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Ethics and Geoengineering: Reviewing the Moral Issues Raised by Solar Radiation Management and Carbon Dioxide Removal

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Advanced Review

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After two decades of failure by the international community to respond adequately to the threat of global climate change, discussions of the possibility of geoengineering a cooler climate have recently proliferated. Alongside the considerable optimism that these technologies have generated, there has also been wide acknowledgement of significant ethical concerns. Ethicists, social scientists, and experts in governance have begun the work of addressing these concerns. The plethora of ethical issues raised by geoengineering creates challenges for those who wish to survey them. The issues are here separated out according to the temporal spaces in which they first arise. Some crop up when merely contemplating the prospect of geoengineering. Others appear as research gets underway. Another set of issues attend the actual implementation of the technologies. A further set occurs when planning for the cessation of climate engineering. Two cautions about this organizational schema are in order. First, even if the issues first arise in the temporal spaces identified, they do not stay completely contained within them. A good reason to object to the prospect of geoengineering, for example, will likely remain a good reason to object to its implementation. Second, the ethical concerns intensify or weaken depending on the technology under consideration. The wide range of geoengineering technologies currently being discussed makes it prudent that each technique should be evaluated individually for its ethical merit.

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INTRODUCTION

Since the emergence of geoengineering as a serious policy option for addressing climate change, there has been a widespread recognition that ethical considerations form an essential component of the research landscape. Scientific communities have learned from hard experience that the passage from laboratory to field for emerging technologies is more difficult without a concerted effort to address the social and ethical issues in a public and responsible fashion. In the case of geoengineering, the glaring and voluminous nature of the moral challenges means that neglecting to consider them in depth would make it much less likely the technology would ever be implemented. The issues are not only numerous, they are also difficult. Affirming geoengineering's moral minefield, the UK's Royal Society has stated that 'the greatest challenges to the successful deployment of geoengineering may be the social, ethical, legal, and political issues associated with governance, rather than scientific and technical issues' (Ref 1, p. xi).[a,2] Responding to this observation, ethicists have recently begun probing the complicated moral terrain.

Before the publication of Crutzen's landmark essay in *Climatic Change* in 2006,[3] discussion of geoengineering had remained largely in the shadows due to the worry that the mere mention of a technical solution to warming temperatures might weaken

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political efforts at reducing greenhouse gas emissions. The ethics of geoengineering is unusual for how it began with a taboo on even discussing the topic.[4] Also unusual is that most of its advocates see geoengineering as only a temporary measure. Geoengineering therefore stands out among emerging technologies for the way the ethical issues belong in a finite spectrum of temporal spaces stretching from the mere mention of it as a possible future technology through to the question of how to bring geoengineering activities to a close. A helpful way to categorize the ethical issues may be to consider them within this temporal frame based on when each issue first arises. In a discussion of how the precautionary principle factors into the geoengineering discussion, Elliot identified three temporal spaces in which precaution should be considered ('Discussing Geoengineering', 'Researching Geoengineering', and 'Choosing to Geoengineer').[5] This review uses a similar methodology and sifts the ethical issues into categories: (1) Those that arise during mere contemplation of the possibility of geoengineering; (2) Those arising during research and development; (3) Those arising in the course of implementation; and (4) Those that might occur post-implementation. This organizing schema is not perfect. Several of the ethical issues appear in more than one of these temporal phases. The schema is also complicated by the fact that the issues raised by different geoengineering technologies vary. Nevertheless, this organizing mode helps to provide some separation between issues, even though a few will continuously surge and fade in importance throughout each of the temporal frames. No position will be taken on the question of which part of the temporal frame is most ethically significant.

THE BASIC LANDSCAPE OF GEOENGINEERING

A common contemporary definition of geoengineering is 'the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change' (Ref 1, p. 1). The 2009 Royal Society Report established what has become a canonical distinction between those techniques that attempt to address the global warming problem by reducing atmospheric carbon dioxide (carbon dioxide removal, CDR) and those that simply address warming symptoms by reflecting back sunlight (solar radiation mamagement, SRM). Examples of CDR include afforestation, enhanced weathering of rocks, liming the oceans, large-scale production of synthetic algae, direct air capture of carbon dioxide, and ocean fertilization. Examples of SRM include increasing the albedo of terrestrial or marine surfaces (e.g., white roofs, bioengineered crops, or ocean microbubbles), enhancing tropospheric clouds, reducing cirrus clouds, projecting sulfate particles in the stratosphere, and deploying reflective mirrors in space. Overviews of many of these techniques can be found in a 2008 special issue of *Philosophical Transactions of the Royal Society A*,[6] in numerous reports,[1,7,8] and in books by Jeff Goodell[9] and Eli Kintisch.[10]

Since CDR in some of its forms (e.g., direct air capture) is scalable and sounds very much like pollution control, it is common to perceive CDR as less morally problematic than SRM. Furthermore, since some forms of CDR (e.g., afforestation, accelerated phytoplankton blooms) appear to mimic or enhance existing natural processes, public perception of CDR tends initially to be more favorable ('respecting nature'[11]) than for technologies that appear less 'natural' such as stratospheric aerosols or space mirrors.[b,12] The Royal Society Report favored CDR over SRM stating 'CDR techniques offer a longer term approach to addressing climate change than SRM methods and generally have fewer uncertainties and risks' (Ref 1, p. 54). Also counting against SRM is the fact that, by addressing only symptoms rather than causes, SRM leaves carbon dioxide in the atmosphere, ensuring that the problem of ocean acidification will continue.

This preference for CDR has been questioned by those with concerns about the ecological impact of large-scale CDR technologies.[11] Proponents of stratospheric aerosols have also pointed out that, despite its problems, SRM remains 'fast', 'effective', and 'cheap',[13,14] requiring a matter of weeks to take effect rather than decades. They add that it is the only geoengineering technique already observed in action (after previous volcanic eruptions). If geoengineering had to be deployed in the face of an abrupt climate catastrophe—a condition some think would be the only acceptable condition for implementation[3,15]—then, despite its risks, some planetary albedo modification would almost certainly be required.

As much of the discussion below is focused on the moral obstacles to geoengineering, an important point to mention at the start is that, if successful, engineering the climate could potentially lessen an enormous amount of human suffering and environmental harm from global climate change. Lessening these harms is a huge potential benefit of geoengineering (and, of course, is the main reason its advocates pursue it). These advantages are amplified if it could be done with little harm to the global economy. When immersed in an extended discussion of the moral challenges created by geoengineering, one should not lose sight of the huge potential gains that are part of the essential context for any discussion of the ethics of geoengineering.

TEMPORAL SPACE 1: ISSUES RAISED IN CONTEMPLATING THE PROSPECT OF GEOENGINEERING

As indicated by the pre-2006 taboo, some of the ethical issues occur before any work on the technology has even begun. These concerns focus on the whole idea of intentionally engineering the climate. In some cases, if these concerns are decisive, they might preclude the possibility of beginning geoengineering at all. In others, they might lend important shape to how geoengineering proceeds.

Moral Hazard

The reluctance to talk about geoengineering pre-2006 was based largely on the concern that the prospect of a technical solution to climate change created a ‘moral hazard’ that might encourage risky behavior or influence the willingness of parties to engage in mitigation and adaptation. ‘Moral hazard’ is a term taken originally from the insurance industry suggesting that certain types of insurance create behavioral changes increasing an individual’s exposure to risk (Ref 16, p. 116). The suggestion that even the prospect of geoengineering creates a moral hazard is cited in numerous reports and articles as one of the risks of putting the geoengineering option on the table.[1,2,7,16–22] Even those advocating for geoengineering research seem to anticipate this risk by firmly cautioning that continued efforts to reduce greenhouse gas emissions must accompany any geoengineering research.[1,7,13]

The exact impact that the prospect of geoengineering will have on future behavior is, of course, an empirical matter, untestable until the situation actually unfolds.[23] But there is no doubt there are limited economic, institutional, and political resources available to address climate change making it reasonable to suggest that geoengineering could divert energy and resources from mitigation measures.

The moral hazard warning, however, turns out to be a little more complex than it appears. Hale has pointed out that the appellation is ambiguous, lacking clarity on whether it points toward a disincentive to mitigate, a positive incentive to produce more carbon dioxide, or a diversion of resources from adaptation.[16] Simply calling something a moral hazard does not actually establish a wrong unless it can be shown that the behavior the hazard precipitates is itself morally problematic. This ambiguity makes policy responses more difficult. Should a government motivate people to reduce emissions further, should it commit more money to adaptation, or should it endeavor to keep as many options open as possible? Hale is concerned that the blanket warning about a moral hazard gives little guidance.

An additional wrinkle in the moral hazard debate is found in the suggestion that talk of geoengineering might, in fact, have the opposite effect and encourage people to do *more* to mitigate climate change. Only if policy-makers and the public get a true sense of how desperately something needs to be done will they finally become motivated to reduce emissions (Ref 1, p. 43). This suggestion of a ‘reverse moral hazard’ is again an empirical matter, resolvable only through careful social science research. Gardiner doubts the likelihood of reversal, pointing out that the massive political inertia already demonstrated on climate change seems unlikely to vanish simply because scientists start pursuing a particular climate engineering technology (Ref 11, pp. 166–168).

Moral Corruption

Gardiner has added that the prospect of geoengineering creates a ‘deeper ethical hazard’ (Ref 11, p. 167) than the hazard just described. Building on worries about the tendency of those in the rich nations toward moral corruption in the face of the ‘perfect moral storm’ of anthropogenic climate change,[24] Gardiner suggests that the temptation to pursue geoengineering demonstrates the continuing ‘subversion of our moral discourse to our own ends’ (Ref 25, p. 286). Climate change is an unusually difficult problem due to both spatial and temporal separation of its causes and effects, and a lack of available theoretical and institutional resources available to deal with it. Rather than battle this perfect storm it has proven much simpler to find excuses for continuing with business-as-usual, a failure to which certain vested interests in the wealthy nations have clearly succumbed. As Gardiner puts it, ‘groups with which many of us identify are predominantly responsible for creating the problem, are currently largely ignoring the problem, and are also refusing to address the problem in the best way possible because of a strong attachment to lesser values’ (Ref 25, p. 303).

Having failed to do anything effectual about climate change over the last 20 years, the global community might easily continue this pattern of neglect by committing to a risky and untested technological path with uncertain effects on future persons and especially the poor. Gardiner thinks it is culpable self-deception to persuade oneself that a geoengineering program is an adequate alternative to emissions reductions. For Gardiner, this self-deception ‘might reveal just how far we are prepared to go to avoid confronting climate change directly’ (Ref 25, p. 304) while imposing considerable burdens on posterity.[19–21] This may be a ‘tarnishing’, even a ‘blighting’, evil.

Hubris

Another complaint arising at the prospect of geoengineering is that it demonstrates a hubristic attitude about the kind of capabilities that humans possess. Over the last 40 years of environmental thinking, a case has been made that many environmental woes result from the misdirected attempt of humans to exert dominion or control over natural processes rather than to find out how to live alongside them.[26–29] It has been suggested that, as a relatively late arriving species on the earthly scene, humans need to learn some humility and give up on the idea of re-shaping nature entirely to their own transient ends.[30] Failure to do so demonstrates a culpable arrogance.

In one of the earliest articles on the ethics of ‘intentional climate change’, Jamieson drew attention to the hubris in the very idea of geoengineering.[31] He suggested that numerous environmental problems stem from ‘our attempts to manipulate nature in order to make it conform to our desires rather than forming our desires in response to nature’ (Ref 31, p. 331). He noted a regrettable tendency for human interactions with the environment to be ‘arrogant’ and ‘intrusive’. Geoengineering, at least on the surface, appears to continue in this pattern.

Although the argument from hubris does not necessarily preclude geoengineering[c] it fits with a common tendency in environmental ethics to think that earth’s historical biogeochemical processes possess some moral significance in themselves.[32] Preston has suggested this might create a ‘presumptive argument’ against geoengineering based in environmental ethics.[33] He cautions that this argument from the value of historic processes may ultimately be defeasible, but it does place a heavy burden of proof on those who advocate interference when other options are still on the table.

Technological Fix

A further consideration lurking in the background is the question of whether the climate problem is really the type of problem that requires a ‘technological fix’. In 1967, Alvin Weinberg coined the term ‘technological fix’ to capture the strategy of substituting an engineering solution for a difficult social or behavioral problem.[34] Such technical fixes are attractive when citizens have repeatedly demonstrated a failure to make required behavioral changes.[35] Technological solutions can often be simpler, quicker, and demand less from people than the large social transformations that might otherwise be required. Without the assistance of technology, combating climate change would demand massive social and behavioral change. Scott calls SRM proposals ‘textbook examples of a technological fix’ (Ref 36, p. 159).

The moral status of technological fixes is ambiguous. While citizens repeatedly demonstrate a preference for technical fixes when faced with difficult behavioral demands and while technological fixes do appear to frequently solve many difficult social problems,[36,37] the term is often used negatively to connote a superficial and inadequate solution to a deeper problem. A geoengineering solution would permit continuing high levels of consumption, waste, and greenhouse gas emissions. Environmental thinkers usually advocate for a change in these values rather than simply deploying a technology that allows pernicious behaviors to continue.[36,38,39] Corner and Pidgeon warn that ‘[f]or groups and individuals who see climate change as a symptom of a social and economic order that is inherently unsustainable, geoengineering represents the worst kind of “techno-fix”’ (Ref 40, p. 31).

Is this a serious worry? In the case of SRM, the inadequacy of the techno-fix is immediately evident both in the continuation of ocean acidification under elevated atmospheric carbon and in the threat of very rapid warming should SRM have to be withdrawn. With a CDR technology such as direct air capture, it might be less easy to find arguments against consumption of fossil fuels if greenhouse gases had stopped accumulating.[d] The fix may in many ways be adequate.

As these last remarks make clear, the extent to which concerns raised by the mere prospect of geoengineering arise depends, a great deal, on the type of technology under discussion. Afforestation does not appear to display hubris in the same way that placing mirrors in space might, since the former appears to be more ‘natural’ than the latter.[11] Direct air capture of CO_2 may not provide the moral hazard that stratospheric aerosols do, since the technology inherently acknowledges the need to get carbon dioxide out of the atmosphere. The extent to which the global community commits to mitigation and adaptation will also impact the reactions generated by the prospect of engineering the climate.

Despite the influence of these variables, there are clearly constituencies who cannot reconcile themselves to any prospect of geoengineering.[e] These sceptics doubt the ability of any restoration to fully make amends for the original wrong.[41] While a number of years have passed since the taboo on discussing geoengineering was broken by Crutzen, these constituencies will insist that the prospective moral issues are not moot. The categories of pre-emptive moral concern may even re-occur in the later temporal spaces to which we now turn.

TEMPORAL SPACE 2: RESEARCH AND DEVELOPMENT

In the 6 years since discussion of geoengineering emerged openly on the public stage, laboratory research of different technologies has accelerated, publication and discussion of results has been voluminous, and the first few field trials have taken place. Experiments on the effects of iron fertilization in the ocean have occurred,[42] sulfate particles have been sprayed from helicopters to test reflective properties,[43] and a hose and balloon technology for deploying aerosols came close to being trialed.[44] The rapid expansion of activity raises a set of ethical issues of a different kind. These issues center on how to ethically govern this active research area.

A puzzle arises here because geoengineering research is not always cleanly separable from geoengineering deployment. The limitations of computer-based climate models mean that it may be impossible to properly test the response of the global climate system without some measure of implementation. 'Process' experiments to test the efficacy of deployment technologies—such as the proposed S.P.I.C.E. experiment in the UK (see Box 1)—could likely be done at a small scale with negligible climate impact. Field testing the efficacy of space mirrors, on the other hand, may not be possible without watching for an actual change in global temperatures. The line between testing and implementation is sometimes blurry. Leaving this problem aside, several attempts have been made to raise and address ethical issues associated with conducting research.

Principles Governing Research

While there is a general presumption in many democratic nations toward freedom of scientific inquiry, the controversial nature of geoengineering has spawned several attempts to supply ethical principles to govern research and the path to deployment. One of the earliest attempts were the so-called 'Oxford Principles', submitted to the UK House of Commons Science and Technology Select Committee in December 2009.[47] These principles recommend: (1) geoengineering to be regulated as a public good; (2) public participation in geoengineering decision making; (3) disclosure of geoengineering research and open publication of results; (4) independent assessment of impacts; (5). governance before deployment. In addition to the commitment to transparency and wide participation, the Oxford principles are notable for stipulating that geoengineering should not be driven by profit—raising questions about what *are* the appropriate funding

BOX 1

CANCELLATION OF S.P.I.C.E. (STRATOSPHERIC PARTICLE INJECTION FOR CLIMATE ENGINEERING) EXPERIMENT

In May 2012, a small field experiment to test a hose and balloon delivery system for future stratospheric aerosol deployment was cancelled by researchers. The experiment would have attempted to spray a 150 L of water (approximately 2 bathloads) from a height of 1 km. It would have been a 'process' experiment to assess delivery technology rather than an experiment to test the response of the climate system. The scale of the experiment posed no danger of impacting the climate and negligible environmental risk. Nevertheless, an environmental watchdog called the ETC Group publicly objected to the experiment on the grounds that it set the stage to proceed down a 'very high risk technological path'.[45]

Matt Watson, a member of the S.P.I.C.E. team, offered his own opinion of the main reasons for cancellation.[46] In the light of the S.P.I.C.E. team's endorsement of the Oxford Principles, there was some concern amongst team members that no governance structures were yet in place to oversee this field experiment. A patent application for an aerosol delivery system submitted before the S.P.I.C.E. project began created the impression of a conflict on the question of whether the technology would be a public or private good. Finally, the time required for further deliberation and stakeholder involvement made postponement undesirable.

The cancellation demonstrated that public perceptions of geoengineering currently make the transition from laboratory studies to small-scale field trials extremely challenging.

sources—and that a workable governance regime must be in place before any attempt at implementation. A slight variation of the Oxford principles was endorsed by a group of 175 experts in science, ethics, and policy who gathered at Asilomar, California in March 2010 to discuss voluntary guidelines for research.

A different take on the ethical requirements for research was offered in an article published in *Environmental Research Letters*. Morrow et al.[48] recommended borrowing certain principles—with roots in Kant[49] and Aristotle[50]—from medical ethics in order to govern research outside of the lab. A principle of respect requires the public's consent before initiating any potentially harmful field research. Principles of beneficence and justice demand both a favorable risk–benefit ratio before commencing research and the fair distribution of any benefits or harms that do occur. A minimization principle requires experiments to be as small as possible to test a given hypothesis. While generally meeting with approval within the ethics community, both this article and the Oxford principles were merely recommendations with no binding force.[f] They are also both vague enough that it is not always clear when their conditions are met.

Lock-In and Path Dependency

Expensive technologies requiring the development of large amounts of institutional structure and research expertise are prone to the phenomenon of 'path dependency' or 'lock-in'.[7,21,25,31] According to Jamieson, the institutional and human structures developed to research an emerging technology function as 'an interest group promoting the development of the technology they are investigating' (Ref 31, p. 333). The more time and money that are invested in research, the harder it becomes to stop that technology from moving toward implementation.

Technological lock-in means that the pressure to implement geoengineering from vested institutions could potentially overwhelm the caution the technology demands. Ott warns that the beginning of research into geoengineering sits at the top of a 'slippery slope' toward deployment (Ref 21, pp. 37–39). Gardiner similarly notes the considerable 'institutional momentum' a geoengineering project might accumulate (Ref 25, p. 289). Hourdequin observes that newly created interests 'may create momentum to implement SRM strategies despite the risks or before just decision-making procedures are established' (Ref 20, p. 27).

One might observe that some measure of path dependency is an unavoidable phenomenon associated with any large technological endeavor. Experience suggests this is particularly true in the energy field due to the enormous infrastructure investments required.[51] Given these facts, is there any reason to be particularly concerned about lock-in with geoengineering?

Gardiner's warnings about moral corruption and the political inertia around climate change in general make the potential lock-in of geoengineering particularly worrisome. The populations of wealthy nations have shown themselves to be particularly obtuse on the issue of climate action.[g] Geoengineering might therefore prove to be tempting in a way that the technology does not warrant. The risky technological fix may drown out the more sober structural changes of a safer path forward. As Buck[52] and Ott[21] have pointed out, stratospheric aerosol technologies in particular promise a type of lock-in that might dangerously restrict future options.

Participation of the Vulnerable

It has been noted that uncertainty about the effects of many geoengineering technologies on regional weather make it quite likely that, alongside those who will be made better off, some of those most vulnerable to the effects of climate change might end up being harmed.[h] The SRMGI report warned that 'SRM research could constitute a cheap fix to a problem created by developed countries, while further transferring environmental risk to the poorest countries and the most vulnerable people' (Ref 7, p. 21). An article otherwise more positive about the effect of stratospheric aerosols on the global food supply cautioned that significant regional variability means SRM may still 'pose a risk to local food security if subsistence farming prevails and adaptation is not possible' (Ref 53, p. 3). A Woodrow Wilson Center report expressed concern that '[p]opulations living at the edge of subsistence—those with the least capacity to adapt to the impacts of climate change and almost no voice in international deliberations—are precisely the populations that will be most vulnerable to any negative side effects that geoengineering experiments may have...' (Ref 54, p. 39). The many injustices of climate change foisted on the global poor could be unintentionally compounded by geoengineering.[55,56] Given this potential for compound injustice, the need for vulnerable populations to be represented in the research discussion that will set the path for geoengineering is clear.

Calls for public engagement in the development of major technologies are increasingly common in social science.[40,57–59] Engagement with the most marginalized and vulnerable to climate disruption presents some of the greatest challenges. As Anthony Lieserowitz has put it '[w]hat does informed consent mean in a world where more than two billion people are unaware that climate change is a problem?'[60] Despite the challenges, Corner and Pidgeon suggest that '[p]ublic engagement need not (and should not) be restricted to the citizens of industrialized, Western nations' (Ref 40, p. 34). The importance of incorporating the views of the vulnerable and the marginalized in the discussion of future geoengineering presents a significant moral demand.

Despite these good intentions, some remain deeply skeptical based on past experience about the likelihood of any genuine attempt to engage with indigenous peoples over geoengineering.[61] Far more likely, says Whyte, a member of the Potawatomi Nation, is that a geoengineering agenda will already be set before tribes are 'consulted' about what is going to happen anyway. Such an approach, according to Whyte, continues to propagate the assumption that 'developing nations have the privileged role in determining the vision and priorities for Indigenous peoples' (Ref 61, p. 75). Whyte advocates an alternative 'partnership model' consistent with the UN Declaration on the Rights of Indigenous people. Such a model would guarantee to indigenous people a fundamental 'respect for their sovereignty over the territories that they depend on for their basic needs and for fulfilling their preferred lifeways' (Ref 61, p. 75). Developing a similar theme, Preston observes how the burdens of climate change have the potential to be compounded for certain vulnerable peoples.[62] Given both the risks and the likelihood of technological lock-in, he argues these populations deserve to have some input into the shape of today's geoengineering research agenda. But this call for the inclusion of marginalized voices is not simply a moral call. Such input also has the potential to make substantive improvements to the research itself. This is especially true for technologies that promise large social impacts in a framework of high uncertainty.[57,63–65] Including marginalized voices in planning geoengineering research may not just be good ethics, it may also be good science.

TEMPORAL SPACE 3: IMPLEMENTATION

While not a consensus view, some participants in the SRMGI process felt that ethical considerations become more urgent as the technology moves from computer modeling to field testing to actual deployment and implementation.[7] At the point of implementation certain matters of basic justice foreshadowed at earlier stages become urgent and new ethical concerns surface for the first time.

Procedural Justice

If the problems of participation and consent first arise in the context of research, there is no doubt whatsoever that their reappearance in the context of implementation is one of the biggest ethical challenges geoengineering faces. As an engineering project promising global impacts, some form of consent—at least from the representatives of those affected—would appear to be a non-negotiable requirement of just procedure.[66,67] Corner and Pidgeon put it this way: 'the prospect of controlling the global thermostat is something that all citizens could reasonably claim to have a legitimate stake in' (Ref 40, p. 29). In addition to the fundamental question of whether or not to proceed, questions about how to balance geoengineering efforts with mitigation efforts, how rapidly to ramp up the chosen technology (if it is scalable), how to most effectively evaluate the impacts of the technology, what to set as targets, and which political entity (or entities) should take charge all require stakeholder input. Many of these questions are theoretically captured under the broad umbrella of the Oxford Principles' demand for 'governance before deployment'. But that broad umbrella gives little sense of the magnitude of the task. Gardiner advises 'the emergence of geoengineering may signal special issues of political legitimacy, prompting the need for new or strengthened global norms of justice and community, and novel institutions' (Ref 11, p. 171). As in the perfect moral storm of climate change, the institutions for resolving the procedural questions may simply not exist at this point.

The goal of creating a just governance procedure is, of course, an enormous challenge with any global technology. The barriers to achieving effective governance on climate change are likely to be exacerbated in geoengineering where divergence between the interests of different countries is projected to increase over time.[68] But the interests of the different players cannot be ignored. As David Keith has pointed out, both SRM and CDR are ultimately engineering technologies.[69] Engineers serve clients with a huge variety of wants and needs. Geoengineers need stakeholder involvement. Balancing the diverging interests of more than seven billion stakeholders, however, is an unlikely task. Since these interests also extend far into the future and include the interests of non-human nature, there is little possibility of any familiar form of consent.[20,70]

Under the banner of procedural justice one might also add the considerable security concerns that geoengineering presents. The ability to alter the climate is of obvious strategic interest to global powers and those invested in the political stability of particular regions. Modification of the weather for military or hostile purposes has been banned by the Environmental Modification Convention (ENMOD) since 1977. However, some climate engineering techniques might still be performed unilaterally, either for hostile purposes or simply in an attempt by one nation to reduce the negative impacts of rising temperatures on their population.[14] Alternatively, a particularly wealthy individual—the so-called 'greenfinger' scenario—might initiate geoengineering for what is perceived to be the greater good.[9,10] Some members of the international community might even publicly frown upon unilateral geoengineering, while privately embracing the fact that someone had gone ahead with an action that was otherwise politically impossible.

It is far from clear how these complicated procedural and political questions will ever be answered satisfactorily.[55] Geoengineering activities taking place entirely on a country's own soil, such as carbon capture, might raise fewer political and legal questions than those taking place on the global commons, such as stratospheric aerosols or marine cloud enhancement. With technologies involving the commons, the SRMGI report concedes that 'it may be impossible to reach agreements that are acceptable to all parties owing to significant differences based on geopolitical, ethical, equity, and climate issues' (Ref 7, p. 52). Under conditions of an extreme planetary emergency—if such a state could be adequately defined—the requirements for just procedure might end up being loosened. Hyping such an emergency is obviously in the interests of those who want to develop and test geoengineering now.[25] For this reason, one should pay close attention to the way geoengineering is framed in the emerging cultural discourse (see Box 2).[22]

BOX 2

THE RHETORIC AND FRAMING OF CLIMATE ENGINEERING

As a relatively new technology emerging in an age of instant and obsessive media scrutiny, the question of how geoengineering gets publicly framed creates significant ethical issues of its own.

Already, a number of different framings suggest different ethical approaches. The idea of geoengineering as a 'plan B' or 'insurance' presents the technology as embodying a mature and cautious wisdom, even though it creates some worry about how insurance can encourage risky behavior.[1,2,7,16–22] SRM, however, is a type of insurance attended by significant costs of its own in terms of the burdens it may impose. Scott suggests that 'planetary emergency device' (Ref 36, p. 157) might better capture this risky reality. An alternative 'lesser of two evils' framing might increase the sense of an urgent and unavoidable need to address anthropogenic warming, even though some worry this framing increases the likelihood of moral corruption and procrastination on emissions reduction.[25]

Geoengineering researchers have tried to reframe the technology. 'Sunlight Reflection Methods' sounds less hubristic than 'Solar Radiation Management', even though they fortuitously share the same acronym. A recent report attempted to rebrand climate engineering as 'Climate Remediation', a move that created some dissent among the report's authors.[71] Caldeira has suggested that the term 'geoengineering' is both vague and emotionally-charged, recommending that individual technologies be considered on their merits rather than lumped together under a single, unhelpful umbrella term.[i]

With a technology so powerful, it is unsurprising that the way geoengineering is characterized has consequences.

Distributive Justice

Though predicted to be uncertain and uneven,[72,73] efforts must be made to distribute the benefits and burdens of CDR and SRM fairly. In the case of SRM, Keith et al. have stressed 'it is vital to remember that a world cooled by managing sunlight will not be the same as one cooled by lowering emissions' (Ref 74, p. 426). There will be no return to the exact conditions of some Edenic, pre-industrial climate. To the degree that the characteristics of an engineered climate can be predicted, choices will have to be made about *who* gets *what* in a geoengineered world. Clearly there are concerns that the interests of the most powerful would be protected, while those less powerful will get secondary consideration (if they are considered at all). If, *contra* the Oxford Principles, geoengineering were to be controlled privately, then market-based incentives might steer the benefits away from those who most need them toward those most able to pay. Since those most vulnerable to adverse impacts are also those least likely to have caused climate change, are least capable of adapting to it, and have the least input into geoengineering technologies, vulnerability to burdens is skewed heavily in certain directions. This demands extreme vigilance, and more conscience than has yet been shown, if distributional justice is to be protected.[55]

When burdens are borne by the vulnerable, some sort of compensation mechanism will be required, a point recognized from the earliest ruminations on climate engineering to the present.[75,76] Since the precise regional effects of climate engineering will not be predictable, contingency planning will need to be in place for negative impacts descending rapidly upon a population. These impacts might include the need to be swiftly relocated, the need to replace housing destroyed by extreme weather events, and the need for emergency potable water. While the demand for such compensation mechanisms seems daunting, objecting to geoengineering on the grounds of uneven burdens is an overreaction. Anthropogenic climate change is already causing uneven burdens that need to be compensated, something recognized by the call for 'differential responsibilities' in the United Nations Framework Convention on Climate Change in 1992. This need is certain to continue with geoengineering.

Determining when a future burden is the consequence of a 'natural' weather event, of anthropogenic climate change, or of geoengineering will be next to impossible.[7,77] Benefits and burdens are also likely to fall more upon future generations-whose number and identity are not yet known-than on the present generation, making the demands of distributive justice extremely challenging to satisfy.[78,79] With the various needs crossing geographical, generational, and species lines, it is hard to see how the challenges of distributional justice are going to be any more readily solvable than those of procedural justice.

'Incidentals'

In addition to the two major justice issues, a wide range of supplemental concerns have been raised in relation to the actual implementation of geoengineering. Atmospheric scientist Alan Robock articulated 20 reasons why geoengineering may be a bad idea.[80] Several reasons raise concerns that might be described as 'incidental' to changing temperatures and atmospheric carbon concentrations.[j] With SRM, ocean acidification will continue, leading to coral reef damage and degradation of marine habitat. In the case of stratospheric aerosols, the ozone layer is likely to be damaged, leading to uncertain impacts on phytoplankton, plants, eyes, and skin. The diffuse light caused by cloud and aerosol modifications will have impacts on crop productivity and on the effectiveness of photovoltaic panels. Stratospheric aerosols will cause less aesthetically appealing whiter skies and create challenges for astronomy. While many of these incidental impacts are undesirable, not all of them are obviously bad. More diffuse light can increase crop productivity[81] and the filtering effect of aerosols on ultra violet light is likely to decrease the incidence of skin cancers. Sunsets could also be more beautiful.[80] Good or bad, the fact that these incidental impacts have a bearing on human and environmental well-being brings additional ethical considerations into play.

While sidestepping a number of the atmospheric impacts of SRM detailed by Robock, some forms of CDR have generated their own ecological concerns. Attempts at ocean fertilization have been stopped on environmental grounds and the Convention on Biological Diversity recently imposed a nominal moratorium on geoengineering 'until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks'.[k] The type of CDR technology under discussion clearly makes a difference to the ecological impacts. Direct air capture may raise different questions from liming the oceans due to the way the materials employed will disperse through an ecosystem.[l]

Another caution about the incidental impacts of CDR concerns the scale on which these technologies have to operate to have a significant impact on atmospheric carbon. Axon and Lubansky have made rough estimates of the engineering infrastructure required for removing the 30 gigatons (Gt) of carbon dioxide emitted globally each year. Direct air capture could require up to 120 Gt of clean water each year, possibly depriving up to 53 million people of their water supply.[82] For enhanced weathering of rocks, 100 Gt of olivine would be required which is approximately 12,500 times current global production.[m] Latham et al.[83] have estimated that tropospheric cloud seeding would require approximately 1500 spray producing vessels operating continuously across the oceans, a more manageable infrastructure perhaps, but still a costly one. While the calculations are rough, they illustrate how some CDR technologies create their own environmental effects simply through the scale of the engineering required.

TEMPORAL SPACE 4: POST-IMPLEMENTATION

At this point it should be clear that there are a wide range of ethical issues to be solved before implementation of geoengineering. Any number of these might prove decisive. It is far from obvious that all these moral requirements could today be satisfied. But let us assume they could be met, or that a climate catastrophe of such magnitude loomed that the requirements were loosened. Are there other ethical worries to consider?

Termination Problem

If SRM is initiated then it is likely that, in the absence of any dramatic success in reducing emissions, greenhouse gases will continue to accumulate in the atmosphere even as planetary temperatures cool. As already mentioned, this feature of SRM allows the continuation of ocean acidification. Another problem awaits. Should any event—either geopolitical or climatic—make it necessary to rapidly cease SRM then temperatures would rise very quickly indeed under these elevated carbon dioxide scenarios.[84,85] In addition to the obvious danger for humanity, the threat posed to species would be significant. While some highly mobile species might be able to survive climate change by migrating north (or upwards) or simply by adopting different behaviors, the chances of doing so decrease dramatically as the rate of temperature change increases.[86] One might hope that this 'termination problem' could be avoided through careful research of potential SRM side effects and through stable political institutions being established prior to implementation. However, the complexity of the climate system, the challenge raised by the limited ability to field test, and the perfect moral storm of climate change mean that a number of scientific and political uncertainties about long-term deployment are likely to remain.

Cessation Mechanisms

Geoengineering is often framed as a question of 'buying time'[7,87,88] until adequate mitigation and/or adaptation measures can be put in place. It may not be easy, however, to determine when enough time has been bought. With CDR, it would theoretically be possible to set a long-term parts per million (ppm) target for atmospheric carbon as a trigger point for cessation. This target would not only take a long-time to achieve, but climate inertia caused by the large heat capacity of the oceans may mean that even a 'satisfactory' ppm number would not necessarily indicate that temperatures were about to return to 'normal'.[89] Warmer temperatures and the dangers associated with them would be in store for many decades as the oceans slowly cooled. In the interim, some coupling of CDR and SRM may be necessary to temporarily reduce these temperatures.

Furthermore, cessation of CDR would depend entirely on progress on emissions reduction. If a promising CDR strategy had the effect of persuading people to let emissions levels remain high, any ppm trigger point for cessation may rapidly be exceeded again as soon as CDR is removed. In all likelihood, with economic costs comparable to mitigation, both CDR and mitigation would be occurring simultaneously. The distinction between removing carbon from the atmosphere and not emitting it in the first place—CDR versus further emissions reduction—may then become increasingly blurry. At that point, CDR could become the favored mitigation strategy and the idea of perpetual CDR could become attractive, forever changing the political calculus and creating a 'new normal'.

In the case of SRM, the same questions about incentives for mitigation and adaptation arise, but with an additional complicating factor. Even if emissions have been dramatically reduced, the already accumulated carbon dioxide in the atmosphere would only have been masked by SRM and not reduced. Whenever SRM was removed, planetary warming would continue. The timescale over which that carbon dioxide would be naturally re-absorbed into the world's oceans[90]—and the current slowing of that rate[91]—suggests that SRM would have to continue long into the future unless some cocktail approach of 'SRM plus CDR' was employed. Technologies to combat ocean acidification would also be needed to counter continued elevated atmospheric carbon dioxide.

Cessation of geoengineering technologies is clearly not as simple as hitting a temperature or ppm target and saying 'stop'. Decisions about the pathway toward emissions reduction and removal of any geoengineering technology would be contentious. The global community would face a complicated politics akin to the current challenges presented by climate change. While this politics may not prove impossible, the future of both SRM and CDR would always be woven both into each other and into ongoing mitigation and adaptation.

Designer Climates

The fact that difficult choices would need to be made over when and how to cease geoengineering bleeds over into a different problem concerning design. Questions raised earlier about distributional justice hint at the fact that some countries may be better off under some climate change or geoengineering scenarios than they were before. Canadians, for example, may perceive themselves to reap economic benefits from an ice-free Northwest Passage. Parts of Russia may be on track to become more suitable for growing crops under warming temperatures and increased carbon dioxide levels. Parts of Africa may look forward to the benefits of increased precipitation if it could be reliably manufactured.

Attempts at modifying the weather have a long and undistinguished history.[92] Should geoengineering make it possible to design climates by carefully tweaking certain carbon dioxide or solar radiation parameters, it might be tempting to do so. The taboo mentioned earlier about open discussion of geoengineering also applies to its implementation. Once the taboo against intentional climate modification had been broken, it seems probable that there would be a slippery slope toward 'designer climates' where the whole idea of restoring a 'natural' climate had been abandoned entirely. Ellis enthusiastically embraces this hope, stating '[c]reating the future will mean going beyond fears of transgressing natural limits and nostalgic hopes of returning to some pastoral or pristine era ... [w]e must not see the Anthropocene as a crisis, but as the beginning of a new geological epoch ripe with human-directed opportunity' (Ref 93).

Szerszynski and Galarraga[94] have discussed various lenses through which one might consider this work of 'making climate'. Since the climate is a constantly changing 'metastable' system, they suggest geoengineers would not be able to simply adjust one variable and then sit back and watch things unfold (Ref 94, p. 223). More likely is that a series of continual adjustments would be required in order to keep the climate heading where its manipulators wanted it to go. This places those in control, they suggest, more into the role of 'artists' than anything else, forced into a continuous realm of decision making and creative engineering endeavor. To some extent, today's efforts at pollution control on marine diesel engines and coal-fired powerplants are already 'making climate'. Geoengineering would make the design questions explicit.

CONCLUSION

The range of ethical issues discussed does not exhaust those that would have to be considered before an ethically acceptable geoengineering project could be implemented. It merely hints at the complexity. The schema utilized should also not mask the continuous ebb and flow of these issues across the various temporal spaces described. As indicated, the type of technology deployed, the seriousness of the crisis being faced, and the plans in place for adaptation, mitigation, and cessation would all influence the different ethical considerations.

In 1996 in the first article by a professional ethicist on geoengineering, Dale Jamieson concluded that the conditions for moral permissibility of intentional climate change 'are not now satisfied' (Ref 31, p. 323). Sixteen years later, with climate impacts more apparent and the ethical concerns more widely recognized and numerous, Jamieson's statement likely still holds true. It should be clear, however, that it can now be delivered with increasingly less calm.

NOTES

[a]The social and governance issues the report refers to are difficult precisely because the ethical desiderata one would be required to meet for democratic governance of geoengineering are so tough.

[b]The NERC report[12] showed that this was not always the case.

[c]Some ultimately praiseworthy actions, such as running for national office can often include a bit of hubris.

[d]Certainly other arguments are possible. Opponents talk about the finite nature of fossil fuel resources, the concentration of power that follows their extraction, and their tendency to foster geopolitical instability.

[e]See the Web sites of Hands off Mother Earth (www.handsoffmotherearth.org) and the ETC Group (www.etcgroup.org) for examples.

[f]The S.P.I.C.E. project did voluntarily adopt those principles to govern their own ill-fated field experiment.

[g]An example of this obtuseness is the widely perceived failure of the 'make or break' Copenhagen conference in December 2009.

[h]The extent of the variability in effectiveness of SRM is under debate with some believing the unevenness may not be as great as suggested.[95]

[i]See a discussion on the Geoengineering googlegroup in 2011 under the threads 'HOME article' and 'We don't need a "geoengineering" research program.'

[j]The use of the term 'incidental' here is tongue-in-cheek. In no way is it intended to diminish the significance of the additional concerns. It is intended to point out that there are numerous unintended side-effects of geoengineering schemes that might in themselves provide sufficient reason not to proceed.

[k]UN Convention on Biological Diversity COP 10 Decision X/33, section 8 (w) http://www.cbd.int/decision/cop/?id=12299 (Accessed July 8, 2012).

[l]The U.S. Congressional Research Service has differentiated between 'encapsulated' and 'unencapsulated' geoengineering technologies, suggesting that the latter are generally perceived as presenting more environmental risk.[96]

[m]A more detailed discussion of material requirements for enhance weathering can be found in Ref 97.

REFERENCES

1. Shepherd J, Caldeira K, Cox P, Haigh J, Keith D, Launder B, Mace G, MacKerron G, Pyle J, Rayner S, et al. Geoengineering the climate: science, governance, and uncertainty 2009. Available at: http://royalsociety.org/policy/publications/2009/geoengineering-climate. (Accessed June 26, 2012).
2. Blackstock J. Researchers can't regulate climate engineering alone. *Nature* 2012, 486:13.
3. Crutzen P. Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Climatic Change* 2006, 77:211–219.
4. Lawrence M. The geoengineering dilemma: to speak or not to speak. *Climatic Change* 2006, 77:245–248.
5. Elliot K. Geoengineering and the precautionary principle. *International Journal of Applied Philosophy* 2010, 24:237–252.
6. Launder M, Thompson J. Geoscale engineering to avert dangerous climate change. *Philosophical Transactions of the Royal Society A* 2008, 366.
7. Solar Radiation Management Governance Initiative (SRMGI). Solar radiation management: the governance of research. Available at: http://www.srmgi.org/files/2012/01/DES2391_SRMGI-report_web_11112.pdf. (Accessed June 27, 2012).
8. Bracmort K, Lattanzio R, Barbour E. Geoengineering: Governance and Technology Policy (US Congressional Research Service Report). Available at: www.fas.org/sgp/crs/misc/R41371.pdf. (Accessed July 4, 2012).
9. Goodell J. *How to Cool the Planet*. New York: Houghton Mifflin; 2010.
10. Kintisch E. *Hack the Planet: Science's Best Hope—or Worst Nightmare—for Averting Climate Catastrophe*. Hoboken, NJ: Wiley Publishing; 2010.
11. Gardiner S. Some early ethics of geoengineering the climate: a commentary on the values of the royal society report. *Environmental Values* 2011, 20:163–188.
12. Ipsos Mori *Experiment earth*?: Report on a public dialogue on geoengineering 2010. Available at: http://www.nerc.ac.uk/about/consult/geoengineering-dialogue-final-report.pdf. (Accessed June 26, 2012).
13. Keith D, Parson E, Morgan M. Research on global sun block needed now. *Nature* 2010, 463:426–427.
14. Barrett S. The incredible economics of geoengineering. *Environmental & Resource Economics* 2008, 39:45–54.
15. Schneider S. Geoengineering: could—or should—we do it? *Climatic Change* 1996, 31:291–302.
16. Hale B. The world that would have been: Moral hazard arguments against geoengineering. In: Preston C, ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 113–131.
17. Keith D. David Keith's unusual idea on climate change. Available at: www.ted.com/talks/lang/eng/david_keith_s_surprising_ideas_on_climate_change.html. (Accessed June 27, 2012).
18. Bunzl M. An ethical assessment of geoengineering. *Bulletin of the Atomic Scientists* 2008, 64:18.
19. Smith P. Domination and the ethics of solar radiation management. In: Preston C, ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 113–131.
20. Hourdequin, M. Geoengineering, solidarity, and moral risk. In: Preston C, ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 15–32.
21. Ott K. Might solar radiation management constitute a dilemma. In: Preston C, ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 113–131.
22. Scott D. Insurance policy or technological fix: the ethical implications of framing solar radiation management. In: Preston C, ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 113–131.
23. Lin A. Does geoengineering present a moral hazard? *Ecology Law Quarterly* 2012. In press.
24. Gardiner S. *A Perfect Moral Storm: The Ethical Tragedy of Climate Change*. Oxford: Oxford University Press; 2011.
25. Gardiner S. Is "arming the future" with geoengineering really the lesser evil? In: Gardiner S, Caney S, Jamieson D, Shue H, eds. *Climate Ethics: Essential Readings*. Oxford: Oxford University Press; 2010, 284–312.
26. White L. The historical roots of our ecological crisis. *Science* 1967, 155:1203–1207.

27. Merchant C. *The Death of Nature: Women, Ecology, and the Scientific Revolution*. New York: Harper Collins; 1980.
28. Berman M. *The Re-Enchantment of the World*. Ithaca, NY: Cornell University Press; 1981.
29. Leopold A. *A Sand County Almanac: And Sketches Here and There*. Oxford: Oxford University Press; 1949.
30. Hill T. Ideals of human excellence and preserving natural environments. *Environmental Ethics* 1983, 5:211–224
31. Jamieson D. Ethics and intentional climate change. *Climatic Change* 1996, 33:323–336
32. Rolston H III. *Environmental Ethics: Duties to and Values in the Natural World*. Philadelphia, PA: Temple University Press; 1988.
33. Preston C. Re-thinking the unthinkable: environmental ethics and the presumptive argument against geoengineering. *Environmental Values* 2011, 20:457–479.
34. Weinberg A. *Reflections on Big Science*. Cambridge, MA: MIT Press; 1967.
35. Borgmann A. The setting of the scene: technological fixes and the design of the good life. In: Preston C, ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 189–200.
36. Scott D. Insurance policy or technological fix? The ethical implications of framing solar radiation management. In: Preston C, ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 151–168.
37. LeCain T. When everybody wins does the environment lose? The environmental techno-fix in twentieth-century mining. In: Rosner L, ed. *The Technological Fix: How People Use Technology to Create and Solve Social Problems*. New York: Routledge; 2004; 137–153
38. Katz E. The call of the wild: the struggle for domination and the technological fix of nature. *Environmental Ethics* 1992, 14:265–273.
39. Hamilton C. Ethical anxieties about geoengineering: moral hazard, slippery slope, and playing God, 2011. Available at: http://www.clivehamilton.net.au/cms/media/ethical_anxieties_about_geoengineering.pdf. (Accessed July 4, 2012).
40. Corner A, Pidgeon N. Geoengineering the climate: the social and ethical implications.*Environment* 2010, 52:24–37.
41. Hale B. Getting the bad out: remediation technologies and respect for others. In: Kabasenche WP, O'Rourke M, Slater M, eds. *The Environment: Philosophy, Science, and Ethics*. Cambridge, MA: MIT Press; 2012, 223–244.
42. Alfred Wegner Institute, Lohafex provides new insights on plankton ecology—Only small amounts of atmospheric carbon dioxide fixed 23 March 2009. Available at: http://www.awi.de/en/news/press_releases/detail/item/lohafex_provides_new_insights_on_plankton_ecology_only_small_amounts_of_atmospheric_carbon_dioxide/?cHash=1eb5f2e233. (Accessed July 4, 2012).
43. Izrael Y, Zakharov V, Petrov N, Ryaboshapko A, Ivanov V, Savchenko A, Andreev Y, Puzov Y, Danelyan B, Kulyapin V. Field experiment on studying solar radiation passing through aerosol layers. *Russian Meteorology and Hydrology* 2009, 34:265–373
44. Oxford Geoengineering Programme. Stratospheric Particle Injection for Climate Engineering (S.P.I.C.E.) Available at: http://www.geoengineering.ox.ac.uk/research/oxford-university-research/spice/. (Accessed July 4, 2012).
45. ETC Group. Open letter about S.P.I.C.E. geogengineering test, 2011, 26 September. Available at: http://www.etcgroup.org/sites/www.etcgroup.org/files/publication/pdf_file/SPICE-Opposition%20Letter.pdf. (Accessed July 4, 2012).
46. Watson M. Testbed news 2012, 16 May. Available at: http://thereluctantgeoengineer.blogspot.de/2012/05/testbed-news.html. (Accessed July 4, 2012).
47. Rayner S, Redgwell C, Savulescu J, Pidgeon N, Kruger T. Oxford memorandum submitted to the House of Commons Select Committee on Science and Technology, 2009. Available at: http://www.geoengineering.ox.ac.uk/oxford-principles/history/. (Accessed July 4, 2012).
48. Morrow D, Kopp R, Oppenheimer M. Toward ethical norms and institutions for climate engineering research. *Environment Research Letters* 2009, 4:1–8.
49. Kant I. *Grounding for the Metaphysics of Morals* (trans. Ellington J). 3rd ed. Indianapolis, IN: Hackett Publishing; 1993.
50. Aristotle. *Nichomachean Ethics* (trans. Irwin T). 2nd ed. Indianapolis, IN: Hackett Publishing; 1999.
51. Lohmann L. Carbon trading: a critical conversation on climate change, privatisation and power. *Development Dialogue* 2006, 48. Available at: http://www.dhf.uu.se/pdffiler/DD2006_48_carbon_trading/carbon_trading_web.pdf. (Accessed July 4, 2012).
52. Buck, H. Climate remediation to address social development challenges: going beyond cost-benefit and risk approaches to assessing solar radiation management. In: Preston C, ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 133–148.
53. Pongratz J, Lobell D, Cao L, Caldeira K. Crop yields in a geoengineered climate. *Nature Climate Change* 2012, 2:1–5.
54. Olson R. Geoengineering for decision makers. Woodrow Wilson Center Report November 2011. Available at: http://www.wilsoncenter.org/sites/default/files/Geoengineering_for_Decision_Makers_0.pdf. (Accessed July 4, 2012).

55. Svoboda T, Keller K, Goes M, Tuana T. Sulfate aerosol geoengineering: the question of justice. *Public Affairs Quarterly* 2011, 25:157–180.
56. Shue H. The unavoidability of justice. In: Hurrell A, Kingsbury B, eds. *The International Politics of the Environment*. Oxford, UK: Oxford University Press; 1992, 373–397.
57. Stirling A. 'Opening up' and 'closing down': power, participation, and pluralism in the social appraisal of technology. *Science, Technology, & Human Values* 2008, 33:262–294.
58. Wilsdon J, Willis R. *See-Through Science: Why Public Engagement Needs to Move Upstream*. London: Demos; 2004.
59. Leach M, Scoones I, Wynne B, eds. *Science and Citizens: Globalization and the Challenge of Engagement*. London, UK: Zed Books; 2005.
60. Leiserowitz A. Climate change and geoengineering in the public mind. Presentation at Asilomar International Conference on Climate Intervention Technologies (slide 12). Available at: http://www.climateresponsefund.org/images/Conference/leiserowitz-4-24-10-red.pdf. (Accessed July 7, 2012).
61. Whyte K. Indigenous peoples, solar radiation management, and consent. In: Preston C, ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 65–76.
62. Preston C. Solar radiation management and vulnerable populations: the moral deficit and its prospects. In: Preston C., ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 77–94.
63. Intemann K. Putting feminist research principles into practice: objectivity and social justice in climate change studies. In: Hesse-Biber S, ed. *The Handbook of Feminist Research: Theory and Praxis*, 2nd ed. London: Sage Publications; 2011, 495–510.
64. Beatty J. Masking disagreement among experts. *Episteme: A Journal of Social Epistemology* 2006, 3:52–67.
65. Biddle J, Winsberg E. Value judgments and the estimation of uncertainty in climate modeling. In: Magnus PD, Busch J, eds. *New Waves in Philosophy of Science*. Hampshire, UK: Palgrave Macmillan; 2011, 172–197.
66. Rawls J. *A Theory of Justice*. Cambridge, MA: Harvard University Press; 1999.
67. Grasso M. A normative ethical framework in climate change. *Climatic Change* 2007, 81:223–246.
68. Ricke K, Morgan G, Allen M. Regional climate response to solar–radiation management. *Nature Geoscience* 2010, 3:537–541.
69. Keith D. Just how many knobs, bells and whistles do you want on that there climate control box? Presentation at Ethics of SRM Workshop, University of Montana, October 18th, 2010.
70. Sandler R. Solar radiation management and non-human species. In: Preston C, ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 95–109.
71. Bipartisan Policy Center. Task Force on Climate Remediation Research. Available at: http://bipartisanpolicy.org/library/report/task-force-climate-remediation-research. (Accessed July 4, 2012).
72. Matthews H, Caldeira, K. Transient climate—carbon simulations of planetary geoengineering. *Proceedings of the National Academy of Sciences* 2007, 104:9949–9954.
73. Bala G, Duffy P, Taylor K. Impact of geoengineering schemes on the global hydrological cycle. *Proceedings of the National Academy of Sciences of the United States of America* 2008,105:7664–7669.
74. Keith D, Parson E, Morgan M. Research on global sunblock needed now. *Nature* 2010, 463:426–427.
75. Kellogg W, Schneider S. Climate stabilization: for better or for worse? *Science* 1974,186:1163–1172.
76. Bunzl M. Geoengineering harms and compensation. *Stanford Journal of Law, Science, and Policy* 2011, 4:69–75.
77. Robock A. Will geoengineering with solar radiation management ever be used? *Ethics, Policy, Environment* 2012, 15:202–205.
78. Dworkin R. What is equality? *Philosophy and Public Affairs* 1981, 10:185–246.
79. Sen A. *Choice, Welfare and Measurement*. Cambridge, MA: Cambridge University Press; 1982.
80. Robock A. Twenty reasons why geoengineering might be a bad idea. *Bulletin of the Atomic Sciences* 2008, 64:14–18.
81. Mercado L, Bellouin N, Sitch S, Boucher O, Huntingford C, Wild M, Cox P. Impact of changes in diffuse radiation on the global land carbon sink. *Nature* 2009: 458, 1014–1017.
82. Axon C, Lubansky A. Stripping CO_2 from air requires largest industry ever. *New Scientist* Available at: http://www.newscientist.com/article/mg21428593.800-stripping-co2-from-air-requires-largest-industry-ever.html. (Accessed July 4, 2012).
83. Latham J, Rasch P, Chen C, Kettles L, Gadian A, Gettelman A, Morrison H, Bower K, Choularton T. Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds. *Philosophical Transactions of the Royal Society A* 2008, 366:3969–3987.
84. Burns W. Climate geoengineering: solar radiation management and its implications for intergenerational equity. *Stanford Journal of Law, Science & Policy* 2011, 4:39–55.
85. Robock A, Bunzl M, Kravitz B, Stenchikov L. Atmospheric science: a test for geoengineering? *Science* 2010, 327:530–531.

86. Chen I, Hill J, Ohlemüller R, Roy D, Thomas C. Rapid range shifts of species associated with high levels of climate warming. *Science* 2011, 333:1024–1026.

87. Geo-engineering the climate: buying time to decarbonize the world. *Strategic Direction* 2010, 26:35–38.

88. Institute of Physics, Geoengineering: Challenges and global impacts, 2009. Available at: http://www.iop.org/publications/iop/2009/file_44080.pdf. (Accessed July 9, 2012).

89. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller H, eds. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York: Cambridge University Press; 2007.

90. Siegenthaler U, Sarmiento J. Atmospheric carbon dioxide and the ocean. *Nature* 1993, 356:119–125.

91. Le Quéré C, Rödenbeck C, Buitenhuis E, Conway T, Langenfelds R, Gomez A, Labuschagne C, Ramonet M, Nakazawa T, Metzl N, Gillet N., Heimann M. Saturation of the southern ocean CO_2 sink due to recent climate change. *Science* 2007, 316:1735–1738.

92. Fleming J. *Fixing the Sky: The Checkered History of Weather and Climate Control*. New York; 2010.

93. Erle E. The planet of no return. *Breakthrough Journal* 2011, 2. Available at: http://breakthroughjournal.org/content/authors/erle-ellis/the-planet-of-no-return.shtml. (Accessed July 7, 2012).

94. Galarraga M, Szerszynski B. Making climates: solar radiation management and the ethics of fabrication. In Preston C, ed. *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press; 2012, 221–236.

95. Moreno-Cruz J, Ricke K, Keith D. A simple model to account for regional inequalities in the effectiveness of solar radiation management. *Climatic Change* 2012, 110:649–668.

96. Bracmort K, Lattanzio R, Barbour E. *Geoengineering: Governance and Technology Policy* (US Congressional Research Service Report). Available at: www.fas.org/sgp/crs/misc/R41371.pdf.

97. Renforth P. The potential of enhanced weathering in the UK. *International Journal of Greenhouse Gas Control* 2012, 10:229–243.

