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Review

Geoengineering the climate: an overview and update

By J. G. Shepherd*

School of Ocean and Earth Science, National Oceanography Centre, University of Southampton, European Way, Southampton SO14 3ZH, UK

The climate change that we are experiencing now is caused by an increase in greenhouse gases due to human activities, including burning fossil fuels, agriculture and deforestation. There is now widespread belief that a global warming of greater than 2°C above pre-industrial levels would be dangerous and should therefore be avoided. However, despite growing concerns over climate change and numerous international attempts to agree on reductions of global CO_2 emissions, these have continued to climb. This has led some commentators to suggest more radical 'geoengineering' alternatives to conventional mitigation by reductions in CO_2 emissions. Geoengineering is deliberate intervention in the climate system to counteract man-made global warming. There are two main classes of geoengineering: direct carbon dioxide removal and solar radiation management that aims to cool the planet by reflecting more sunlight back to space. The findings of the review of geoengineering carried out by the UK Royal Society in 2009 are summarized here, including the climate effects, costs, risks and research and governance needs for various approaches. The possible role of geoengineering in a portfolio of responses to climate change is discussed, and various recent initiatives to establish good governance of research activity are reviewed.

Key findings include the following.

— Geoengineering is not a magic bullet and not an alternative to emissions reductions.
— Cutting global greenhouse gas emissions must remain our highest priority.
  (i) But this is proving to be difficult, and geoengineering may be useful to support it.
— Geoengineering is very likely to be technically possible.
  (i) However, there are major uncertainties and potential risks concerning effectiveness, costs and social and environmental impacts.
— Much more research is needed, as well as public engagement and a system of regulation (for both deployment and for possible large-scale field tests).

*j.g.shepherd@noc.soton.ac.uk

One contribution of 12 to a Discussion Meeting Issue 'Geoengineering: taking control of our planet's climate?'.

— The acceptability of geoengineering will be determined as much by social, legal and political issues as by scientific and technical factors.

Some methods of both types would involve release of materials to the environment, either to the atmosphere or to the oceans, in areas beyond national jurisdiction. The intended impacts on climate would in any case affect many or all countries, possibly to a variable extent. There are therefore inherent international implications for deployment of such geoengineering methods (and possibly also for some forms of research), which need early and collaborative consideration, *before* any deployment or large-scale experiments could be undertaken responsibly.

Keywords: geoengineering; climate change; governance; uncertainty

1. Introduction

It is not yet clear whether, and if so when, it may become necessary to consider deployment of geoengineering to augment conventional efforts to moderate climate change by mitigation, and to adapt to its effects. However, global efforts to reduce emissions have not yet been sufficiently successful to provide confidence that the reductions needed to avoid dangerous climate change will be achieved. There is a serious risk that sufficient mitigation actions will not be introduced in time, despite the fact that the technologies required are both available and affordable [1]. It is likely that global warming will exceed 2°C this century unless global CO_2 emissions are cut by at least 50 per cent by 2050, and by more thereafter [2]. There is no credible emissions scenario under which global mean temperature would peak and then start to decline by 2100. Unless future efforts to reduce greenhouse gas emissions are much more successful than they have been so far, additional action such as geoengineering may be required should it become necessary to cool the Earth at some time during this century.

Proposals for geoengineering or climate intervention[1] are numerous and diverse, and for the Royal Society study [3], we deliberately adopted a broad scope in order to provide a wide-ranging review. There has been much discussion in the media and elsewhere about possible methods of geoengineering, and there is much misunderstanding about their feasibility and potential effectiveness and other impacts. The overall aim of the study was therefore *to reduce confusion and misinformation, and so to enable a well-informed debate* among scientists and engineers, policy-makers and the wider public on this subject.

The working group that undertook the study was composed of 12 members, mainly scientists and engineers, but also, including a sociologist, a lawyer and an economist. The members were mainly from the UK, but included one member from the USA and one from Canada, and the study itself had an international remit. The working group members were not advocates of geoengineering, and held a wide range of opinions on the subject, ranging from cautious approval to serious scepticism.

[1]The term geoengineering is widely used, but the terms *climate intervention, climate engineering, Earth system engineering* and *climate remediation* or *restoration* are preferred by some authors: all are here regarded as synonymous.

The *terms of reference* for the study were *to consider, and so far as possible evaluate,* proposed schemes for moderating climate change by means of geoengineering techniques, and specifically:

— to consider *what is known, and what is not known,* about the *expected effects, advantages and disadvantages* of such schemes;
— to assess their *feasibility, efficacy, likely environmental impacts* and any *possible unintended consequences*; and
— to identify *further research requirements*, and any specific *policy and legal implications.*

The scope adopted included any methods intended to moderate climate change by deliberate large-scale intervention in the working of the Earth's natural climate system, but *excluded*:

— low-carbon energy sources and conventional methods for reducing emissions of greenhouse gases;
— carbon capture and storage at the point of emission; and
— conventional afforestation and avoided deforestation schemes

because these are either not regarded as geoengineering *per se* and/or they have been extensively considered elsewhere [4].

2. General issues

The methods considered fall into two main classes, which differ greatly in many respects, including their modes of action, the time scales over which they are effective, their effects on temperature and on other important aspects of climate, so that they are generally best considered separately. These classes are:

— *carbon dioxide removal* (CDR) techniques that address the root cause of climate change by removing greenhouse gases from the atmosphere and
— *solar radiation management* (SRM) techniques that attempt to offset the effects of increased greenhouse gas concentrations by reflecting a small percentage of the sun's light and heat back into space.

CDR methods reviewed in the study include:

— land-use management to protect or enhance land carbon sinks;
— the use of biomass for carbon sequestration as well as a carbon neutral energy source;
— acceleration of natural geological weathering processes that remove CO_2 from the atmosphere;
— direct engineered capture of CO_2 from ambient air; and
— the enhancement of oceanic uptake of CO_2, for example, by fertilization of the oceans with naturally scarce nutrients, or by increasing upwelling processes.

SRM techniques would take only a few years to have an effect on climate once they had been deployed, and could be useful if a rapid response is needed, for example, to avoid reaching a climate threshold. Methods considered in the study include:

- — increasing the surface reflectivity of the planet, by brightening human structures (e.g. by painting them white), planting of crops with a high reflectivity, or covering deserts with reflective material;
- — enhancement of marine cloud brightness (reflectivity);
- — mimicking the effects of volcanic eruptions by injecting aerosol particles (e.g. sulphates) into the lower stratosphere; and
- — placing shields or deflectors in space to reduce the amount of solar energy reaching the Earth.

The spatial scale of the impact required to ameliorate climate change is global, and its magnitude is large. To have a practically useful effect on man-made global warming by an SRM method, one would need to achieve a negative radiative forcing of a few watts per square metre, and for an effective CDR method, one would need to remove several billion tonnes of carbon per year from the atmosphere for many decades.

There are many criteria by which geoengineering proposals need to be evaluated, and some of these are not easily quantified. For the Royal Society study [3], we undertook only a preliminary and semi-quantitative evaluation of the more promising methods according to our judgement of several technical criteria, namely, their *effectiveness*, *affordability*, *safety* and *timeliness*. The cost estimates available are extremely uncertain, and it would be premature to attempt any detailed cost–benefit analysis at this time.

3. Technical aspects: feasibility, cost, environmental impacts and side effects

The study concluded that geoengineering of the Earth's climate is very likely to be technically possible. However, the technology to do so is barely formed, and there are major uncertainties regarding its effectiveness, costs and environmental impacts. If these uncertainties can be reduced, geoengineering methods could potentially be useful in the future to augment continuing efforts to mitigate climate change by reducing emissions. Given these uncertainties, it would be appropriate to adopt a precautionary approach: and more and better information will be required to enable potential risks to be assessed, and either avoided or accepted. Potentially useful methods should therefore be the subject of more detailed research and analysis, especially on their possible environmental impacts (as well as on technological and socio-economic aspects).

In most respects, CDR methods would be preferable to SRM methods because they effectively return the climate system to a state closer to its natural pre-industrial state, and so involve fewer uncertainties and risks. Of the CDR methods assessed, none has yet been demonstrated to be effective at an affordable cost, with acceptable side effects. In addition, removal of CO_2 from the atmosphere only works very slowly to reduce global temperatures (over many decades). If safe and low-cost methods can be deployed at an appropriate scale, they could eventually make an important contribution to reducing CO_2 concentrations and could provide a useful complement to conventional emissions reductions. They would also address the ocean acidification problem, and it is possible that they could eventually even enable future *reductions* of atmospheric CO_2 concentrations.

CDR methods that remove CO_2 from the atmosphere without perturbing natural systems, and without large-scale land-use change requirements, such as CO_2 capture from air (and possibly also enhanced geochemical weathering) are likely to have fewer side effects. Techniques that sequester carbon but have land-use implications (such as biomass-based methods, including biochar and soil-based enhanced weathering) may be useful contributors on a small scale although the circumstances under which they are economically viable and socially and ecologically sustainable remain to be determined. The extent to which methods involving large-scale manipulation of ecological systems (such as ocean fertilization) can sequester carbon affordably and reliably without unacceptable environmental side effects is not yet clear.

SRM techniques are expected to be relatively cheap and would take only a few years to have an effect on the climate once deployed. However, there are considerable uncertainties about their consequences and additional risks. It is possible that in time, assuming that these uncertainties and risks can be reduced, that SRM methods could be used to augment conventional mitigation. However, the large-scale adoption of SRM methods would create an artificial, approximate and potentially delicate balance between continuing increased greenhouse gas concentrations and reduced solar radiation, which would have to be maintained, potentially for many centuries. It is doubtful that such a balance would really be sustainable for such long periods of time; particularly, if emissions of greenhouse gases were allowed to continue or even increase. The implementation of any large-scale SRM method would therefore introduce additional risks and so should only be undertaken for a limited period, and in parallel with conventional emissions reduction and/or CDR methods.

Of the SRM techniques considered, stratospheric aerosol methods appear to have the most potential because they should be capable of producing large and rapid global temperature reductions, as their effects would be more uniformly distributed than for most other methods, and they could be probably be fairly readily implemented. However, there are potentially significant side effects and risks associated with these methods that would require detailed investigation, even before large-scale experiments were undertaken. Cloud brightening methods are likely to be less effective and would produce primarily localized temperature reductions, but they may also prove to be readily implementable, and should be testable at small scale with fewer governance issues than other SRM methods. Space-based SRM methods would provide a more uniform cooling effect than surface- or cloud-based methods, and if long-term geoengineering is required, might eventually become a more cost-effective option than the other SRM methods, although development of the necessary technology would be likely to take many decades.

4. The human dimension and international aspects

The acceptability of geoengineering is likely to be determined as much by social, legal, ethical and political issues as by scientific and technical factors. The climate of the Earth has already been modified on a global scale by climate change, and geoengineering technologies would further modify it, by design. There are therefore serious and complex national and international governance issues that would need to be resolved if geoengineering is ever to become an acceptable method for moderating climate change (as there are already in implementing reductions of CO_2 emissions).

There are no existing international treaties or bodies whose remit covers all the potential methods, but some could potentially be handled by the extension of existing treaties, rather than creating wholly new ones (although this may not be easy). An example of this is the successful extension of the remit of the London Convention and Protocol to cover ocean fertilization research. It would be highly undesirable for geoengineering methods, which involve activities or effects that extend beyond national boundaries (other than simply the removal of greenhouse gases from the atmosphere), to be deployed before appropriate governance mechanisms are in place. Some geoengineering methods could conceivably be implemented by just one nation acting independently, and some maybe even by corporations or individuals. The consequences would however affect all nations and all people, and even though the intended overall effect may be positive (to ameliorate climate change), neither the intended nor the unintended side effects are likely to be uniform. There are likely to be both winners and losers, and any deployment should therefore be subject to robust governance mechanisms. Nevertheless, there remains potential for unilateral action by any technologically capable nation or organization. In the case of CDR methods, this could have only an incremental effect, which for *contained* methods (e.g. air capture, but not ocean fertilization) could be regarded as non-threatening and requiring little governance; at least until such time as it became possible to *reduce* the atmospheric CO_2 concentration (after which it would be necessary to reach international agreement on the level to which it should be reduced to, e.g. 350 or 280 ppm or some other level, etc.). However, unilateral action is much more likely to involve premature deployment of SRM technology in response to a perceived climate threat, of which loss of Arctic summer sea-ice cover, perceived impacts on equatorial rainfall systems (monsoons), and Mediterranean or Amazonian drying are all obvious and plausible candidates. It is not clear what international mechanisms, if any, would be capable of preventing or managing such an intervention.

The most appropriate way to create effective governance mechanisms (for both research and development and deployment) therefore needs to be determined, and a review of existing bodies, treaties and mechanisms should be initiated as a high priority.

5. Recent developments

There has been a number of other relevant meetings, publications and other developments, since the Royal Society report was published in September 2009 [3]. Some of the most significant of these are as follows.

— In the UK, the Research Councils, led by the Engineering and Physical Sciences Research Council, established a small seed-corn research programme on climate geoengineering. The funding available is £3M over a 3 year period (i.e. 3% of that suggested in the Royal Society report [3]) and has been allocated to two projects [5].

— Also in the UK, the House of Commons Select Committee on Science and Technology undertook an enquiry on the regulation of geoengineering. The report is available [6] as is the government response [7], which makes extensive reference to the recommendations of the Royal Society report [3].
— Governance issues in relation to geoengineering research were considered at a major international conference on climate intervention technologies held at Asilomar, CA, USA in March 2010. A summary statement from the Scientific Organising Committee and a full report are available [8].
— The UK Natural Environment Research Council [9] undertook a public dialogue exercise entitled 'Experiment Earth', to elicit views on possible future funding for research, and has published a report on the results.
— In the USA, the House of Representatives Committee on Science and Technology held three public hearings, of which the Chairman's report is now available [10]. The US Congressional Research Service [11] and the US Government Accountability Office [12] have also recently released related reports.
— The US National Commission on Energy Policy, which is a project of the US Congressional Bipartisan Policy Center, has carried out an extended study on geoengineering and climate change. The report has been published [13] and recommends that a substantial US research programme should be established.
— The Royal Society, in partnership with the Academy of Sciences for the Developing World and the Environmental Defense Fund launched an SRM governance initiative to facilitate and promote wider international and multi-sectoral consideration of governance issues, which arise especially in relation to SRM technologies. A first report has been published [14].
— In October 2010, the United Nations (UN) Convention on Biological Diversity (CBD) adopted a resolution on geoengineering at its COP10 meeting in Nagoya, Japan. The core of the text of the resolution is

> ... Invites Parties and other Governments ... to consider the guidance below ... (w) Ensure ... that no climate-related geoengineering activities that may affect biodiversity take place ... with the exception of small scale scientific research studies that would be conducted in a controlled setting in accordance with Article 3 ... and are subject to a thorough prior assessment of the potential impacts on the environment.
>
> [15, para. 8(w)]

The resolution therefore seeks to prevent premature deployment of risky geoengineering technology while permitting suitably regulated research. The meaning of 'a controlled setting' is unclear, but the reference to Article 3 implies that research studies would be subject to national jurisdiction, and that trans-boundary impacts should be avoided. The resolution is advisory rather than prescriptive, and the wording is also ambiguous. As written, it would rule out activities that would affect biodiversity positively as well as those that would have adverse effects, which is presumably not its intent. Its impact on future geoengineering research activity is uncertain, but the CBD has since established a liaison group of experts to consider the implications for biodiversity in more detail [16].

6. Principal conclusions and recommendations

Geoengineering has received considerable public and media attention in the past few years, and excites strong opinions, both for and against both its consideration as a policy option, and research into potential methods. Despite this and the considerable number of meetings held and studies that have been undertaken, the volume of actual research and the amount of hard new information that is becoming available remain small. The uncertainties remain and the conclusions reached by the Royal Society study [3] remain valid. They may be summarized as follows.

— The safest and most predictable method of moderating climate change is to take early and effective action to reduce emissions of greenhouse gases. No geoengineering method can provide an easy or readily acceptable alternative solution to the problem of climate change. Geoengineering is not a magic bullet and it is not an alternative to emissions reductions.
— Cutting global greenhouse gas emissions must remain our highest priority. Parties to the UN Framework Convention on Climate Change should make increased efforts towards mitigating and adapting to climate change, and in particular to agreeing to global emissions reductions of at least 50 per cent by 2050 and more thereafter. Nothing now known about geoengineering options gives any reason to diminish these efforts.
— Geoengineering is very likely to be technically possible. However, there are major uncertainties and potential risks concerning effectiveness, costs and social and environmental impacts. Further research and development should be undertaken to investigate whether low-risk methods can be made available if it becomes necessary to reduce the rate of warming this century. This should include appropriate observations, the development and use of climate models, and carefully planned and executed experiments. An expenditure of around £10M per year for 10 years would be an appropriate initial level for a UK contribution to an international programme, to which one would hope that the European Union and the USA would also contribute a substantially larger amount.
— The acceptability of geoengineering will be determined as much by social, legal and political issues as by scientific and technical factors. Much more research on these is needed, as well as public engagement and development of a system of regulation (for both potential deployment and for possible large-scale field tests). The governance challenges posed by geoengineering should be explored in more detail by an appropriate international body (e.g. the UN Commission for Sustainable Development), and processes should be established for the development of policy mechanisms to resolve them.
— Some geoengineering methods of both types would involve release of materials to the environment, either to the atmosphere or to the oceans,

possibly in areas beyond national jurisdiction. The intended impacts on climate would in any case affect many or all countries, possibly to a variable extent. There are therefore inherent international implications for controlling the deployment of such geoengineering methods (and possibly also some forms of research), which need early and collaborative consideration, *before* any deployment or large-scale experiments could be undertaken responsibly.

While some progress has been made on some issues (as summarized earlier), in the absence of funding for research at anything like the (rather modest) level proposed, it is unlikely that the uncertainties will be sufficiently resolved before the need for some form of geoengineering technology becomes urgent.

References

1 Stern, N. 2007 *The economics of climate change: the Stern review*. Cambridge, UK: Cambridge University Press.

2 Intergovernmental Panel on Climate Change (IPCC). 2007 Climate change 2007: the physical science basis. In *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. D. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquie, K. B. Averyt, M. Tignor & H. L. Miller). Cambridge, UK: Cambridge University Press.

3 Royal Society. 2009 'Geoengineering the climate: science, governance and uncertainty': Royal Society Policy Document 10/09. See http://royalsociety.org/policy/publications/2009/geoengineering-climate/.

4 IPCC. 2005 *IPCC special report on carbon dioxide capture and storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change (eds J. T. Houghton, Y. Ding, D. J. Griggs, M. Nouger, P. J. van der Linden & D. Xiaosu). Cambridge, UK: Cambridge University Press.

5 Engineering and Physical Sciences Research Council. 2010 Climate geoengineering sandpit. See http://www.epsrc.ac.uk/funding/calls/2010/Pages/climategeoengsandpit.aspx.

6 House of Commons. 2010 Select Committee on Science & Technology report: the regulation of geoengineering. See http://www.publications.parliament.uk/pa/cm200910/cmselect/cmsctech/221/22102.htm.

7 Department for Energy and Climate Change. 2010 Government response to the House of Commons Science and Technology Committee 5th report of session 2009–10: the regulation of geoengineering. See http://www.official-documents.gov.uk/document/cm79/7936/7936.pdf.

8 Climate Response Fund. 2010 The Asilomar conference: recommendations on principles for research into climate engineering techniques. See http://www.climateresponsefund.org/images/Conference/finalfinalreport.pdf.

9 Natural Environment Research Council. 2010 Report of public dialogue on geoengineering 'Experiment Earth'. See http://www.nerc.ac.uk/about/consult/geoengineering-dialogue-final-report.pdf.

10 US House of Representatives. 2010 Committee on Science & Technology, Chairman's report Engineering the Climate: Research Needs and Strategies for International Collaboration. See http://www.whoi.edu/fileserver.do?id=74967&pt=2&p=81828.

11 US Congressional Research Service. 2010 Geoengineering: governance and technology policy. See http://www.fas.org/sgp/crs/misc/R41371.pdf.

12 US Government Accountability Office. 2010 Climate change: a coordinated strategy could focus federal geoengineering research and inform governance efforts. See http://democrats.science.house.gov/Media/file/Reports/GAO_ClimateChangeandGeoengineering.pdf.

13 Bipartisan Policy Center. 2011 Geoengineering: a national strategic plan for research on the potential effectiveness, feasibility, and consequences of climate remediation technologies. See http://www.bipartisanpolicy.org/sites/default/files/BPC%20Climate%20Remediation%20Final%20Report.pdf.

14 Solar Radiation Management Governance Initiative. 2011 Solar radiation management: the governance of research. See http://www.srmgi.org/report/.

15 Convention on Biological Diversity. COP 10, Decision X/33. See http://www.cbd.int/decision/cop/?id=12299.

16 Convention on Biological Diversity. 2011 Report of the Liaison Group meeting on climate-related geo engineering as it relates to the Convention on Biological Diversity. See http://www.cbd.int/doc/meetings/cc/lgcrg-eng-01/official/lgcrg-eng-01-05-en.pdf.