (2008) asks if the geoengineering cure is not worse than the climate change disease. Our calculation of this choice will change as the impacts of climate change worsen and the negative impacts become a universal experience. At some point, unless we succeed in addressing climate change fundamentally by stabilizing concentrations at a level that is low enough, the geoengineering cure will appear irresistible.

A geoengineering regime

Because every country will be affected whether or not geoengineering is used, it will be in the interests of every country that there exist rules for determining whether, under what conditions, and how, geoengineering is to be used. This is especially true since, as I have emphasized, a significant number of countries will have the capability to use this technology. If only one country had such a capability, that country might prefer to be unencumbered by rules. With at least a half dozen countries having such a capability, each is almost certain to agree to restraints on its own activities in exchange for others agreeing to restraints on their activities.

Currently, no rules of this kind exist. According to Daniel Bodansky (1996: 316), "international law has relatively little specific to say about climate engineering." Moreover, he adds, "we should be cautious about drawing conclusions from existing rules, for the simple reason that these rules were not developed with climate engineering in mind" (Bodansky, 1996: 316). Geoengineering creates a new institutional challenge.

We have already been able to glimpse how existing rules might adapt to address this new technology. The parties to two international treaties (the Convention on Biological Diversity and the London Convention/Protocol) have cautioned against large-scale ocean fertilization. However, and as noted previously, a joint German-Indian research team is currently carrying out a large ocean fertilization experiment in the South Atlantic. Interestingly, the parties to the Framework Convention on Climate Change have been silent on this matter. Which of these institutions, if any, should be permitted to rule on this matter? That question is currently unsettled.

In my view, the rules governing geoengineering should be incorporated within and under the Framework Convention. This is for two reasons. First, and as explained previously, geoengineering needs to be a part of climate change policy—even if countries decide that its use ought to be prohibited. Since the Framework Convention addresses the other policy dimensions of climate change, it should address this one. Second, and as also explained previously, every country will be affected by the use or non-use of geoengineering, and nearly every country in the world is a party to the Framework Convention (the only non-participants are Andorra, the Holy See, Iraq, and Somalia; and even these states have observer status). By contrast, the United States is not a party to the Convention on Biological Diversity, and India is not a party to the London Convention/Protocol. Indeed, less than half of all countries are members of the latter agreement. Incorporating geoengineering into the Framework Convention will contribute to the legitimacy of the decisions that are made about this technology.

The Framework Convention currently ignores geoengineering. The objective of the Framework Convention is to stabilize "greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." However, and as I argued previously, the problem is more appropriately cast as being one of risk avoidance. Geoengineering, as the term has been defined in this paper, would not affect atmospheric concentrations. In this sense, geoengineering is akin to adaptation—it reduces risk without affecting concentrations. The Framework Convention addresses the need for adaptation. It should address geoengineering as well.

The purpose of the Framework Convention is to frame the world's response to climate change. It is not to make detailed decisions about means. As regards emission reductions, that is the purpose of the Kyoto Protocol—an agreement that resides *under* the Framework Convention. Is an agreement like Kyoto needed for geoengineering? The need for this kind of agreement is not essential. The main task of the Kyoto Protocol and future mitigation agreements is to address the collective action problem. As already explained, geoengineering is less vulnerable to free rider incentives. There may be a need for an agreement on cost sharing, but such an agreement would not require the participation of a great many countries. The focus of international negotiations should be on establishing a framework for geoengineering—rules for its use or non-use.

What rules are needed? The most important would be a requirement that any research on geoengineering be conducted in an open and transparent manner. In addition, states should be required to provide advanced notification of any attempt to carry out geoengineering, whether for research or other purposes.

More restrictive rules should be considered. For example, it would be desirable for decisions about actual deployment to be based on consensus. This rule might be strengthened to require that deployment require the consent of a (super) majority (possibly weighted), should consensus not be possible. It might seem that the geoengineering-capable countries would prefer not to be constrained by this last rule. However, each of these countries may be willing to accept such a constraint in exchange for other countries accepting the same constraint.

Additionally, states should cooperate in carrying out periodic reviews of the research undertaken—a role suited to the Intergovernmental Panel on Climate Change.

Precedent

As I have explained elsewhere (Barrett, 2007; 2008), the closest analogy to the geoengineering challenge may be a situation that arose just over a decade ago. This is the decision of whether to retain the remaining official stockpiles of smallpox virus for research purposes or to destroy them. As with geoengineering, there are risk-risk tradeoffs. If the stocks are retained, they can be used to develop improved vaccines and antiviral medicines—advancements that would help all countries should there be a bioterrorist attack (there is a fear that smallpox samples may be held unofficially). If the stocks were destroyed, however, the chances of an accidental release from these sources would be eliminated. Every state has an interest in the outcome, but only two states are known to possess stockpiles—Russia and the United States.

These two states wanted to retain their stocks for research purposes. Most other states wanted their stocks to be destroyed. A consensus was reached through the mechanism of the World Health Assembly (an institution that, like the U.N. General Assembly, gives each member country of the World Health Organization, or WHO, one vote), allowing the stocks to be retained provided they were used for research purposes "with the agreement and under the control of the WHO."[10] Decisions by the World Health Assembly are guided by advice given by the WHO's Advisory Committee on Variola Virus Research, which is now to be constituted so as to "ensure balanced geographical representation, with the inclusion of experts from developing countries, and substantial representation of public-health experts, and the independence of the members of this Committee from any conflict of interest."[11] The current arrangement also prohibits Russia and the United States from using genetic engineering to manipulate the smallpox virus.

Why did the U.S. and Russia agree to be bound in this way? One reason is historical. Their laboratories were designated WHO collaborating centers, obligated to serve the global interest. As well, some countries had given their stocks to the United States, and it is unclear whether, in doing so, they had given up their rights to decide the fate of these stocks. A second reason is that it wouldn't be easy for either state to ignore the objections of other third parties. The U.S. and Russia may have the upper hand, so to speak, on this one issue, but they have to interact with other states on many other issues. A third reason, of course, is that the U.S. and Russia both want the other country's use of their stocks to be constrained. From the perspective of each country, mutual restraint may be preferred to mutual freedom (though individual freedom would be preferred to mutual restraint).

As with smallpox destruction, my view is that consensus and transparency should be hallmarks of a geoengineering regime. Agreement to prohibit certain activities may also

---

[10] "Smallpox Eradication: Destruction of Variola Virus Stocks," Agenda Item 12.2, Sixtieth World Health Assembly, WHA60.1, 18 May, 2007.

[11] See previous footnote.

prove desirable. An inspections regime for field-testing may be needed, if only to enhance trust.

One lubricant to consensus building is likely to be collective financing of joint research. This was not needed in the case of smallpox destruction. It may not be needed for geoengineering. However, even if cost sharing were not needed, it may be desirable all around. In exchange for receiving financial support, a geoengineering-capable state may be willing to share decision-making.[12]

Geoengineering's role in climate policy

Even in an ideal world, ruling out geoengineering would seem reckless. As I have explained, the risk-risk tradeoff involved in using geoengineering changes dramatically in a world of catastrophic and abrupt climate change. It is possible that we are already "committed" to abrupt changes and that we simply don't know it. As noted previously, even if concentrations were stabilized at today's level, temperature will keep on rising, and it is possible that this temperature rise may trigger abrupt changes. NASA's James Hansen has suggested that we need to stabilize atmospheric concentrations of CO_2 at 350 ppm. We are already at 385 ppm. So, to get to his desired target, we would need to put our emissions-generating vehicle into reverse (requiring air capture). Given the failure even to limit emissions described earlier in this paper, this seems (in Paul Crutzen's words), "a pious wish" (Crutzen, 2006: 217).

The case for geoengineering depends very much on our ability to limit concentrations. As I have explained, getting the world to reduce emissions is a colossal collective action problem. We have not yet figured out a way to address it. If we continue to fail to limit emissions, we may someday be glad we have the option to geoengineer the climate.

As noted previously, it is often remarked that the possibility of geoengineering reduces the incentive for countries to limit emissions. Even in an ideal world in which collective action was easily orchestrated, the possibility of geoengineering may make it attractive to ease up somewhat on reducing emissions (remember, reducing emissions is not only costly but entails risk). In a world in which countries fail to act collectively to reduce emissions, the future use of geoengineering seems virtually inevitable. The world we live in falls somewhere in between these extremes. But even before the possibility of geoengineering was widely acknowledged, virtually nothing was done to reduce emissions. So I doubt that recognition of its possibility will have a large negative impact on mitigation. Indeed, concerns about geoengineering risks, and the possibility that countries could deploy it unilaterally, could conceivably strengthen the case for emission reductions. In any event, knowledge about geoengineering is now in the public domain.

It is not yet in the policy domain. Not long ago, the same was true of adaptation. In recent years, that has changed, partly because our continued failure to reduce emissions has

---

[12] See Barrett (2007), Chapter 4 for a general discussion and examples from other areas, such as the financing and conduct of the Gulf War.

increased the returns to adaptation. It has also increased the returns to geoengineering. It is time now that we contemplate geoengineering's role in climate change policy.

What should we do? One conclusion that stands out in this analysis is the very strong case for a program of geoengineering R&D. As I have argued, this should be undertaken within the framework of a revised Framework Convention on Climate Change.

References

Angel, Roger (2006). "Feasibility of Cooling the Earth with a Cloud of Small Spacecraft Near the Inner Lagrange Point (L1)," *Proceedings of the National Academy of Sciences*, 103(46): 17184-17189.

Barrett, Scott (2005). *Environment and Statecraft: The Strategy of Environmental Treaty-Making*. Oxford: Oxford University Press (paperback edition).

Barrett, Scott (2007). *Why Cooperate?: The Incentive to Supply Global Public Goods*. Oxford: Oxford University Press.

Barrett, Scott (2008) "The Incredible Economics of Geoengineering," *Environmental and Resource Economics*, 39: 45-54.

Bodansky, Daniel (1996). "May We Engineer the Climate?" *Climatic Change*, 33: 309-321.

Caldeira, Ken and Lowell Wood (2008). "Global and Arctic Climate Engineering: Numerical Model Studies," *Philosophical Transactions of the Royal Society A*, 366(1882): 4039-4056.

Canadell, Josep G., Corinne Le Quéré, Michael R. Raupach, Christopher B. Field, Erik T. Buitenhuis, Philippe Ciais, Thomas J. Conway, Nathan P. Gillett, R.A. Houghton, and Gregg Marland (2007). "Contributions to Accelerating Atmospheric CO_2 Growth from Economic Activity, Carbon Intensity, and Efficiency of Natural Sinks," *Science*, 104(47): 18866-18870.

Cline, William R. (2007). *Global Warming and Agriculture: Impact Estimates by Country*. Washington, DC: Peterson Institute for International Economics.

Crutzen, Paul J. (2006). "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?" *Climatic Change*, 77: 211-219.

Govindasamy, B., S. Thompson, P.B. Duffy, K. Caldeira, and C. Delire (2002). "Impact of Geoengineering Schemes on the Terrestrial Biosphere," *Geophysical Research Letters*, 29(22): 18.1-18.4.

Gu, Lianhong, Dennis D. Baldocchi, Steve C. Wofsy, J. William Munger, Joseph J. Michalsky, Shawn P. Urbanski, and Thomas A. Boden (2003). "Response of a Deciduous Forest to the Mount Pinatubo Eruption: Enhanced Photosynthesis," *Science*, 299(5615): 2035-2038.

Iklé, Fred and Lowell Wood (2008). "Climatic Engineering," *The National Interest*, 93: 18-24.

Intergovernmental Panel on Climate Change (2007). "Summary for Policymakers," in: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds). Cambridge; New York: Cambridge University Press.

Keith, David W. (2000). "Geoengineering the Climate: History and Prospect," *Annual Review of Energy and the Environment*, 25: 245-284.

Latham, John, Philip Rasch, Chih-Chieh Chen, Laura Kettles, Alan Gadian, Andrew Gettelman, Hugh Morrison, Keith Bower, and Tom Choularton (2008). "Global Temperature Stabilization via Controlled Albedo Enhancement of Low-Level Maritime Clouds," *Philosophical Transactions of the Royal Society A*, 366(1882): 3969-3987.

Lenton, T.M. and N.E. Vaughan (2009). "The Radiative Forcing Potential of Different Climate Geoengineering Options," *Atmospheric Chemistry and Physics Discussions*, 9: 2559-2608.

National Academy of Sciences (1992). *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*. Washington, DC: National Academy Press.

Rasch, Philip J., Simone Tilmes, Richard P. Turco, Alan Robock, Luke Oman, Chih-Chieh Chen, Georgiy L. Stenchikov, and Rolando R. Garcia (2008). "An Overview of Geoengineering of Climate Using Stratospheric Sulphate Aerosols," *Philosophical Transactions of the Royal Society A*, 366(1882): 4007-4037.

Robock, Alan (2008). "20 Reasons Why Geoengineering May be a Bad Idea," *Bulletin of the Atomic Scientists*, 64(2): 14-18.

Salter, Stephen, Graham Sortino, and John Latham (2008). "Sea-Going Hardware for the Cloud Albedo Method of Reversing Global Warming," *Philosophical Transactions of the Royal Society A*, 366(1882): 3989-4006.

Schelling, Thomas C. (2006). "The Economic Diplomacy of Geoengineering," in: Thomas C. Schelling, *Strategies of Commitment and Other Essays*, Cambridge: Harvard University Press, 45-50.

Schlenker, Wolfram and Michael Roberts (2008). "Estimating the Impact of Climate Change on Crop Yields: The Importance of Nonlinear Temperature Effects," National Bureau of Economic Research Working Paper No. W13799.

Schneider, Stephen H. (2008). "Geoengineering: Could We or Should We Make it Work?" *Philosophical Transactions of the Royal Society A*, 366(1882): 3843-3862.

Teller, E., L. Wood, and R. Hyde (1997). "Global Warming and Ice Ages: I. Prospects for Physics-Based Modulation of Global Change," Lawrence Livermore National Laboratory, UCRL-JC-128715.

Tilmes, Simone, Rolf Müller, and Ross Salawitch (2008). "The Sensitivity of Polar Ozone Depletion to Proposed Geoengineering Schemes," *Science*, 320(5880): 1201-1204.

Trenberth, Kevin E. and Aiguo Dai (2007). "Effects of Mount Pinatubo Volcanic Eruption on the Hydrological Cycle as an Analog of Geoengineering," *Geophysical Research Letters* 34, L15702.

Victor, David G. (2008). "On the Regulation of Geoengineering," *Oxford Review of Economic Policy*, 24(2): 322-336.

Wigley, T.M.L. (2006). "A Combined Mitigation/Geoengineering Approach to Climate Stabilization," *Science*, 314(5798): 452-454.