

Unilateral Geoengineering

Non-technical Briefing Notes for a Workshop

At the Council on Foreign Relations

Washington DC, May 05, 2008

Katharine Ricke, M. Granger Morgan and Jay Apt, Carnegie Mellon

David Victor, Stanford

John Steinbruner, University of Maryland

Summary

There are a variety of strategies, such as injecting light-reflecting particles into the stratosphere, that might be used to modify the Earth's atmosphere-ocean system in an attempt to slow or reverse global warming. All of these "geoengineering" strategies involve great uncertainty and carry significant risks. They may not work as expected, imposing large unintended consequences on the climate system. While offsetting warming, most strategies are likely to leave other impacts unchecked, such as acidification of the ocean, the destruction of coral reefs, and changes in composition of terrestrial ecosystems. Yet, despite uncertain and very negative potential consequences, geoengineering might be needed to avert or reverse some dramatic change in the climate system, such as several meters of sea level rise that could impose disaster on hundreds of millions of people.

Unlike the control of greenhouse gas emissions, which must be undertaken by all major emitting nations to be effective and is likely to be costly, geoengineering could be undertaken quickly and unilaterally by a single party, at relatively low cost. Unilateral geoengineering, however, is highly likely to impose costs on other countries and run risks with the entire planet's climate system.

This workshop will focus on the question of strategies for constraining and shaping geoengineering. We will explore formal, legal strategies as well as informal efforts to create norms that could govern testing and deployment of geoengineering systems and their possible undesirable consequences. We will probe whether it is possible to limit the use of geoengineering to circumstances of collective action by the international community in the face of true global emergencies and what might happen when there are disputes over when the emergency "trigger" should be pulled.

Background

The circulation of the earth's atmosphere and oceans, and most life on earth, is powered by energy from the sun. This energy largely arrives in the form of visible light. About 30% of that energy is immediately reflected back into space. This reflected fraction is called the "planetary albedo."

The other 70% of the energy is absorbed by clouds, the land and the oceans. As these bodies warm they radiate their absorbed energy as infrared. However, while the atmosphere is transparent to visible light it is opaque to infrared. This is because of absorption by water vapor, carbon dioxide (CO₂) and other trace gasses that occur naturally in the atmosphere. As a consequence the earth heats up until it reaches a temperature at which enough heat energy is radiated off the top of the atmosphere to bring the outward flow of energy into balance with solar radiation that is being absorbed.

As a result of this natural "greenhouse effect" the average temperature of the earth is about 33°C (about 60°F) warmer than it would be if these trace gases did not exist in the atmosphere. This situation is shown in Figure 1.

Concerns about anthropogenic "greenhouse warming" stem from the additional buildup of CO₂ and other gases due to human activity such as burning coal, oil and natural gas and clearing land. The most important greenhouse gases have long atmospheric lifetimes. They accumulate slowly, and once there, the accumulation is difficult to reverse. There is now evidence that this accumulation is causing significant changes in climate, and impacts to ecosystems.¹

As the accumulation grows the danger of harmful changes mounts although, given disagreement about what is "harmful" and uncertainty about the changes, there is no unanimity about just what level is "safe." What is clear is that policy efforts to limit climate change are plagued by two sober facts. First, because emitted CO₂ remains in the atmosphere for over centuries to millennia, just to stabilize its atmospheric concentration of CO₂ would require that global emissions be reduced by over two thirds. Second, world emissions are rising steadily and sharply as a byproduct of economic growth. So far,

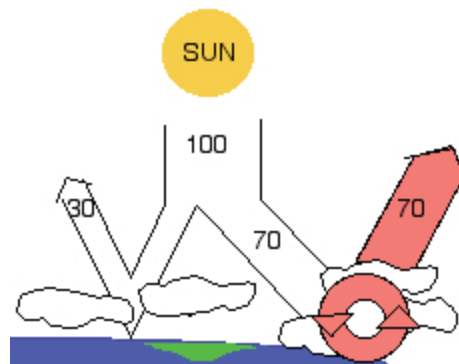


Figure 1: About 30% of the energy that comes in to the earth from the sun is directly reflected back into space. This fraction is called the "planetary albedo". The balance is absorbed by the earth. It is trapped by various "greenhouse gasses" such as water vapor and carbon dioxide. As a result the planet warms until the same amount of energy is radiated back to space.

¹ For a detailed assessment of climate change and its likely impacts, see the recent reports of the IPCC Fourth Assessment, available at www.ipcc.ch.

efforts to cap and reverse this exponential growth of emissions have caused little change in behavior.

As a result of concerns that the needed deep reductions in global emissions are not occurring, there has been renewed dialogue within the scientific community about counteracting global warming through such "geoengineering."

Geoengineering Strategies

Among all geoengineering schemes, those currently considered most feasible involve increasing the planetary albedo, that is, reflecting more sunlight back into space before it can be absorbed. There are a number of different methods that could be used to increase the planet's reflectivity:

1. Add more small reflecting particles in the upper part of the atmosphere (the stratosphere which is located between 15 and 50 kilometers above the Earth's surface).
2. Add more clouds in the lower part of the atmosphere (the troposphere)
3. Place various kinds of reflecting objects in space either near the earth or at a stable location between the earth and the sun.
4. Change large portions of the planet's land cover from things that are dark (absorbing) such as trees to things that are light (reflecting) such as open snow-cover or grasses.

Stratospheric Aerosols

Adding more of the right kind of fine particles to the stratosphere can increase the amount of sunlight that is reflected back into space. Figure 2 illustrates the basic idea.

There is clear evidence from many large past volcanic eruptions that this mechanism can cool the planet. For example, the eruption of Mount Pinatubo in the Philippines (Figure 3) in 1991 produced global scale cooling of about 0.5°C^2 (the cooling probably would have been closer to 0.6°C if there had not been an El Niño event at the same time). The change in albedo was caused by the large quantity of sulfur dioxide injected into the stratosphere which was converted into small particles and resulted in the creation of more high cirrus clouds. Changes in temperature began to occur within just a short time after the eruption.

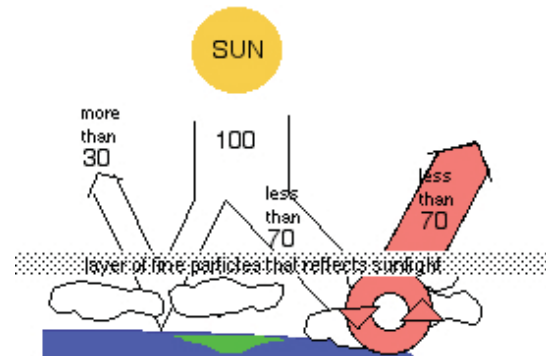


Figure 2: By injecting very fine particles into the stratosphere, the amount of sunlight reflected back into space can be increased, thus offsetting the warming effect of a higher a concentration of CO_2 and other greenhouse gasses. However, doing this would *not* offset other impacts such as the growing acidification of the oceans caused by rising CO_2 concentration.

² B. J. Soden, et al., "Global Cooling After the Eruption of Mount Pinatubo: A Test of Climate Feedback by Water Vapor," *Science*, **296**, 727-730, 2002.

Applied to geoengineering, various technologies could be used to loft particles into the stratosphere, such as naval guns, rockets, hot air balloons or blimps, or a fleet of high-flying aircraft. Potential types of particles for injection include sulfur dioxide, aluminum oxide dust or even designer self-levitating aerosols that might be engineered to migrate to particular regions (e.g. over the arctic) or to rise above the stratosphere (so as not to interfere in stratospheric chemistry). Because of the relative horizontal stability of the stratosphere compared to the troposphere, the residence time of injected particles is approximately 1-2 years.³ As a result, such a scheme would require only annual or biannual replenishment.



Figure 3: The eruption of Mount Pinatubo (left) injected large quantities of sulfur dioxide into the stratosphere (right) where it remained for several years in the 2 layers seen here at ~ 30 km altitude, causing global cooling of several tenths of a degree. (Photo source: NASA)

A 1992 report of the National Research Council⁴ was the first to systematically estimate the potential costs of a program of stratospheric albedo modification. Their estimate was based on the use of a standard naval gun system dispensing commercial aluminum oxide dust to counteract the warming effect of a CO₂ doubling. Undiscounted annual costs for a 40-year project were estimated to be \$100 billion. More recent analysis⁵ has suggested that well designed systems might reduce this cost to as little as a few hundred million dollars per year – clearly well within the budget of almost all nations, and much less costly than any program to dramatically reduce the emissions of CO₂. Indeed, there are a handful of individuals who could create the endowment necessary to generate an annual annuity to operate such a program.

Recently David Keith⁶ has suggested that it should be possible to create microscopic

³ P. Crutzen, "Albedo Enhancement By Stratospheric Sulfur Injections: A Contribution To Resolve A Policy Dilemma?" *Climatic Change*, **77**, 211–219, 2006.

⁴ NAS Panel on Policy Implications of Greenhouse Warming, *Policy Implications of Greenhouse Warming: Mitigation, adaptation and the science base*, National Academy Press, 918pp, 1992.

⁵ E. Teller, L. Wood and R. Hyde, "Global Warming and Ice Ages: Prospects for physics based modulation of global change," Lawrence Livermore National Laboratory, Report UCRL-JC-128715, xxpp, Aug 15, 1997.

⁶ D. Keith, "Photophoretic levitation of aerosols for geoengineering," *Geophysical Research Abstracts*, **10**, EGU2008-A-11400, 2008.

reflecting composite particles that would be self-orienting and self-levitating under the combined influences of solar radiation, differential forces from molecular collisions, and the earth's electric and magnetic fields. Keith notes that "photophoretic levitation could loft particles above the stratosphere reducing their capacity to interfere with ozone chemistry...[Such] levitated particles can have long lifetimes, reducing the need for continual replenishment of the aerosol...[and] could be engineered to migrate poleward enabling albedo modification to be tailored to reduce polar warming so as to reduce the risk of rapid deglaciation and consequent sea level rise."

Cloud Cover Modification

The albedo can also be increased by increasing the quantity and reflectivity of lower cloud layers. Most proposals suggest that this be done by increasing the abundance and reflectivity of the low-altitude stratocumulus clouds that naturally cover about 30% of the Earth's surface. Enhanced cloud coverage would be accomplished by artificially increasing the concentration of cloud condensation nuclei (CCN). Proposals for this strategy typically target the low-level marine stratocumulus clouds that frequently lie off the upwind coast of most continents.

A cloud cover modification system requires a supply or mechanism for the generation of cloud condensation nuclei (CCN) as well as a vehicle for CCN dispersal. A 1992 NAS report considered a theoretical system that would use sulfuric acid as CCN. The level of SO₂ emissions required to counteract the effects of double CO₂ concentrations was estimated as 31,000 tons per day, an amount equivalent at the time to the SO₂ emissions from a coal-fired power plant for an entire year. A system of ships was proposed as a dispersal mechanism with associated estimated capital and operating costs of approximately \$1 trillion over 40 years, the equivalent of a yearly cost of approximately \$1 billion.⁷ Clearly such an approach would have massive environmental impacts in the form of acid rain.

More recently, John Latham of the National Center for Atmospheric Research proposed that salt from seawater could be effectively used as CCN, a material that has the advantage of not (currently) being considered a pollutant. Stephen Salter of the University of Edinburgh has designed an "albedo spray vessel" which would put the Latham theory into practice. He estimates a fleet of 500 such wind-powered vessels would counteract the warming effects of double CO₂ concentrations. Salter calculated that vessels would cost 1 million British pounds (approximately \$2 million) each

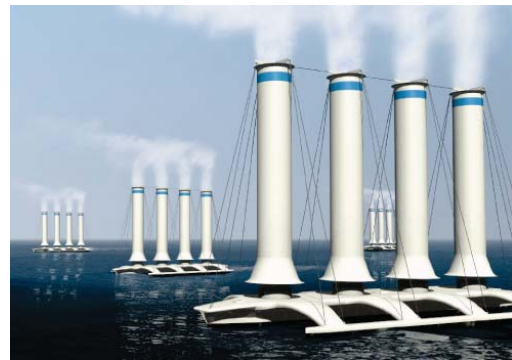


Figure 4 . Illustration of the type of vessel proposed by Stephen Salter of the University of Edinburgh. Source: S. Salter

⁷ NAS Panel on Policy Implications of Greenhouse Warming, see note 4.

to build, and that a total project investment of approximately \$1.1 billion would produce a fleet that could operate for 20 years.⁸ Operating costs were not estimated.

Of course, any such action undertaken on the high seas would be much easier to interdict than an action taken within the continental boundaries of a nation state.

Space-based interventions

Sunlight could also be reflected away from the Earth before it ever reaches the atmosphere, by deploying reflective particles or other devices in space. Dust or mirrors could be deployed in low-Earth orbit. Space-deployed albedo modification schemes may have an advantage over some atmospheric schemes in terms of maintenance, in that some of the proposed technologies have lifetimes of up to 50 years. They would also avoid the risk for disrupting chemical processes in the stratosphere. However, most of the proposed space technologies have estimated costs that are much higher than those of stratospheric or tropospheric programs.

Another space option that has been discussed in the literature is the idea of putting a series of mirrors or sun shades at a gravitationally stable point between the earth and the sun (called the L1 Lagrange point). Roger Angel of the University of Arizona has estimated that such a system of space sunshades could be deployed at L1 for a few trillion dollars. He estimates that the system's lifetime would be about 50 years.⁹ The cost of reaching the L1 Lagrange point and the dispersion of the sunshades over a very large area would make it prohibitive for most nations to remove such a system, but a few nations might be able to develop and deploy the countervailing capability.

Land Cover Modification

A few large continental nations might be able to produce significant changes in planetary albedo through massive modifications in land cover. This would entail replacing dark forest cover with much lighter and more reflective cover such as grass lands or steppe. For example, an assessment by Gordon Bonan and colleagues¹⁰ found that when they removed the boreal forest in a coupled ocean-atmosphere climate model run by the National Center for Atmospheric Research, air temperature was 12°C at 60°N in April and were still as much as 5°C colder in July. These impacts resulted from large open expanses of snow cover. Once the trees had been removed, minor changes in land cover such as the growth of tundra, had little effect.

Of course a strategy of land cover modification would have massive ecological impacts and be far more expensive than injecting fine particles into the stratosphere. It could however be undertaken within the boundaries of at least a few states that are well-endowed with large expanses of dark landscapes.

⁸ S. Salter, "Sea-Going Hardware for the Implementation of the Cloud Albedo Control Method for the reduction of Global Warming," preprint submitted to EIC 2006 Climate Change Conference, Ottawa, CA, May 2006.

⁹ R. Angel, "Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1)," *PNAS*, **103**, 17184-17189, 2006.

¹⁰ G. B. Bonan, et al., "Effects of boreal forest vegetation on global climate," *Nature*, **359**, 716-718, 1992.

Other geoengineering strategies

In contrast to several of the geoengineering strategies that would modify planetary albedo, none of the other strategies that have been discussed in the scientific literature could be undertaken effectively on a unilateral basis.

One of the more widely discussed is the possibility of removing larger amounts of carbon dioxide from the atmosphere by fertilizing the ocean with iron (or other scarce nutrients) to induce greater uptake by phytoplankton. Under this scheme, the effects of anthropogenic CO₂ emissions would be directly counteracted by stimulating increased capture of CO₂ by the Earth's oceans.

If it could be made to work, one advantage of this approach is that it removes CO₂ from the atmosphere and thus more directly compensates for the buildup of anthropogenic CO₂, imposing fewer environmental externalities than strategies that rely on the more imperfect method of increasing planetary albedo.

A number of field experiments have been conducted. Results from these and from model studies raise doubts about just how effective such an approach may be.¹¹ Jorge Sarmiento¹² argues that any such modification is likely to lead to upwelling of carbon from the deep ocean in other locations, and that it would likely be impossible to directly determine whether the strategy was causing more or less CO₂ to be sequestered in the ocean.

There are also folks working on engineered systems that would directly scrub CO₂ out of the atmosphere. Several small-scale prototype systems have been built. There is some disagreement about whether this should be called geoengineering. Clearly, such technology does not raise the same concerns as the strategies discussed above.

Potential Environmental Impacts of Albedo Modification

A geoengineered solution to global warming that only increases albedo and does not lower CO₂ concentrations in the atmosphere will not address the detrimental impacts of ocean acidification upon marine ecosystems caused by high atmospheric CO₂ concentrations. Ocean acidification occurs when carbon dioxide dissolves into seawater and creates carbonic acid this increasing to ocean's acidity (i.e. lowering the ocean's pH). The IPCC's fourth assessment indicates that ocean acidification has already increased the concentrations of hydrogen ions (the chemical substance involved in the dissolution of calciferous compounds) in ocean surface waters by 30%. A more acidic ocean makes it more difficult, and ultimately impossible, for marine life to make calciferous shells. Organisms affected include echinoderms (sea urchins), shellfish and pteropods (tiny

¹¹ See for example: P. Boyd et al. "The decline and fate of an iron-induced subarctic phytoplankton bloom," *Nature*, **428**, 549-553, 2004 ; S. Blain et al. "Effect of natural iron fertilization on carbon sequestration in the Southern Ocean," *Nature*, **446**,1070-1075, 2007.

¹² Sarmiento is Director of Atmospheric and Oceanic Sciences Program at Princeton and has done extensive modeling and analysis of planetary carbon balance.

marine snails that are a component of the food base for organisms ranging from zooplankton to salmon to baleen whales).¹³ As acidification increases, damage will also occur to the coral reefs that serve as protective barriers to many coastlines and are keystones to much of the ocean ecosystem. IPCC's assessment report states that the doubling CO₂ concentrations in the atmosphere would reduce calcification of corals by 20-60%.¹⁴

The hydrological impacts of the eruption of Mount Pinatubo in 1991 were measured by scientists and provide some insight into the hydrological impacts that might be expected to result from geoengineering activities. In the 6-18 months following the Pinatubo eruption, there was a substantial decrease in rainfall and river discharge, particularly in the tropics.¹⁵ Climate models suggest that similar outcomes would accompany geoengineering—decreased precipitation over land (and especially the tropics) and increased precipitation over sea.¹⁶ Such changes would plausibly raise the risk of major droughts in some regions, with possibly large impacts on agriculture and fresh water supply. It is unclear how to weigh those highly uncertain impacts against the highly uncertain hydrologic impacts of unchecked changes in climate. It is also unclear whether one-time injection of particles into the stratosphere by a volcanic eruption is an appropriate analog for the impacts of a steady-state climate geoengineering scheme, under which hydrological cycles would settle into a (perhaps new) pattern. Studies of these possible impacts with climate models are still in their infancy, and because precipitation is among the most difficult variables to model, may face fundamental limits.

One basic measure of ecological health is net primary productivity (NPP), or the rate of biomass production in an ecosystem. Several investigators have used terrestrial biosphere models to explore whether geoengineering schemes that increase albedo would have a significant impact on global NPP. The answer seems to be no, because only a small reduction in solar flux is necessary to counteract warming due to anthropogenic emissions.¹⁷ In fact, a realistic scenario for a geoengineered climate that includes reduced solar flux and doubled atmospheric concentrations of CO₂ could actually increase global NPP due to the dominating impact of CO₂, fertilization. However, since not all plants respond in the same way to increased CO₂, there might be differential impact that would advantage some at the expense of others, thus shifting the make-up and balance between species in terrestrial ecosystems.

¹³ J. C. Orr et al. "Anthropogenic ocean acidification over the twenty-first century and its impact of calcifying organisms," *Nature*, **437**, 681-686, 2005.

¹⁴ Fischlin et al. "Ecosystems, their properties, goods, and services". Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (Cambridge: Cambridge University Press, 2007): 211-272.

¹⁵ K. E. Trenberth and A. Dai, "Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering," *Geophys. Res. Letters*, **34**, 2007.

¹⁶ H. D. Matthews and K. Caldeira, "Transient climate-carbon simulations of planetary geoengineering," *PNAS*, **104**, 9949-9954, 2007.

¹⁷ B. Govindasamy et al., "Impact of geoengineering schemes on the terrestrial biosphere," *Geophys. Res. Letters*, **29**, 2061, 2002.

The stratosphere is a highly reactive environment with strong ultraviolet radiation and oxygen. Many stratospheric chemical reactions are facilitated by processes that occur on the surface of particles. Hence, injection of aerosols into the stratosphere might damage the Earth's ozone layer or have other undesirable consequences. While the materials proposed for use in stratospheric geoengineering do not have the destructive capacity of CFCs and other ozone depleting materials that are already regulated under the Montreal Protocol, local ozone destruction has been observed after large volcanic eruptions. Any type of particle injected into the stratosphere might at least weakly facilitate the chemical destruction of ozone, although details are uncertain. Injecting large numbers of aerosol particles in the stratosphere might also accelerate the special reactions that cause the ozone hole, as those reactions are accelerated when they occur on the surfaces of particles.

Sulfur dioxide, one potential candidate for aerosol injection into the stratosphere, is a primary precursor to acid rain. While the residence time of aerosol particles is much longer in the stratosphere than in the troposphere, eventually injected sulfates would precipitate out, exacerbating problems associated with SO₂ emissions.

Special Incentives for Unilateral Geoengineering

Assuming that we are lucky and that the world is spared rapid and unexpected climate surprises, the local impacts of climate change could nevertheless become quite severe by the later part of the century.

As the IPCC reviews have indicated, some parts of the world will likely experience much greater variability in precipitation, periods of extreme drought, periods of extreme flooding, and similar stresses. While for the next few decades, agricultural productivity will likely increase in some parts of the world, by the latter part of the century it could begin to experience serious decline in many locations.

A nation that has not done much to prepare, either in reducing its contributions to global emissions or in building adaptive capacity, might conclude that the consequences of climate change had become sufficiently severe that it was going to unilaterally engage in geoengineering – imposing large negative externalities on the rest of the world in order to reduce its own impacts.

The danger of stopping once geoengineering starts

If albedo-adjusting geoengineering were to proceed for an extended period while CO₂ emissions continued or grew, cessation of geoengineering could yield rapid, large and damaging shocks to the climate system. While this issue has not been studied with much detail, one recent simulation¹⁸ suggests that if a system reducing solar flux abruptly failed or was terminated, carbon sinks would weaken, potentially leading to unprecedented global temperature increases of 2-4°C per decade (more than ten times the current rate of

¹⁸ H. D. Matthews and K. Caldeira, "Transient climate-carbon simulations of planetary geoengineering." *PNAS*, **104**, 9949-9954, 2007.

temperature change). Such a rapid increase would surely have profound negative impacts on ecosystems and much else that depends on climate.

Developments that could justify geoengineering

Despite great uncertainty about geoengineering, and the likely negative environmental consequences that it could have, if we are surprised by unexpectedly rapid or large climate change, there might be situations in which the governments of the world would be justified in taking collectively action. Here are just two examples:

- At the moment sea level is rising gradually, mainly due to the expansion of warming ocean water. (To date, melting ice has been a modest contributor.) However, suppose that the Greenland ice cap were to suddenly start melting far faster than anyone now expects. Much of the ice in Greenland is above sea level. If it were all to melt, sea level would rise by about 7 meters. Roughly half of the world's people live within 100 km of the coast, and 10%, roughly 600 million people, live at elevations of only a few meters. Many nations—notably the Small Island Developing States (SIDS)—lie entirely within elevations ranging from 1 to 5 meters above sea level. If sea level were to start rising at rates of several centimeters per year (as opposed to the current rate of about 30 cm per century) hundreds of millions of people and trillions of dollars of buildings and other infrastructure would be put at risk.
- There are large amounts of carbon, much of it in the form of methane, that is tied up in the frozen lands of the arctic. There are also large quantities of frozen methane in the sediments at the edge of continental shelves. If, as the earth warms, all this methane were to suddenly and unexpectedly be released to the atmosphere, warming could increase at a disastrous pace, causing enormous damage to natural and managed ecosystems, extreme droughts, flooding from rapid sea level rise, and many other very serious problems. The lives and welfare of billions of people would be at risk.

Climate scientists can point to several other possible "climate surprises." While all of these are now thought to be unlikely to occur, their consequences would be sufficiently disastrous on a global scale that, despite the uncertainties and potential large negative consequences, the world may have no choice but to collectively choose to engage in geoengineering. It may prove to be extremely difficult to identify the signal of a climate surprise, especially in advance of its occurring. And unpleasant surprises for some nations may be welcome changes for others, which could make it difficult in practice to reach agreement on when it is appropriate to pull the trigger on a geoengineering scheme that is designed to be used only in case of emergency.

What Could be Done?

Clearly there is a lot more work to be done on the engineering and scientific aspects of geoengineering. Better particles and lofting schemes will likely be developed; more research is badly needed on identifying and assessing possible negative consequences and all the ways that geoengineering schemes could fail.

But here we focus on the question of regulation, for it is likely that nations or perhaps even individuals will be tempted to geoengineer before all the facts are in, and it is hard to devise a useful research program on geoengineering without knowing where real-world geoengineering efforts might head. Our purpose in this section is to outline key questions and frameworks; our goal for the workshop is to focus on answers (and areas where research can produce answers).

Treaties

The standard response to an international regulatory challenge is a treaty. There could be a role for treaties in this instance, although much of the canon of international environmental law will not be directly relevant. The standard problem in international environmental law is collective action—getting many parties, often with diverging interests, to agree to a common effort that usually involves spending more resources than each would have devoted individually. By contrast, the problem in this case is restraint. As Tom Schelling noted a decade ago, geoengineering turns the politics of the international regulatory effort in climate change on its head.¹⁹ In some respects, geoengineering makes international action easier because many fewer nations must participate—the only nations whose behavior must be affected are those that have the capability to geoengineer. In other respects, though, the problem of cooperation is devilishly difficult because a decision by any country to buck the trend could be a failure for all.

International environmental law includes some restraint regimes, such as the 1972 London Dumping Convention, which prohibits some kinds of ocean dumping. It is hard to assess the LDC's effectiveness, but clearly in some areas it has had an impact. Seabed disposal of radioactive waste was taken seriously in 1970; since the LDC research on that option has nearly entirely stopped. (That case also underscores the need for caution in setting taboos. Well designed ocean dumping of some wastes might actually be safer than the current land-based systems.) The LDC also reveals a maxim of international law, which is that inconvenient rules often get changed. Faced with the possibility that sequestration of CO₂ deep under the seabed might be illegal under the LDC, countries changed the rules over the last few years just to be sure that these schemes could continue apace. And the first sub-seabed sequestration scheme—Norway's Sleipner project—went ahead despite the old inconvenient rules.

There is one treaty that is plausibly focused on exactly the problem of geoengineering—the Environmental Modification Convention (Enmod) of the 1970s. That agreement arose in an era when militaries were looking to weather modification as an instrument of

¹⁹ T. Schelling, "The Economic Diplomacy of Geoengineering," *Climatic Change*, **33**, 303-307, 1996.

war. The treaty prohibits such hostile uses and offers referral to the UN Security council as a sanction. It has never been tested, probably because the treaty is weak and mainly because weather modification strategies never worked well. Militaries lost interest; the treaty gathers dust.

There may be useful lessons to be drawn from other restraint regimes, such as the prohibitions against developing and using biological and chemical weapons. Insofar as those regimes have worked they have deployed a combination of export controls and norms. In the case of geoengineering, export controls are probably unlikely to have much impact since the technologies are widely available. It might be possible to slow geoengineers by restricting access to rocket technology and heavy lift stratospheric-capable aircraft, but there are so many different available routes for geoengineering that it seems difficult to contain the technology.

Norm-building exercises

A different, complementary strategy might aim to set norms about responsible geoengineering. This approach would recognize that international law is weak (especially when inconvenient), but norms can be powerful if they become internalized within the communities that might contemplate geoengineering. Historically, similar norms emerged around the deployment of nuclear weapons—for example, against the “first use” of nuclear weapons and against reckless testing of weapons—and probably helped reduce the danger of nuclear war. Important norms have emerged about safe testing and deployment of genetically engineered crops.

At the workshop we should discuss what norms should govern geoengineering and how they might gain widespread adherence. The norms might include the need for collective open research and risk-averse assessment, as well as full transparency in environmental assessments of geoengineering options. Special norms might be created to require that deployment of geoengineering systems or experiments be done only with international teams and include extensive assessment to monitor actual effects. Special “red teams” might be required to assess possible harms. Additional norms may relate to minimizing and compensating for harms created by geoengineering.

Getting all relevant nations to adhere to such norms may be especially difficult. Aggressive norms might stymie research on geoengineering within countries that are most likely to honor the norms—that is, the countries that are most likely to give closest attention to possible collateral damage from geoengineering—while doing little to thwart dangerous unilateral geoengineering by countries and institutions that care less about international norms. Moreover, the relevant units may not be countries since geoengineering seems to be so inexpensive that large NGOs and rich individuals could do these things on their own.

Acknowledgements

This background paper contributed to the discussion at a May 2008 meeting of foreign policy experts at the Council on Foreign Relations and to a policy-oriented essay published in the March/April 2009 issue of *Foreign Affairs*. We are grateful to Scott Barrett, Susan Basu, Daniel Bodansky, Martin Bunzl, Ken Caldeira, Ralph Cicerone, Josh Cohen, Richard Cooper, John Deutch, David Doniger, Erika Engelhaupt, Sylvia Generoso, Jay Gullede, Jim Hoge, Fred Ikle, Donald Johnston, Devesh Kapur, David Keith, Klaus Keller, Robert Keohane, Steven Koonin, Lee Lane, Michael Levi, Peter Ogden, Stephen Pacala, Jonathan Pershing, Sasha Polakow-Suransky, Nigel Purvis, Arathi Rao, Trigg Talley, Samuel Thernstrom, Mitchel Wallerstein, and Paul Wolfowitz, for their comments on the drafts and related discussions. Thanks also to participants in the Stanford University Program on Global Justice and the Environmental Norms and Institutions Policy Workshop for related discussions on regulatory strategies concerning geoengineering.

For Further Reading

For those who would like to learn a little more about this topic, we would be happy to provide you with copies of any of the following:

1. D. Keith, "Geoengineering the Climate: History and prospect," *Annu. Rev. Energy Environ.*, 25, 245-284, 2000.
2. P. J. Crutzen, "Albedo Enhancement By Stratospheric Sulfur Injections: A contribution to resolve a policy dilemma?" *Climatic Change*, 77, 211-219, 2006.
3. National Academy of Sciences, *Policy Implications of Greenhouse Warming: Mitigation, adaptation, and the science base*, National Academy Press. See Chapter 28 and Appendix Q, 1992.
4. E. Teller, L. Wood and R. Hyde, "Global Warming and Ice Ages: Prospects for physics based modulation of global change," Lawrence Livermore National Laboratory, Report UCRL-JC-128715, 18pp., August 15, 1997.
5. H. D. Matthews and K. Caldeira, "Transient Climate-carbon Simulations of Planetary Geoengineering," *PNAS*, 104, 9949-9954, 2007.
6. Orr et al., "Anthropogenic Ocean Acidification Over the Twenty-first Century and Its Impact of Calcifying Organisms," *Nature*, 437, 681-686.
7. T. Schelling, "The Economic Diplomacy of Geoengineering," *Climatic Change*, 33, 303-307, 1996.
8. D.G. Victor, "On the Regulation of Geoengineering," *Oxford Review of Economic Policy*, in press.
9. S. Barrett, "The Incredible Economics of Geoengineering," *Environmental Resource and Economics*, 39, 45-54, 2007.
10. D. Bodansky, "May we engineer the climate?," *Climatic Change*, 33, 309-321, 1996.
11. J. R. Fleming, "The pathological history of weather and climate modification: Three cycles of promise and hype," *Historical Studies in the Physical and Biological Sciences*, 37, 3-25, 2007.
12. American Association for the Advancement of Science, "Should We Study Geoengineering? A Science Magazine Panel Discussion," *Science Online*, <http://www.sciencemag.org/cgi/content/full/sci;318/5853/1054/DC1>.

To obtain a copy of any of these, please send e-mail to Kate Ricke (kricke@andrew.cmu.edu).