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On the regulation of geoengineering

David G. Victor*

Abstract New evidence that the climate system may be especially sensitive to the build-up of greenhouse gases and that humans are doing a poor job of controlling their effluent has animated discussions around the possibility of offsetting the human impact on climate through 'geoengineering'. Nearly all assessments of geoengineering have concluded that the option, while ridden with flaws and unknown side effects, is intriguing because of its low cost and the ability for one or a few nations to geoengineer the planet without cooperation from others. I argue that norms to govern deployment of geoengineering systems will be needed soon. The standard instruments for establishing such norms, such as treaties, are unlikely to be effective in constraining geoengineers because the interests of key players diverge and it is relatively easy for countries to avoid inconvenient international commitments and act unilaterally. Instead, efforts to craft new norms 'bottom up' will be more effective. Such an approach, which would change the underlying interests of key countries and thus make them more willing to adopt binding norms in the future, will require active, open research programmes and assessments of geoengineering. Meaningful research may also require actual trial deployment of geoengineering systems so that norms are informed by relevant experience and command respect through use. Standard methods for international assessment organized by the Intergovernmental Panel on Climate Change (IPCC) are unlikely to yield useful evaluations of geoengineering options because the most important areas for assessment lie in the improbable, harmful, and unexpected side effects of geoengineering, not the 'consensus science' that IPCC does well. I also suggest that real-world geoengineering will be a lot more complex and expensive than currently thought because simple interventions—such as putting reflective particles in the stratosphere—will be combined with many other costlier interventions to offset nasty side effects.

Key words: abrupt catastrophic climate change, climate policy strategy, research and development policy

JEL classification: F51, F53, F55, F59, K32, K33, Q54, Q56, Q58

I. Introduction

Nearly all of the political debate around climate policy has focused on the mitigation of emissions. Until recently, this bias has been logical and appropriate because true solutions

*Stanford University and Council on Foreign Relations, e-mail: dgvictor@stanford.edu

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to the problem of climate change require a focused effort at the root cause. However, a mitigation-focused policy strategy is not enough. Actual mitigation efforts are already falling far short of what many analysts think is needed to avoid dangerous changes in climate (see IPCC, 2007*b*; Stern, 2007). These failings arise from a political logic that will soon be difficult to rectify. Deep cuts may be costly and thus politically difficult to organize and sustain; they imply radical changes in energy systems that will be difficult for many countries to administer effectively even if they could mobilize the needed political support. Moreover, it has proved extremely difficult to design competent international institutions for coordinating and enforcing worldwide efforts to mitigate emissions (Victor, 2001; Barrett, 2003, 2007*b*).

Such sobering facts have encouraged analysts to concentrate on adaptation as a complementary element of a climate-change strategy (IPCC, 2007*b*). They have also kindled nascent and uneasy interest in 'geoengineering'—that is, planetary-scale, active interventions in the climate system to offset the build-up of greenhouse gases.

Most geoengineering envisions increasing the reflectivity ('albedo') of the planet by injecting particles into the stratosphere. Modifying the albedo offers, in theory, large potential leverage on the heat balance; reducing incoming sunlight by just a few per cent could crudely offset the higher temperature caused by the build-up of greenhouse gases. Putting particles in the stratosphere (about 10–50 km above the Earth's surface) is attractive, in theory, because the stratosphere is stable and thus particles injected at that location will remain in place for 1–3 years before needing replenishment. Sulphate particles have attracted most attention because volcanoes already naturally inject large quantities of emissions that yield sulphate when they erupt, offering natural analogues for envisioning and studying possible man-made geoengineering systems. In addition to these ideas, other imagined schemes include putting diffraction gratings in outer space (which can deflect a bit of incoming sunlight away from the planet) or installing machines on the ocean that could blow water vapour into the atmosphere, which increases the cover of reflective bright clouds. It is also possible to change the albedo of large land areas from dark to light, such as by converting forests into more reflective grasslands. Many other schemes can also be imagined.[1]

The option of geoengineering is ridden with danger. All the most promising geoengineering methods have likely side effects that are worrisome. The unknown harms from large-scale tinkering with the planet could be even more grave than the predictable effects. Merely talking about geoengineering, say some, will take pressure off politicians to make serious efforts to mitigate emissions—its mere existence as an imagined option may thus assure its use. And yet geoengineering is inexorably rising in political salience. Formerly a freak show in otherwise serious discussions of climate science and policy, geoengineering today is a bedfellow, albeit one of which we are wary. The option may be needed as a hedge against unexpectedly harsh changes in climate (Weitzman, 2007).

Geoengineering must be taken seriously because it turns the politics of climate protection upside down. The politics of actually stopping global climate change by mitigating emissions

[1] Keith (2000) provides a detailed survey of options and also explores the economics, politics, and ethics, and NAS (1992) provides a comprehensive (if now quite dated) look at the economics of climate-protection options including geoengineering. Bodansky (1996) points to many possible legal constraints; Barrett (2007*a*) examines the seemingly inexpensive economics of geoengineering and outlines a possible path for pursuing the option. Recent conference reports offer a useful catalogue of the complaints (Ames/Carnegie, 2006; Ricke *et al.*, 2008; Victor *et al.*, 2008), and Fleming's (2007) beautiful history of geoengineering is laden with warnings.

are nasty, brutish and endless. With today's technologies, achieving a deep cut in emissions will require costly investment for uncertain benefits that accrue mainly in the distant future—attributes that tend not to be rewarding for politicians.[2] The politics of mitigating emissions are additionally difficult because deep cuts in emissions are possible only with the cooperation of many nations with diverging preferences.[3] The countries that are most keen to control their emissions, such as the European nations and Japan, are a shrinking part of the problem because their economies expand at a relatively sluggish pace and their populations are in numerical decline. By contrast, the countries most wary about emission controls, such as China and India, are getting richer and expanding demographically much more rapidly (IEA, 2007). Some nations that matter, such as frigid Russia as well as other fossil-fuel exporters, may conclude that they stand to lose massively if the rest of the planet actually makes deep cuts in emissions.

Geoengineering, by contrast, offers prompt benefits with seemingly small costs—attributes that greatly simplify the problem of collective action (Schelling, 1996). Most geoengineering methods involve deployment of technologies—for example, rocket launchers or large artillery units that could loft particles into the stratosphere or beyond—that geoengineers, themselves, already control. Once particles are dispersed in the stratosphere it would be difficult for anti-geoengineers to remove them. Unlike collective efforts to control emissions, which are plagued by the constant threat of defection, the incentives to sustain cooperation are much stronger once geoengineering has begun, because failure to keep a geoengineering mask in place will lead to exceptionally rapid (and dangerous) climate change. Some estimates suggest that once a geoengineering scheme is in place, failure to sustain it could lead to climate warming at a pace 20 times greater than the warming evident today (Matthews and Caldeira, 2007). Once geoengineering has begun, even those who are hostile to the idea will reluctantly find they must support continued action.

Geoengineering may not require any collective international effort to have an impact on climate. One large nation might justify and fund an effort on its own. A lone Greenfinger, self-appointed protector of the planet and working with a small fraction of the Gates bank account, could force a lot of geoengineering on his own. Bond films of the future might struggle with the dilemma of unilateral planetary engineering.

With so many temptations, what can be done to impose useful discipline on geoengineers? Until recently, this question was not practically relevant because there had been so little effort to devise geoengineering systems; most analysts who examined the options closely had concluded that it would be reckless to mess with the planet. Today that is changing, and the question demands an answer.

[2] Some studies have suggested that emissions control could be relatively inexpensive and amount to perhaps 1 per cent of GDP or less (Stern, 2007; IPCC, 2007*a*). That might be true for an optimally implemented policy that gives firms plenty of time to innovate and apply new technologies. But the cost of real policy could be a lot higher because political systems do not seem prone to make the needed complementary investments in research and development (e.g. EPRI, 2007). Least-cost strategies also usually envision the extensive use of 'offsets', which can encourage inexpensive emission controls in developing countries, that are proving difficult to administer (e.g. Paltsev *et al*., 2007; EPA, 2008). As real costs inflate so will the political challenges in adopting real policies.

[3] At first, perhaps just a dozen countries are needed and cooperation could emerge tacitly, which is less daunting than getting all nations on the planet to agree. However, even the core group of important countries—such as China, the United States, the EU, and Russia—assign radically different preferences for economic growth and environmental protection (Victor, 2006). Eventually, explicit obligations that cover all nations are probably needed, because an open world economy makes it unlikely that important countries will tolerate high costs for long if their trading partners pay a lot less.

Based on the experience with other international environmental challenges, the standard answer is that a legally binding regulatory treaty is needed, along with a careful global assessment that gives all nations the opportunity to participate formally in evaluating geoengineering science.[4] Applied to geoengineering, that answer would suggest the need for a comprehensive assessment by the Intergovernmental Panel on Climate Change (IPCC) as well as negotiations toward a binding treaty to constrain geoengineers of the future.

Here I suggest answers that point in very different directions. In brief, my conclusions are fourfold. First, most treaties on geoengineering will be useless or actively harmful because, at present, experts and governments do not know enough about the scope and hazards of possible geoengineering activities to frame a meaningful treaty negotiation. Diverging interests and the lack of knowledge about how to frame negotiations that focus on the most relevant topics will make it impossible to gain meaningful agreement.

Second, a taboo against geoengineering—as many of geoengineering's detractors imply is needed—would be the most dangerous policy. A taboo is likely to be most constraining on the countries (and their subjects) who are likely to do the most responsible testing, assessment, and (if needed) deployment of geoengineering systems. A taboo would leave less responsible governments and individuals—those most prone to ignore or avoid inconvenient international norms—to control the technology's fate. A much better approach would be an active geoengineering research programme, possibly including trial deployments, that is highly transparent and engages a wide range of countries that might have (or seek) geoengineering capabilities. That approach would be designed to explore the safest and most effective options while also socializing a community of responsible geoengineers. (Similar approaches have been followed in other international scientific collaborations that have had potentially hazardous side effects, such as the European Organization for Nuclear Research (CERN) and the Human Genome Project.)

Third, nearly all the geophysical analysis, to date, has focused on simple geoengineering options, such as tuning the planetary albedo, that are unlikely to be deployed in practice. If society ever deploys geoengineering it is likely to be in a more complex form—for example, albedo modification along with active efforts to offset ecological side effects, ocean acidification, and other harms that the simple primary geoengineering system cannot rectify. The economics, politics, and ethics surrounding these complex geoengineering systems are radically different from the simple geoengineering methods that occupy most technical analysis to date.

Fourth, at this stage the nature of the underlying science and geoengineering is particularly ill-suited to the consensus-oriented IPCC process. Instead, multiple competing assessments by small groups linked to active research programmes—reviewed and published openly—would be more effective.

[4] That approach—binding treaties coupled to scientific assessments—has been successful in many other areas of international environmental cooperation, notably the depleting ozone layer (e.g. Benedick, 1998). In time, it might prove helpful in addressing global warming. The standard response of treaty-making is so ingrained in the international environmental community that it is hard to identify a single definitive source that outlines this strategy, but for a thoughtful argument about the centrality of treaty-making as a response to environmental (and other) problems see Chayes and Chayes (1998). On the role of integrated assessments in addressing international environmental problems see Mitchell *et al*. (2006).

II. The state of geoengineering science: three implications

There is a small but growing literature on geoengineering methods. Careful reviews are published elsewhere (Keith, 2000; Ames/Carnegie, 2006; Ricke *et al.*, 2008). Three observations from that technical literature help to frame the options for the design of regulatory systems.

First, the option of geoengineering must be taken seriously because the cost of geoengineering systems that could crudely offset the human-caused build-up of greenhouse gases appears to be shockingly small. Early estimates suggest that the discounted present cost of a geoengineering programme extended into perpetuity is of the order of $100 billion, which compares favourably with the $1 trillion order-of-magnitude costs for mitigation. However, it is especially difficult to assess the cost of geoengineering schemes because humans have never tried to deploy such systems on a planetary scale.[5] Analogues with natural events, such as volcanoes, make it possible to calculate the scale of effort that would be needed to offset crudely some of the effects of some climate warming. Moreover, it is already possible to test some geoengineering methods at very low cost and without undue risk of irreversible effects on the planet. In short, it is possible to imagine actual development and deployment of geoengineering systems with today's technology, and likely innovation will probably lower those costs.

Second, the technical literature is highly stylized for many reasons. One is that nearly all studies evaluate the impacts of single interventions, such as pulsing the stratosphere with aerosols. However, it seems unlikely that such 'silver bullet' geoengineering will be deployed because the research demonstrates that all silver bullets have severe side effects. For example, attempting to offset rising emissions of greenhouse gases by modifying the albedo is likely to yield several harmful side effects, some of which have been analysed directly and others which can be inferred from analysis of analogous events such as volcanic eruptions:

- acidification of the oceans, which is due to the still-high concentration of carbon dioxide (CO_2) in the atmosphere (Ames/Carnegie, 2006);
- massive ozone depletion if the albedo scheme includes injection of particles into the stratosphere (Crutzen, 2006);
- possible changes in rainfall, with attendant risks for drought (Liepert *et al.*, 2004; Oman *et al.*, 2006; Trenberth and Dai, 2007);
- alteration of ecosystems due to effects such as the impact of dimming on light-sensitive plants, the availability of water, and fertilization of some plants in a CO_2-rich atmosphere (e.g. Stanhill and Cohen, 2001; Govindasamy *et al.*, 2002; Naik *et al.*, 2003; Mohan *et al.*, 2006; D'Arrigo *et al*, 2007);
- uneven offsetting of climate change, since albedo adjustments do not perfectly mimic the spatial changes in climate that are induced by greenhouse gases (Govindasamy and Caldeira, 2000; Oman *et al.*, 2005).

In addition to this known list of side effects it is likely that other ills will appear once analysts start looking for them more aggressively.

Some of the geoengineering literature ignores such possible side effects, and by implication dismisses them as unimportant (e.g. Teller *et al.*, 1997). Other analysts of geoengineering pursue the opposite and equally extreme logic, concluding that the cure of geoengineering might

[5] This assessment is based on the first costing exercise in NAS (1992) and critical reviews of Keith (2000) and Ames/Carnegie (2006) which do not raise concerns that would alter the order of magnitude. With innovation and effort, total discounted present cost for a perpetual programme could be an order of magnitude smaller.

be worse than the disease.[6] Most likely, however, is that the impacts of global climate change will have reached such a nasty state by the time societies deploy large-scale geoengineering that some side effects will be tolerated. These societies will be willing to spend handsomely on geoengineering, and the systems they deploy will not be a silver bullet but rather many interventions deployed in tandem—one to focus on the central disease and others to fix the ancillary harms. The strategy may be somewhat like the treatment of AIDS, with a constantly shifting 'cocktail' of drugs.

As the number of interventions rises so will the cost and complexity. More complex systems will be harder to assess because they will involve so many different interactions. To date, none of the technical or economic assessments of geoengineering have examined this kind of complex multi-faceted geoengineering—what I'll call 'cocktail geoengineering'. Moreover, the exact mix of interventions will pose difficult trade-offs. For example, simple modification of the albedo will not offset the ocean acidification caused by the build-up of CO_2 in the atmosphere. Liming the whole ocean to offset the acid appears to be impractical, but it might be feasible to buffer special highly valued zones; indeed, technologies have been imagined that could be deployed for exactly that purpose (e.g. House *et al*., 2007). Perhaps a network of acid-offsetting pipes should be installed to rebalance special ecosystems such as the Great Barrier Reef and a few other gems. Fake reefs may need construction, as is already done for other reasons today. Similarly, the possibilities that albedo modification schemes might have an adverse impact on rainfall could animate countries to invest more heavily in water management systems. These are the real trade-offs for geoengineering—how many patches should be added, and at what cost? The hardest trade-offs will involve ecosystems because they are difficult to value and thrive on complex and unpredictable interactions. It will be difficult to gain agreement on the triage of nature. Moreover, ecosystem interventions will create special ethical challenges because, in the extreme, they turn the whole planet into a zoo of managed ecosystems.

In short, the claim that geoengineering is remarkably cheap is based on simple assessments of silver-bullet geoengineering. In practice, however, the geoengineering cocktails that are likely to be deployed will not be cheap.[7]

Third, because it is hard to predict the effects of geoengineering—especially in its more plausible cocktail mode—today's discussions around investment in geoengineering systems

[6] Most of the critical literature adopts this approach, though often with the caveat that the option should be explored in case climate changes are particularly severe. See, for example, Schneider (1996) who concludes uneasily that geoengineering merits some investigation but only if that does not become an excuse for sharply curtailing society's addiction to carbon fuels.

[7] It might be useful to think of supply and demand for geoengineering in the context of a fuller climate strategy that includes mitigation and adaptation. If the y-axis is cost and the x-axis is climate protection, then the supply curve rises from the origin—the first flat segment is *simple geoengineering*, which costs little but has many side effects; as the curve rises to include additional patches it enters the much more costly realm of complex *geoengineering cocktails*. Similarly, it might be useful to think about the shape and location of the demand curve. Most discussion about geoengineering has imagined a dreamworld where geoengineering is interesting because it is cheap and because it is thought about largely in isolation from the economics of other policy options. In the real world, geoengineering is probably a price-taker that gets deployed at large scale when costly options to control emissions have failed. In that world, geoengineering is being weighed against still more costly options such as shutting down energy systems before the end of their useful lifetime or severe curtailment of demand. The former demand curve is nearly vertical and 'clears' only on the low-cost options; the latter demand curve is horizontal and clears deep in the territory of complex geoengineering.

have a ring of falsehood. Many studies seem to conclude that society should invest in enough knowledge about geoengineering to put the option ‘on the shelf’ in case it is needed if a climate emergency appears. The shelf analogy is misplaced for two reasons. One is a matter of incentives. Other than with nuclear weapons, societies have not spent massively to put an option on the proverbial shelf and not use it.[8] Some partial exceptions to that rule include stockpiling of anthrax treatments and strategic oil stocks, though the difficulties in getting most countries to invest adequately in these options and to develop viable plans for deployment are a warning for those who think that societies will invest adequately to put geoengineering on the shelf. The brightest young minds and the most entrepreneurial organizations rarely mobilize themselves to put complex technologies on the shelf—especially when rival activities such as inventing the next YouTube exude greater rewards. The way societies usually get something on the shelf, politically and organizationally, is to use it.

The other weakness with the ‘shelf’ analogy is more important for our purposes. Long ago, Tom Schelling pointed out that most of the ‘known’ effects of atmospheric testing of nuclear weapons were not predicted. Electromagnetic pulse, for example, was discovered through atmospheric testing. The same insight probably applies to cocktail geoengineering. It is impossible to assess the options—and thus put them on the shelf—without actually testing them at scale. Readying the option for use in an emergency probably requires actually using it, at least for test deployments.

III. Assessment and regulation

Finally we turn to the regulatory politics of geoengineering. Our starting point is the argument already made earlier and by other authors. Namely, geoengineering has the potential to transform the politics of the climate problem because countries, alone or in small groups, can pursue geoengineering with planetary effect. By contrast, mitigation of emissions requires many countries to participate. Thus the regulatory task in geoengineering requires the setting of norms that restrain all potential geoengineers as well as principles to govern the trade-offs that geoengineers will face as they decide which cocktails of geoengineering systems to deploy. (If geoengineering proves costly, then agreements might also be needed on how to share the expense.) Effective restraints and norms to govern trade-offs will require agreement on underlying facts about geoengineering options and dangers. Here we explore these two issues—assessment and regulation—and how effective systems for each could arise.

[8] Nor is it clear that nuclear weapons have not been ‘used’. Of course they were used against Japan in 1945, but even the investment in weapons since that date has been usable as a deterrent in some settings. Their mere existence altered outcomes—such as in Quemoy and Matsu (1950s), in Turkey and Cuba (1960s), probably in Israel (since the 1980s), and elsewhere. By contrast, geoengineering probably has no deterrent effect and may actually amplify the risks that give rise to its deployment. Gaia aside, the planet is geophysically unaware that it is being deterred from harmful climate outcomes when humans build geoengineering capabilities. But humans are aware of their own investments in geoengineering, and that awareness may make them less likely to invest mightily in controlling emissions and adapting to climate changes if they know geoengineering is available. The impact of such investments on human willingness to spend resources on controlling emissions is hard to assess; my impression, however, is that the option of geoengineering will not amplify the extent to which humans engage in reckless behaviour by not investing in emission controls. That’s because careful assessments of geoengineering will show its many faults and side effects as well as unknown harms; indeed, identification of such harms has been the tenor of geoengineering research in recent years.

(i) Assessment

As geoengineering rises in prominence so will calls for a comprehensive international assessment. So far, however, essentially all comprehensive assessments of geoengineering—with the exception of the now dated NAS study (NAS, 1992), which was commissioned by the US government—have been the work of lone researchers pursuing interesting questions. Would a comprehensive international assessment be useful?

Comprehensive assessments have played an essential role in building consensus around important facts (e.g. Mitchell *et al*., 2006; NAS, 2007). The IPCC is a testimony to the importance of these activities, as are the technical and economic assessments linked to the Montreal Protocol on the ozone layer and in many other areas, such as acid precipitation. But the fact that comprehensive assessments have played important roles in regulating pollutants is not proof that such assessments work in all situations. Close attention is needed to the nature of underlying scientific knowledge to determine whether assessments actually produce usable knowledge.

Nearly all of the successful assessments reflect circumstances where the knowledge is relatively well structured and where 'normal' science can resolve controversies.[9] Thus the IPCC, for example, has done a very good job of reviewing the 'normal' and relatively well-understood effects of climate change on sea level through melting glaciers and thermal expansion of seawater. But it has fallen far short of providing useful knowledge about possible outlier effects that could yield much higher sea levels, such as the possibility that landed glaciers could melt and slide more rapidly than standard ice physics had traditionally estimated (Oppenheimer *et al*., 2007). Similar arguments apply to the IPCC assessments of the effects of aerosols on climate forcing (for example, see Morgan *et al*., 2006). For normal science, consensus-oriented assessments are useful; for scientific questions, where paradigms are weak or highly contested, such assessments produce either pabulum or silence (Cullenward and Victor, 2007). In general, consensus assessments have a harder time accurately portraying the long 'tails' that are pervasive in any science about complex and poorly understood systems such as the climate. Yet many of the most worrisome side effects of geoengineering are in the tails.

Geoengineering is also particularly ill suited for standard assessments, such as through the IPCC, because some of the most important issues involve the evaluation of trade-offs, which is the realm of the social sciences. Outside of economics, the social sciences do not have strong enough and sufficiently well-accepted intellectual paradigms to yield usable knowledge through standard international assessments.[10]

The IPCC particularly struggles where paradigms are contested because it is, by design, an open and weak institution.[11] Without the aid of a strong paradigm, weak institutions have

[9] By 'normal' I mean science pursued within a given intellectual paradigm or research programme with agreed boundaries (Kuhn, 1962; Lakatos and Musgrave (eds), 1970). Where the boundaries of the paradigm are known and where the assessors can agree on core facts and theories (and on who qualifies as a 'scientist'), comprehensive assessment by the community of scientists is possible.

[10] The endless trials of IPCC's working group III supply many data points to support this hypothesis; some day, perhaps, the IPCC will wisely abandon its efforts in this area. The IPCC's nasty and inconclusive effort to evaluate trade-offs that involved assigning a value to lives lost in different economies is a warning of the hazards to researchers who attempt such work in a universal, comprehensive assessment.

[11] The term 'weak' is not intended pejoratively—rather, it is a factual statement of the ability of the institution itself to make decisions and steer outcomes. Most international institutions are 'weak'. Many governments are 'weak' by this same logic—including the US government, because, by design, it tends to gridlock and indecision. Most democracies, by design, have weak central institutions.

a hard time embracing novel ideas and conveying the true diversity of opinions in the 'tails' while, at the same time, keeping charlatans at bay.[12]

This suggests a different strategy for assessment of geoengineering. The IPCC (or any such consensus-based process) is unlikely to produce useful shared knowledge because a proper full evaluation of geoengineering options and their impacts is fundamentally ill suited for consensus. The penchant for IPCC to review published literature—which is the standard method for determining the identity of accepted science—rather than formally to enlist new studies is an additional difficulty since the most interesting critiques and challenges to geoengineering will come from ideas that circulate in the unpublished grey literature.[13] Assessment, at this stage, is best combined with the ability to steer a research agenda. The actual published literature on geoengineering, in fact, is so short and can be read over a long weekend and there is little gain from a general synthesis and assessment; it is interesting more for its omissions than its robust findings.

A better approach would enlist multiple strong assessment institutions rather than a single, global, and weak institution. A few competent groups could prepare assessments in parallel—ideally groups that are connected to active scientific research in the area—and then compare the assessments. Their charge would include a special need to look at the many ways that geoengineering could go wrong. Academies of science are probably the best place to begin the process because they are usually well connected to the setting of research priorities and political decision-making. Russia is a good candidate because of that country's long history of dreaming about (and studying) climate modification and its role in heavy space lift (which is important for some geoengineering options). So is the USA, which must play a central role because most geoengineering science is, at the moment, American. To that small group China must be added, as that nation is building the capability to understand the issues and possibly deploy geoengineering systems. Maybe other countries should be added, with an eye to evaluating special options—for example, Brazil or other forested nations, if tinkering with the forests is envisioned. Throughout, the goal of these assessments would be a plurality of ideas and new evaluations, not consensus. Elsewhere, several colleagues and I have explored how such an academy-based assessment process could operate (Victor *et al*., 2008).

(ii) Regulatory treaties and norms

As geoengineering is considered more seriously, the question of norms to govern deployment will arise. Norms might be needed not only to determine when such systems might be used but also the kinds of evaluations that geoengineers might be required to make before deployment, compensation for parties harmed, cost sharing, and commitments to maintain geoengineering systems once deployed. Bluntly, whose hands will be allowed on the thermostat?

[12] Making the assessment institution stronger will not fix the problem because strong assessment institutions are prone to becoming captured by their masters. For its core tasks, the IPCC has the right design—a weak institution, charged with assessment of agreed science and open to scrutiny by anyone.

[13] My goal is not to disparage the IPCC, for these problems are intrinsic to global omnibus assessments. Witness the magisterial *Global Biodiversity Assessment* (GBA), which remains, along with the Millennium Ecosystem Assessment, the most useful reference source on biodiversity. Yet the GBA, although originally conceived as policy-relevant, was largely orthogonal to the policy debate in the biodiversity treaty because the latter became focused on issues such as genetic engineering of crops and revenue-sharing for germplasm that were largely removed from the scientific debate. On the real hazards and trade-offs involved in such highly charged issues, the conservative scientific process in the GBA had little to contribute. See Watson *et al*. (1995); Hassan *et al.* (2005).

The standard answer to the question of norm-creation, like most in the realm of international environmental regulation, looks to the treaty system to negotiate, codify, and enforce norms. Treaties undergo extensive review and ratification by governments before they become binding and thus represent the best-considered desires and capabilities of the governments that join them (Chayes and Chayes, 1998). These strengths of treaties, however, are also exactly their liability. They are the by-product of a negotiating process through which nations evaluate closely whether they can and will comply. Such processes are inherently conservative. Indeed, efforts to measure compliance with environmental treaties generally find that compliance is nearly perfect—because countries adjust their commitments to the point where they are sure that compliance is feasible and because they do not join when commitments are too demanding (Downs *et al*., 1996; Victor *et al*., eds, 1998). The Kyoto process is one manifestation of that general observation about treaty-making (Victor, 2001).

From today's vantage point, a treaty negotiation would yield inconclusive outcomes. Most nations would probably favour a ban on geoengineering because only a few countries actually have the capability to geoengineer on their own.[14] The rest have little to gain from being permissive and would be wary about letting the geoengineers tinker with the planet. Faced with pressure for a taboo, the few nations with unilateral geoengineering capabilities would seek favourable (i.e. vague) language; if unsuccessful, those countries could simply refuse to join. Exactly this outcome followed the hotly contested negotiations leading to the 1992 Convention on Biological Diversity (CBD), which contained European-inspired language that was hostile to genetically engineered crops and developing country-inspired language that demanded complicated revenue-sharing for some kinds of germplasm collections. The USA, world leader in these investments, simply refused to join the treaty. Investment in the genetic engineering and in new crops that faced complicated new revenue-sharing requirements was slowed, despite their large potential benefits.[15] A treaty on geoengineering, if attempted today, would follow a similar diplomatic pathway. Most countries would push for a ban, and most of the possible geoengineers would balk.

In general, when it is not widely agreed how to frame the problem at hand, or if the framing creates strongly opposing interests, the outcome of treaty negotiations is stalemate. Sometimes that stalemate takes the form of vague language—a growing body of treaty language that might be called 'junk law', akin to the large amounts of 'junk DNA' that seems to serve no genomic purpose. In other instances, the outcome is a collapse of the treaty negotiations, as was the case for a planned treaty on forests in the early 1990s that could not yield agreement because important nations could not resolve how to frame and settle their disputes. Analysts and advocates are generally less mindful of these failures because they like to study success and there is no good theory of junk law. Thus bookshelves are filled with studies about the

[14] Exactly how many nations could unilaterally geoengineer depends on the geoengineering system and on important practical considerations. Nations with space-lift capability, missiles, or other vehicles that could inject material into the stratosphere all have the capability, in principle, to geoengineer. That list could extend to a dozen today and perhaps two dozen with a decade or two of sustained investment. However, in practice, a large territory (or willingness to operate on the high seas in the face of acute disputes) and reliable lift systems would be needed for this to be done with global impact. That list of countries is much smaller and might include Australia, Brazil, China, India, the EU (if it could agree to act as one), Russia, and possibly Japan.

[15] For more on the CBD and its outcomes, see Raustiala and Victor (2004) and for its harm on crop innovation see Victor and Runge (2002). Other environmental treaties have similar histories. For example, the ban on some forms of ocean dumping under the 1972 London Dumping Convention effectively halted all significant research on sub-sea disposal of nuclear waste, which could have been an environmentally superior to the land-based disposal options that have dominated nearly all investment since that time.

success in protecting the ozone layer, but nobody writes about dormancy and death in the treaty-making process.

A treaty negotiation at this stage would also raise some questions that could become highly contested without purpose. For example, who owns the Lagrangian point L1—an orbit that affords uninterrupted position between Sun and Earth and thus could be an ideal site for space-based sunshades? At the moment, nobody knows how to assign property rights at L1, but surely some governments will imagine great riches and demand their share. That occurred, for example, when governments sought to allocate rights to deep-seabed minerals through the Law of the Sea (Sebenius, 1984). Imagined riches never appeared, despite a decade of wrangling over revenue-sharing agreements. Such negotiations can be distracting and are probably irrelevant if underlying circumstances make the deal that is reached inconvenient for important players. At this stage, attempting to allocate L1 would not be useful. It is not clear whether L1 is uniquely special because jostling hardware at that slot could be hazardous for the planet as a whole. Or perhaps L1 will become like geostationary orbits—once imagined to be scarce and thus highly valuable, but today much less scarce thanks to innovation in low-power satellites and higher gain antennas. Disputes over ownership of L1 could lead governments to question whether systems could ever be placed in that orbit, and that would lead them to forgo possibly useful investment in L1-based geoengineering options.

A more effective approach to building a relevant regulatory system would concentrate, today, on laying the groundwork for future negotiations over norms rather than attempting to codify immature norms now. Meaningful norms are not crafted from thin air. They can have effect if they make sense to pivotal players and then they become socialized through practice. To be sensible the norms must be based on evidence and reason; they must be relevant and responsive to core interests of pivotal players.

What can be done to craft sensible norms? Formal, integrated scientific assessments, such as through the IPCC, seem unlikely to work for the reasons already discussed. Direct negotiation of norms, too, seems unlikely to bear fruit because not enough is known about geoengineering options and their effects to frame a useful formal negotiation. Here I explore a different approach, which is to build norms from the 'bottom up'. The decentralized process of research and assessment, already outlined above, can generate the information needed to assess different geoengineering options. If done openly with extensive review as well as complementary funding to examine scenarios for actual geoengineering deployment, then such a process will likely create a base of accepted, shared information that could inform later formal efforts to create norms.

To be relevant, however, this decentralized process must contend with at least two inconvenient factors. First, the countries that are most wary about actually deploying geoengineering—more or less, the advanced industrialized countries—are the ones that are the best candidates to lead the effort because they are most likely to lade their programmes with prudent assessments. For these reasons, it is probably especially important not to create a taboo against geoengineering, for that would make it very difficult for these countries to mobilize the political support needed for funding geoengineering research and assessment. Second, assessments of geoengineering probably require some well-instrumented, trial deployments of geoengineering systems. Such deployments will be particularly controversial in those same countries whose engagement is most essential.

The process should be open enough so that scientists from prospective geoengineering nations see it as the main source of useful knowledge about geoengineering while, at the same time, become socialized with the prevailing norms and best practices. CERN and ITER come to mind as models, as do the halting joint efforts during the Cold War by Soviet and US scientists to conduct joint seismic research (which was relevant for monitoring of underground testing and helped governments craft workable test ban agreements). Such institutions do not guarantee that all nations will adhere to the emerging norms, but it is interesting to note that often it is the scientists who are in the midst of international scientific assessments and collaborations who are the strongest advocates for regulation and also best positioned within their governments to press for complementary efforts within pivotal nations. If successful, this effort would create the necessary base of information for lead countries to create their own capable domestic institutions to fund and regulate geoengineering. In time, those connected national efforts would link together in a transnational partnership of expert regulators, as has happened in many other areas where regulation rests on expert assessment and profits from international coordination (Slaughter, 2004).

Greenfingers might be invited to participate in this transnational assessment process, provided they subscribe to the emerging norms. The success of Craig Venter's for-profit Celera in applying a new method for sequencing the human genome (Venter's genome, to be precise) is a reminder that the world has entered a new era where big science is no longer solely the province of government. That experience is also a reminder that whatever regulatory system is created will be under constant pressure to be relevant—because if it fails or is overly restrictive then rival geoengineers could act on their own. Unlike other areas of R&D where there are promises of large commercial rewards, at present it seems unlikely that private-sector finance would play a major role in geoengineering. There are no markets for geoengineering services, and if geoengineering systems were deployed at scale then governments would probably regulate the activity to prevent extranormal profits. However, if a few key capabilities for geoengineering could be identified, then prizes could be established for the parties that demonstrate them—akin to the X Prize that has encouraged private investment in space exploration, advanced automobiles, genomics, and other topics.

Along the way enough may be learned to create more formal treaties or other regulatory institutions. Exactly this 'bottom up' process—ambitious norm-setting activities, backed by research and assessment—was followed in the North Sea regulatory process, leading eventually to a complex of precise regulatory treaties. Such systems often benefit from the use of flexible, non-binding agreements in the early stages of the effort when it is not clear which rules should be codified and how governments would implement them (Victor *et al.*, eds, 1998; Victor, 2007).

IV. Conclusion

Growing attention to geoenginering will create pressure for regulation. I have suggested here that efforts to design regulations, at this stage, will probably fail to yield useful outcomes. And they may create a taboo against geoengineering that will have force in some countries. Taboos will make it hard for the countries that are most likely to sponsor informed and careful assessments of geoengineering to invest in the research and deployment of trial geoengineering systems that will be needed to generate useful and relevant knowledge.

Useful norms could arise through an intensive process of research and assessment that is probably best organized by the academies of sciences in the few countries with the potential to geoengineer.

I close by puzzling about what should be done if norm-setting from the bottom up is too plodding or does not work? A particular nation or Greenfinger might decide that harmful changes in climate compel unilateral action. Demarches and treaties will have little impact when highly concentrated benefits compel action. Trade sanctions, too, are unlikely to work—because they rarely work except when focused on small and vulnerable countries, which are the nations that are perhaps least likely to pursue unilateral geoengineering.

Such a scenario needs attention and careful assessment through techniques such as war games. For the countries not engaged in geoengineering, the best response to unilateral geoengineering might be a sharp increase in their own geoengineering effort. Such a breakout would make it easier to gain credible information on risks and also easier to re-establish norms. Unlike an arms race—in which breakout has the effect of making an adversary feel less secure, thus breeding further expenditure on weapons and rattling of sabres—a breakout in geoengineering could be stabilizing, because its transparent endpoint is to re-assert collective control over the technology. And once a unilateral geoengineer sees other countries engaged in similar efforts they will need to do less geoengineering on their own. But once the process of geoengineering begins—whether unilateral or collective—it is likely the world will be unable to stop. For whatever the ills of global climate change, it is probably even more dangerous to let the climate experience the even more rapid warming that would follow the dismantling of geoengineering systems.

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