# Geoengineering the climate: Science, governance and uncertainty

## Responses to call for evidence

## Part VI

**ETC GROUP**

**Author:** Jim Thomas

6th April 2009

Dear Members of The Royal Society Working Group on Geoengineering,

I am writing on behalf of the ETC Group (Action Group on Erosion, Technology and Concentration). We are a non-profit international organization based in Canada that undertakes research and advocacy work. We monitor emerging technologies and corporate strategies relevant to the protection of biodiversity and the interests of marginalized groups. In January 2007 we published one of the first papers looking at geoengineering from a civil society perspective - entitled "Gambling with Gaia". We have since been monitoring developments in the field with increasing concern.[1]

We are grateful that the Royal Society is willing to accept a submission at this late stage in its proceedings. We regard this submission as an urgent matter, for we are alarmed at the apparent emergence of an "official view", most recently articulated by the UK House of Commons Committee on Innovation, Universities, Science and Skills[1] , which is prepared to sanction real-world geoengineering experiments despite complete absence of any global rules or regulations. We find that emerging view complacent, irresponsible and dangerous. This short note outlines six points on the question of geoengineering governance that no study concerned with policy-making in this critical area should ignore:

1) Governance of the sector must be universal, globally and unanimously agreed, accountable and inclusive.
2) Its scope must reach beyond the climate crisis.
3) It must remain consistent with the precautionary principle
4) Private sector interests will distort geoengineering governance
5) The line in the sand is real world experiments.
6) Ocean fertilization as a bellweather for precaution.

These points are expanded upon in the attached paper and we trust that the Working Group members will give these points careful attention. We thank you in advance for your consideration and please do not hesitate to contact us if you have any need for clarification or explanation.

Yours Sincerely,

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Jim Thomas
ETC Group

**Six Points on Geoengineering Governance**
*Prepared by the ETC Group – April 2009*

**1) Governance Arrangements For Geoengineering Must be Universal, Globally and Unanimously Agreed, Accountable and Inclusive.**

There is almost no exercise of power more overwhelming than claiming the technological means to restructure the entire planet. If such means appear even mildly feasible, governments will pay dearly for that power and wars will be waged to control the relevant technologies and research agendas. Many commentators have emphasized the imbalance between the global reach that geo-engineers aspire to for their technologies and the potential for individual actors, wealthy people, single states or a "coalition of the willing" to unilaterally deploy these measures[2]. Just as the current distribution of political power in the global order reflects the ownership and development of nuclear weapons, so states and others

claiming to own - or almost own andwilling to countenance - geoengineering technologies, even if developed for "peaceful purposes", will deploy those claims as a pawn in geopolitical games. Even if they are never deployed or even proven to work, geoengineering technologies will have a profound impact on the security interests of all states and all peoples. Given the dual-use implications of geoengineering technologies, any decision-making must be unanimous, transparent, accountable and global.

If any of the technologies currently in the research stage was actually deployed at full scale, the direct impact on people would be widespread. This is true by definition, since the goal of geoengineering is to alter planetary-scale phenomena such as the carbon cycle and atmospheric dynamics. From our observations, most geoengineering proposals are inherently transboundary - sulphate aerosols spread across the globe on high winds, fertilized plankton blooms shift with the tides and clouds move and interact with other aspects of the weather system. In many cases, the technologies target the global commons of the oceans, the polar regions, the atmosphere, outer space or the genetic commons of plants and microbial species. Decisions over these commons must be taken with all interests at the table.

In the few cases where a geoengineering proposal at first appears "local" or "regional" the issue of scale will quickly elevate it to the global level. Some biochars, for example, may well prove harmless in small-scale applications. However, as soon as they are scaled up to a level that can sequester significant quantities of atmospheric CO2, biochar production processes will inevitably use unsustainable amounts of biomass[3]. This poses a global threat since ecological studies have documented that human appropriation of the biosphere has already exceeded the safe limits for the proper functioning of ecosystems.[4] Air-capture devices for sequestering carbon dioxide might appear static and local in impact. However, if enough CO2 is subsequently sequestered in a geological formations to counteract warming, it poses a risk of badly undoing mitigation efforts should those gases ever escape[5]. Seen this way, carbon capture and storage schemes present as great a risk as radioactive waste disposal and point therefore to the need for some legitimate means of global oversight and agreement. New norms governing these issues are necessarily the product of international negotiations, by all nations, not simply those with geoengineering research and development capabilities. Recommendations from the working group should speak to this global governance dimension. A unilateral governance regime by the UK or US Governments, the European Union or the OECD is not an acceptable option.

ETC Group commends the Royal Society in having the courage to address the full suite of geoengineering proposals together. In so far as these technologies have a unity of purpose and vision we believe any governance proposals advanced should also point towards a unified framework for tackling this field as a whole. We have seen with the early political battles over ocean fertilization that even one geoengineering technique can challenge the mandates of several different international bodies, which in turn can be played against each other as protagonists claim legitimacy for the forum that best suits their interests. Shoe-horning the governance of individual technologies into different treaties and institutions not originally designed with geoengineering in mind will likely lead to very limited and inequitable outcomes – a patchwork of rules and regulations that will be easy to skirt around. For example the International Maritime Organization's London Convention and Protocol on the Dumping of Hazardous Wastes at Sea has taken an interest in ocean fertilization [6]. It is, however, limited by its narrow mandate on environmental marine pollution and it cannot legally weigh the impact of the practice on livelihoods of fisherfolk, dual use implications, the modification of weather systems via DMS gas production or the implications of patenting and ownership of ocean fertilization techniques. Rather than allow geoengineering governance to fragment into many ill-fitting containers that cannot properly grapple with its complexity or depth, we encourage the working group to advocate for a single accessible and responsible international forum that can meet the challenge head on. The Working Group should recommend a process under the auspices of the United Nations to take this process forward, where a diversity of views and interests can be heard and whose rules can be universally – or almost universally – applied.

In one technological controversy after another, it has become clear that governance processes that privilege techno-scientific knowledge and perspectives above all other forms of knowledge often deliver inequitable, unsafe and poorly informed judgments.[7] Types of knowledge and perspectives typically excluded by such expert-driven processes (but highly relevant to geo-engineering) include indigenous knowledge of land and wildlife, the knowledge of weather, soils and vegetation held by farmers, the knowledge of oceans and weather developed by fisher-folk and so forth. Failure to solicit and incorporate these forms of knowledge in the past has led to conflict and poor decisions on nuclear waste, synthetic chemicals, hybrid seeds, genetically modified organisms, trawler fishing, biofuels and more. The

Working Group will be well aware that, as a relatively closed expert-driven group convened by an elite science organization, it is incumbent not to replicate those limitations in any proposals put forward. Opening decision-making to more diverse actors representative of wider publics allows for more robust and nuanced governance outcomes.

**2) The Scope of Geoengineering Governance Must Reach Beyond the Climate Crisis.**

By extending the scope of governance beyond climate change we mean two things: (1) keeping in mind geoengineering technologies which have purposes other than climate change mitigation or adaptation and (2) not neglecting impacts on people and eco-systems which are not directly related to global warming.

ETC Group is acutely aware that conclusions reached by the Royal Society at a particular historical moment may shape governance arrangements for years or even decades to come. Often those governance arrangements reach beyond the technologies under consideration to further iterations or analogous technologies that may even be difficult to imagine today.[8] While this Working Group has limited its remit to "climate geo-engineering", we draw your attention to the fact that actions emanating from Royal Society recommendations may shape governance for all geoengineering technologies - not just those related to climate change.

The present focus of geoengineering efforts to counteract global warming, can easily obscure the fact that, historically, geoengineering plans were primarily military[9]. We can see the emergence of geoengineering scale proposals that aspire to address the world water crisis, the global oversupply of reactive nitrogen and the acidification of the world's oceans. [10]We could further imagine geoengineering proposals to "fix" the ozone holes, guarantee the food supply and protect the planet and its population from asteroids and tsunamis. We therefore urge the Working Group to adopt a longer-term perspective when proposing governance actions and to acknowledge that any institutional arrangements developed now for climate geoengineering will likely be later extended or applied to encompass other geoengineering schemes .

Again, this points to the need to tailor the international governance architecture to examine the full social, economic and envirommental impacts of the development of these new technologies in a broader context than just climate change. Various pieces of our existing international law are relevant and have a wider remit: the 1977 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD treaty)[11] ; the Convention on Biological Diversity; the UN Commission on Sustainable Development and the UN General Assembly to name a few. We recommend against handing oversight of geoengineering governance to bodies with a narrow climate and atmospheric focus since this may prove too limited down the road (eg UN Framework Convention on Climate Change or the Montreal Protocol).

The profile and interest generated by geoengineering is the result of a well-deserved sense of urgency around climate change. However, the climate crisis needs to be addressed in concert with other emergencies -- such as global hunger, species extinction, ecosystem destruction, over-appropriation of biomass and ocean acidification. These crises warrant careful attention in considering future harms and the efficacy of particular schemes to counteract anthropogenic global warming. An exclusive focus on climate change as the one overriding consideration by which a particular scheme succeeds or fails is short-sighted and one-sided. Indeed, it is governance decisions driven by such a narrow vision that have propelled society to this point of desperation where geoengineering seems to many to be a viable option. From here on we should seek out governance structures and processes that are much more inclusive, open and long-term in their vision.

**3) Geoengineering Governance Must Remain Consistent with the Precautionary Principle**

Contemporary controversies over risk governance of emerging technologies frequently devolve to a routine stand-off between protagonists advocating the precautionary principle and technology enthusiasts offering some version of what has been called "the proactionary principle". This is already the case in the emerging debate over geoengineering where civil society groups have called for these technologies to be halted via moratoria (eg biochar and ocean fertilization[12]) while geoengineering advocates have argued that a failure to develop these technologies will have catastrophic consequences.

We urge the members of the Working Group to consider this values conflict carefully, to look beyond crude characterizations of these positions and to examine the origins of these formalized attitudes towards risk.

ETC Group strongly advocates that governance associated with geoengineering be founded on the precautionary principle. This is a well-established instrument in international environmental agreements usefully elaborated upon in the European Commission's Communication on the Precautionary Principle (2000). The precautionary principle is a simple but profound commitment affirming that when an activity raises threats of harm to human health or the environment, precautionary measures should be taken, even if causality has not been fully established scientifically. All definitions of the precautionary principle contain the following three core elements: (1) When there is reasonable threat of harm (2) and scientific uncertainty (3) we have a duty to act to prevent harm. At this point we can only identify only one common geoengineering proposal[13] that doesn't readily meet these criteria .

The value of the precautionary principle has been extremely well-established in the field of climate change policy, and was invoked as an overriding rationale for global action on emissions reduction long before the IPCC had definitively established a causal link between human activities and global warming. Indeed the Maastricht Treaty of 1992 requires that all European Union environmental policy - thereby including climate change and future geoengineering policy - be "based on the precautionary principle". Precaution implies more than just "doing nothing". It means setting goals, monitoring effects, considering all the evidence and consequences, heeding early warnings of harm, engaging affected persons in democratic decision-making, choosing safer alternatives and more. [14]

In contrast, the so-called "proactionary principle", largely developed by transhumanist libertarian Max More, posits that freedom to innovate is overwhelmingly critical to human survival[15]. It therefore establishes a high threshold of scientific certainty necessary for opponents of an activity to prevent any innovation. In our experience, this ideological stance is most often employed by industrial interests defending a product or a new technology against controversy. . Supporters of geoengineering claim that society must allow geoengineering technologies to develop because we may have already passed significant tipping points which only radical innovation can amend [16]. Such a position, however, is itself contradictory. It both embraces the precautionary principle in demanding radical action on climate change (that we have passed the tipping points is not scientifically proven) and then rejects precaution in claiming that even the possibility of negative impacts should not forestall development of risky geoengineering technologies. ETC Group notes that the Royal Society has shown admirable support for the Precautionary Principle in previous enquiries and urges the Working Group to remain consistent with these precedents.[17]

**4) Private Sector Interests Will Distort Geoengineering Governance**

ETC Group is alarmed that much of the current interest in geoengineering proposals and particularly the pressure for real-world experiments are being driven by commercial interests and the rise of new markets in carbon and environmental services. For example, in the past few years, we have seen several attempts to carry out ocean fertilization activities by private companies (GreenSea Ventures, Planktos Inc and Ocean Nourishment Corporation) each seeking to make profit by selling voluntary carbon offsets and win fishing rights. A fourth commercial ocean fertilization company, Climos Inc. of San Francisco, is currently investing a significant portion of its multimillion dollar capital in seeking to influence governance processes to its own advantage. It has stated it will also be channeling its funds towards academic scientists to carry out experimental research on its behalf[18]. ETC Group views this as an attempt to "buy" scientific support.

Many in the oceanographic community, including supporters of ocean fertilization, have spoken out against the sale of carbon credits, pointing out that such offsets license emissions increases against unverifiable sequestration techniques. Writing in the journal Science in 2001, Sallie Chisholm, Paul Falkowski and John Cullen first called for ocean fertilization to become ineligible for carbon credits[19], a position echoed in 2008 when 16 scientists wrote that it was premature to sell offsets from ocean fertilization experiments[20]. In May 2008 the Ninth Conference of Parties to the Convention on Biological Diversity agreed to a de facto moratorium on ocean fertilization that explicitly prohibited activities "for generating and selling carbon offsets or any other commercial purposes"[21]. ETC Group believes that that the presence of private companies and their financial backers in this sphere will always skew scientific

assessments and governance decisions in favour of outcomes that maximize profit rather than environmental safety, justice or climate protection.

What is true for ocean fertilization is becoming true across all fields of geo-engineering. The International Biochar Initiative[22], supported by carbon trading companies, agribusiness interests and commercial pyrolysis firms are pushing for inclusion of biochar-amended soils in the Clean Development Mechanism of the Kyoto Protocol and are developing standards for the sales of voluntary offsets long before biochar has been proven as a viable carbon sequestration technology. A typical company operating commercially in this field is Mantria Industries which sells a char product, Eternagreen, produced from municipal waste, sewage sludge and old tires that has not been evaluated for long-term impact on soils.[23] Similar financial offset mechanisms are being proposed for radiative forcing projects. Alvia Gaskill of the Global Albedo Enhancement Project has proposed developing "thermal credits" for geoengineering schemes that reduce the atmosphere's radiative budget.[24]

Equally of concern is the impact of the private Virgin Earth Prize, announced by airline and spaceflight tycoon Richard Branson in 2007[25]. This attempts to emulate the successful X-prize model by offering $25 million (US),the world's largest science prize, for a team who can demonstrate a geoengineering technique enabling continuous net removal of CO2 from the earth's atmosphere. Such privately run commercial prizes exist to spur investment and development of geoengineering technologies by "have-a-go" entrepreneurs. The prize also exists as a public relations exercise by an airline and spaceflight company looking to distract attention from its own significant climate change impacts. Neither motivation represents a careful, precautionary or responsible approach to research and development of this field. ETC Group urges the Working Group to look critically at the presence of commercial entities engaging in geoengineering activities, to condemn the use of commercial prizes in this sphere as irresponsible, and to recommend that no offsets, credits, fishing rights or other financial instruments be bought or sold from existing geoengineering technologies.

**5) The Line in the Sand is Real World Experiments.**

While the Working Group has many aspects of geoengineering to consider we believe your final report will be largely judged by how you handle one overriding question: Should real-world geoengineering experiments proceed at this time? We note with concern that some members of the Working Group[26] are already calling for research efforts to cross the controversial line from observing nature and modeling geoengineering scenarios in-silico to in-situ trials of geoengineering technologies (should we say "in-geo"?) . How the Royal Society handles this matter in its report will signal whether the group has been able to take an impartial, considered and responsible view.

ETC Group opposes more real-world experiments in the current governance vacuum. We regard directly interfering with the soils, skies and seas of the planet for geoengineering purposes as unwise and unnecessary Seen alongside the full set of possible responses to anthropogenic climate change, we regard geoengineering as a wrong and dangerous avenue, towards which further political will and resources will only be squandered. Our research shows that all geoengineering technologies, by virtue of being extremely large-scale, highly centralized and with latent military uses will always deliver unjust and authoritarian outcomes. We further believe that the illusion of a "technofix" just around the corner serves as an all too-convenient excuse for the powerful and comfortable to drag their heels and refrain from making the urgent changes (mostly societal changes) that are required to actually reverse the climate crisis. In a sane and sensible world, the geoengineering option would not be on the table at all, and nobody in their right mind would be agitating for experiments.

Instead we note that such agitation is ramping up and that even seemingly respectable bodies, including the UK House of Commons Committee on Innovation, Universities, Science and Skills have proposed increases in research budgets for geoengineering in a manner that casually gives the nod to real-world experimentation.[27] We believe that crossing this line from in-silico to in-geo geoengineering is a grave and epochal step. To endorse such a step lightly, especially without appropriate governance in place, is reckless and irresponsible and we strongly urge the Working Group to refrain from adopting such a position.

Geoengineering cannot be conscionably deployed without a global agreement governing these technologies. However there are those who appear to presume that geoengineering activities, when labeled as science, constitute something short of deployment and therefore can proceed in the absence

of any legitimate international debate, let alone comprehensive governance arrangements. To observers of previous science controversies, this is an all too familiar proposition. Proponents of industrial whaling practice this form of "scientific exceptionalism" when they hunt protected whales in the Southern Oceans under the guise of "scientific whaling". Proponents of genetically modified crops practice the same double standard when they carry out environmental releases of novel engineered crops, animals or microbes and then exempt them from regulatory review by labeling them as experiments. The closest analogy to what is now occurring with geoengineering is to be found in the history of nuclear weapons testing - a technology which enjoys the same dual-use status as geoengineering technologies. From 1945 until the Limited Test Ban Treaty was signed in 1963, hundreds of atmospheric and underwater nuclear tests, some for supposedly "peaceful purposes", were carried out without a global treaty in place and despite massive protests. These dispersed isotopes of plutonium, cesium, strontium, iodine-131 and other deadly elements killing livestock, sickening civilians, causing leukemia, cancer, genetic deformities and heightening Cold War tensions. Estimates of human deaths, illnesses and casualties resulting from American, Soviet, British, French and Chinese nuclear tests run in the hundreds of thousands.[28]

In the realm of geoengineering there are proposals, such as dispersing nano-particulate matter in the stratosphere, whose geographic reach will exceed that of an atmospheric nuclear test since particles at that height can circulate the globe in a matter of months. There are proposals, such as altering the acidity of the world's oceans by adding silicates or other methods, which if they go the wrong way, could rival the ecological disruption of an undersea nuclear explosion. Such methods cannot be recalled once they are deployed. We believe it would be unconscionable for the Royal Society to make any statement suggesting such methods could move ahead to trials without strong governance.

There are proposals that may initially appear suitable to carry out in a relatively contained manner (eg. plots of biochar-amended soils, albedo enhancement of land and plants, deposition of biomass at sea). However, because geoengineering is by definition large-scale, any small-scale tests will always be regarded as inadequate and pressure will come to bear to move swiftly to larger-scale (and therefore more problematic) interventions. This dynamic has been evident in the case of ocean fertilization where in the wake of 13 smaller, unpromising real-world tests, a small minority are now vocally arguing for the area of impact to be scaled up, claiming that small-scale tests are not scientifically useful to infer the real efficacy of this technique. Had the previous 13 tests delivered more positive results, there would still have been pressure for a scale-up. Hence the actual outcome of any set of geoengineering experiments is irrelevant to the trend to bigger and bigger scale. Diplomats at the the London Convention and the Convention on Biological Diversity are now struggling to choose an imaginary line where ocean fertilization experiments become "large scale", thereby requiring oversight. This struggle could and should be simply resolved by formulating global rules that apply to all and any activities at any scale. Where the intent is to geo-engineer the planet whether now or in the future, any interference with the real world should demand oversight.

We understand that there have already been regrettable instances of real-world geoengineering experiments (most notably in the fields of ocean fertilization, weather modification and biochar). The Royal Society should look to take stock and re-set norms rather than feel obliged to legitimize past mistakes. ETC Group recommends a moratorium on real world geoengineering experiments at any scale, at least until just governance arrangements are established.

**6) Ocean Fertilization as a Bellweather for Precaution.**

In ETC Group's view the Working Group's comments on ocean fertilization will be seen as a bellweather for how seriously the Working Group takes the precautionary principle. There have now been 13 real world experiments in ocean fertilization with dismal results. None have sequestered carbon at anything close to the efficiency of a natural plankton bloom. There is plenty of literature suggesting a reasonable threat of environmental harm - whether via deep ocean anoxia, promotion of harmful algal species (especially in the case of urea) and production of greenhouse and cloud-forming gases.[29] There are clear statements from the Convention on Biological Diversity, the UN Commission on the Law of the Sea and the London Convention and Protocol urging "utmost caution"[30] and far stronger calls for a complete halt to ocean fertilization activities arising from civil society including environmental NGOs and fisherfolk organizations.[31]

ETC Group believes that the Working Group should reflect on the wider meaning of the recent LOHAFEX debacle: Planned for 3 years by leading oceanographers, with the initial support of two national

governments at a cost of several million dollars, untainted by commercial interests, LOHAFEX was not only one of the largest and best-planned experiments to date, it was a last ditch effort to show that ocean fertilization might have some lingering value. That it failed so spectacularly to actually sequester any carbon dioxide[32] is not merely "unlucky" but a sobering reflection on the viability of the technique as a whole. LOHAFEX may have contributed some interesting science on crustacean population dynamics but we echo the reported sentiment of Dr. Ken Caldeira who explained that LOHAFEX represented "The last gasps of ocean iron fertilization as a carbon-storage strategy."[33] In the interests of precaution (and to paraphrase Monty Python) we believe the Working Group would do well to now pronounce this strategy fully dead: passed on.. no more.. ceased to be.. an ex-strategy. [34]

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[1] See Gambling with Gaia at http://www.etcgroup.org/en/materials/publications.html?pub_id=608. ETC Group since been active mainly on the question of ocean fertllization and has issued a number of press releases on related topics. See for example: The better world we seek is not Geo-engineered! A Civil Society Statement against Ocean Fertilization as well as press releases on specific ocean fertilization projects at http://www.etcgroup.org/en/issues/geoengineering.html. See also "Technofixes: Climate Solution or Corporate Scam: a Debate with Jim Thomas and Paul Fitzgerald" in the New Internationalist, August 2008 at http://www.newint.org/features/special/2008/08/01/technofixes/

[2] David G. Victor (2008). "On the regulation of geoengineering". Oxford Review of Economic Policy (Oxford University Press) 24 (2): 322–336.

[3] For discussion of biomass requirements of Biochar as a geoengineering schemes see Section 5 of Almuth Ernsting and Deepak Rughani (2008) "Climate Geo-engineering with 'Carbon Negative' Bioenergy", Biofuelwatch UK - available online at http://www.biofuelwatch.org.uk/docs/cnbe/cnbe.html

[4] Loh J, Collen B, McRae L, Carranza TT, Pamplin FA, Amin R, & Baillie JEM (2008) Living Planet Index (ed Hails C). Living Planet Report 2008. WWF, Gland, Switzerland.

[5] Emily Rochon (2008) "False Hope: Why carbon capture and storage won't save the climate, Greenpeace. available online at http://www.greenpeace.org/international/press/reports/false-hope

[6] IMO RESOLUTION LC-LP.1 (2008) ON THE REGULATION OF OCEAN FERTILIZATION (ADOPTED ON 31 OCTOBER 2008) available online at http://www.imo.org/includes/blastDataOnly.asp/data_id%3D24255/16.pdf

[7] see for example B Wynne, May the sheep safely graze? A reflexive view of the expert-lay knowledge divide. Risk, Environment and Modernity: Towards a New Ecology, 1996.

[8] See for example the discussion on how previous technologies controversies shape governance decisions on subsequent technologies in Kearns, M., Grove-White, R., Macnaghten, P., Wilsdon, J. & Wynne, B. From Bio to Nano: Learning the Lessons, interrogating the Comparison. Science as Culture. 2006;15:291-307.

[9] James Fleming, "The Climate Engineers," Wilson Quarterly (Spring 2007)

[10] Large Dam schemes, re-routing rivers and large-scale desalination might all be considered geo-engineering reponses to the water crisis and deployment of crops or bacteria genetically engineered to improve notrogen fixation could be geoengineering responses to the nitrogen crisis. On ocean acidification see for example Jeremy Elton Jacquot,"Giving Geo-Engineering Another Go: Dumping Limestone into the Oceans to Fight Acidification" - http://www.treehugger.com/files/2008/05/limestone-ocean-acidification.php

[11] Susana Pimiento and Edward Hammond (2002), "A Political Primer on the Environmental Modification Convention (ENMOD)" - http://www.sunshine-project.org/enmod/primer.html

[12] See Calls by Civil Society against BioChar and ocean fertilization:
"The better world we seek is not Geo-engineered! A Civil Society Statement against Ocean Fertilization" - March 2009 - available online at http://www.etcgroup.org/en/materials/publications.html?pub_id=727 and "Biochar, a New Big Threat to People, Land and Ecosystems" released April 2009 - available online at http://www.regenwald.org/international/englisch/news.php?id=1226

[13] The one geo-engineering scheme that does not appear to offer any evidence of harm is the suggestion to paint roofs and pavements white - see Akbari, H. 2008, "Global Cooling: Increasing World-wide Urban Albedos to Offset CO2", Heat Island Group Ernest Orlando Lawrence Berkeley National Laboratory, presetation to the Fifth Annual California Climate Change Conference, Sacramento, CA 9 September 2008

[14] A good source for interpretive scholarship on the precautionary principle is The Science and Environmental Health Network (SEHN) - http://www.sehn.org/precaution.html

[15] Max More (2005) "The Proactionary Principle" - available online at http://www.maxmore.com/proactionary.html

[16] see for example John Nissen, Stephen Salter, John Latham et al (March 2009) "Open letter to Dr Rajendra K. Pachauri, IPCC chair" available online atr http://geo-engineering.blogspot.com/2009/03/open-letter-to-dr-pachauri.html

[17] see THE ROYAL SOCIETY AND THE ROYAL ACADEMY OF ENGINEERING, NANOSCIENCE AND NANOTECHNOLOGIES: OPPORTUNITIES AND UNCERTAINTIES p69 section 8.2 (5) (2004)

[18] "Climos proposes to fund a team of scientists from the international academic/research community who are familiar with the science associated with OIF experiments." http://www.climos.com/faq.php#10

[19] Chisholm S, Falkowski P and Cullen J (2001) Oceans: Dis-crediting ocean fertilization. Science, 294, 309-310

[20] Buesseler, K.O., Doney,S.C., Karl, D.M., Boyd, P.W., Caldeira, K., Chai, F., Coale, K.H., de Baar, H.J.W., Falkowski, P.G., Johnson, K.S., Lampitt, R.S., Michaels, A.F., Naqvi, S.W.A., Smetacek, V., Takeda, S., Watson, A.J., 2008. Ocean iron fertilization--Moving forward in a sea of uncertainty. Science 319 (5860), 162. DOI: 10.1126/science.1154305

[21] The decision of the Conference of the Parties to the CBD on ocean fertilization can be found here: http://www.cbd.int/decisions/cop9/?m=COP-09&id=11659&lg=0
[22] see http://www.biochar-international.org/
[23] see http://www.eternagreen.com/
[24] Alvia Gaskill "Summary of Meeting with U.S. DOE to Discuss Geoengineering Options to Prevent Abrupt and Long-Term Climate Change" Juen 29th 2004. Available online at http://www.see.ed.ac.uk/~shs/Climate%20change/Geo-politics/Gaskill%20DOE.pdf
[25] see http://www.virginearth.com/
[26] for example see Ken Caldeira "We should plan for the worst-case climate scenario" Bulletin of Atomic Scientists - 29 July 2008. http://www.thebulletin.org/web-edition/roundtables/has-the-time-come-geoengineering#rt3845
[27] UK House of Commons Select committee on Innovation, Universities, Science and Skills (2009) "Engineering: Turning ideas into reality" Geoengineering Case Study.
[28] .Glenn Alan Cheney, They Never Knew: The Victims of Nuclear Testing. Impact Books , 1996.
[29] for a critical technical overview of the failure of past ocean fertilization experiments see Allsopp, M., Santillo, D., Johnston, P. (2007), A scientific critique of oceanic iron fertilization as a climate change mitigation strategy,
[30] see "OCEAN FERTILIZATION: A compilation of international statements, agreements and recommendations" - Prepared and submitted to London Convention by UNEP
[31] "The better world we seek is not Geo-engineered! A Civil Society Statement against Ocean Fertilization" - March 2009 - available online at http://www.etcgroup.org/en/materials/publications.html?pub_id=727
[32] National Institute of Oceanography (India) and Alfred Wegener Institute, "LOHAFEX provides surprising insights on plankton ecology that dampen hopes of using the Southern Ocean to sequester atmospheric CO2" 23 march 2009. Available online at http://www.nio.org/projects/narvekar/Lohafex_press_release_23_03_09.pdf
[33] Catherine Brahic "Hungry shrimp eat climate change experiment" New Scientist 25 March 2009. Availabel onlien at http://www.newscientist.com/article/dn16842-hungry-shrimp-eat-climate-change-experiment.html?DCMP=OTC-rss&nsref=online-news
[34] With Apologies to Monty Python's Dead Parrot Sketch - see http://en.wikipedia.org/wiki/Dead_Parrot

**THE GRANTHAM INSTITUTE FOR CLIMATE CHANGE**

**Author:** Brian Hoskins

We will only address albedo-based geo-engineering.

Our understanding of the climate system and ability to model it is sufficiently good that we can say with great confidence that by continuing to increase the level of greenhouse gases in the atmosphere we are performing a very dangerous experiment with planet Earth. However our abilities are presently very limited to understand the impacts of climate change at a regional and decadal scale (though it should continue to increase with further research). Our current confidence in projections of the likely climate impact of proposed geo-engineering schemes aimed at energy compensation is at an even more rudimentary level.

These proposals are in general based on attempting to bring the global energy budget into balance by compensating the reduced long-wave emission from Earth by a reduction the absorbed solar radiation. Even if this is attainable, there would still be an energy imbalance regionally and in time. The climate impact could still be very large, regionally and perhaps globally. The fact that the orbital parameter changes that are thought to trigger the cycle between glacial and interglacial periods lead to predominantly a redistribution of solar radiation rather than a net global change shows how crucial this could be.

Nor would such proposals deal with other aspects of carbon dioxide emissions. The acidification of the ocean and the consequent impacts of this would continue to increase.

The international legal framework for handling geo-engineering and getting agreement to perform it would, we think, make the Kyoto process look easy! However the real danger is rather the reverse –such schemes could easily be done unilaterally imposing another externality on the rest of the world. If one country could act, might others then shoot the mirrors down? It certainly heightens risks of conflict over climate change solutions.

Despite these negative comments, we firmly believe that it is vital that the understanding of the climate system and the ability to make projections of it should improve rapidly to give the best possible guidance for mitigation, adaptation and geo-engineering. This will involve giving the science and the funding of it a profile at least comparable with other large international ventures.

The two proposals with the most credibility are those for increasing low-level cloudiness through the spraying of droplets and for decreasing the transmission through the stratosphere by putting particles there. Understanding and being able to simulate clouds, and their sensitivity to the weather structures in which they are embedded and to aerosol number and nature, is vital for all aspects of the climate problem as well as for evaluating the first proposal. The same comment applies to chemistry interacting with the physical processes in the stratosphere and the modelling of the whole system for the second proposal. Therefore there is no major requirement for separate large-scale funding streams for geo-engineering research, which would be a dangerous diversion of resources and effort. There could, however be a need for limited special investigations.

**GREENPEACE**

**Author:** Doug Parr and David Santillo

**Greenpeace evidence to Royal Society on Geo-engineering**

**Summary**
Geoengineering enters a highly politically charged context where action on reducing greenhouse gas emissions is being opposed and watered down. The concept creates a 'moral hazard' that we will not take the safest and most sustainable options available for countering climate change if faced with the promise, however speculative and potentially unfounded, that the task of avoiding dangerous climate change can be delegated to consortia of geo-engineers..
Given the enormous uncertainties and indeterminacies which surround both the ability of proposed planetary manipulations to bring about positive change and our ability to avoid harmful unintended side effects, geoengineering should not be viewed as a desirable or sustainable response to climate change mitigation. If it is deemed necessary to use geo-engineering techniques for purposes of legitimate scientific research, then any such research propositions should be evaluated and managed by an international committee of experts under UN auspices, using a consistent and precautionary set of criteria to assess not just the technical aspects but also the social, political and economic aspects of the impacts of the research.

**Submission**
Greenpeace is a campaigning organization which has as its main objective the protection of the natural environment. Greenpeace has offices in 40 countries, 2.8 million supporters worldwide and around 150,000 in the UK. It is independent of governments and businesses, being funded entirely by individual subscriptions.
Greenpeace was one of the first organizations to campaign for action to be taken to halt anthropogenic climate change. It has built up considerable expertise and has access to independent expertise on the links between energy use and climate change. The expertise includes scientific knowledge, economics and analysis of state subsidy, as well as understanding of how the development of traditional approaches to energy can have detrimental effects on the development of new, cleaner technology to combat climate change.
This submission will address itself predomiantly to the political and economic context in which geo-engineering research will operate, and the policy framework that should guide it.
It is widely recognised that climate change is the gravest threat presently faced by humanity. The most important greenhouse gas in terms of anthropogenic radiative forcing is carbon dioxide. The 4th Assessment Report from the IPCC[2]presented the firmest evidence yet that the threat of severe climate change impacts means the economies of the developed world must be decarbonised within such a rapid timeframe that radical action is necessary. We have less than a decade in which to slow, stop and reverse the trend of rising greenhouse gas emissions if we are to avoid the worst impacts of climate change.
An average rise in global temperature of 2°C above pre-industrial temperatures is widely regarded as the limit beyond which irreversible climate change impacts will occur. Global greenhouse gas emissions, primarily carbon dioxide, have already generated a rise of 0.7°C and the inbuilt lag in the earth's atmospheric system means we are already committed to a further rise of approximately 0.7°C. It is therefore clear that the window of opportunity to limit global temperature rise below 2°C is closing swiftly. The very latest evidence from the UK Met Office's Hadley Centre confirms the necessity to act very swiftly to cut emissions[3].
The context is clearly that global emissions need to be on a downward path before a further decade has passed – developed country emissions need to be declining immediately. Yet in UK CO2 emissions have barely gone down the past decade. This is despite obvious technical and policy measures that could deliver energy and carbon saving including better management of heat, product standards on appliances and vehicles, better support to renewable energy technologies, proactive policy to deal with the poor thermal quality of the UK building stock etc. Much or all of this critique could be applied to EU and North America. In

[2] Intergovernmental Panel on Climate Change (IPCC) (2007), Fourth Assessment Report: Climate Change 2007: Synthesis Report - Summary for Policymakers
http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf
[3] Vicky Pope, Hadley Centre, Met Office 'Degrees of Caution', Guardian, October 1 2008
http://www.guardian.co.uk/environment/2008/oct/01/climatechange.carbonemissions

other words, the most effective ways of dealing with climate change are not being adopted owing to a lack of political will and commitment to tackling the greatest long-term threat to humanity.

It is also clear that action is being impeded by vested interests including the industries that profit from the status quo. This has been most visible in the case of Exxon[4], vehicles[5], energy intensive industries[6] – other examples of effective industry lobby to avoid environmental protection are from chemicals regulation[7]. Even this month challenges to weaken rules on the EU Emissions Trading Scheme – the preferred low-cost compliance option which is the cornerstone of EU Emissions reduction plans – came from governments representing coal based industry[8]. The reason for this political activity by companies is straightforward – it prevents change that would otherwise undermine their commercial position. Time, money, effort and innovation which could be dedicated to solving the climate crisis are instead dedicated to its maintenance.

Thus the concept of 'geo-engineering' enters a highly charged political and economic context where change on climate policy grounds will create winners and losers. At a societal level we have a 'moral hazard'[9] in that the promise of geo-engineering, however speculative, reinforces behaviour that makes its need more likely. The wider point is not the pros and cons of particular technologies, but that the scientific community is becoming so scared of our collective inability to tackle climate emissions that such outlandish schemes are being considered for serious study. We already have the technology and know-how to make dramatic cuts in global emissions - but it's not happening, and those closest to the climate science are coming near to pressing the panic button. A focus on tinkering with our entire planetary system is not a dynamic new technological and scientific frontier, but an expression of political despair.

Consequently, Greenpeace believes that there need to be very strict conditions attached to research into any potential candidates for geo-engineering. Specifically;

1. All propositions for geo-engineering research must be evaluated using strict and precautionary sets of rules, including scientific, legal and policy components, developed and overseen by international cross-disciplinary advisory committees set up under UN auspices. Scientific expertise needs to include ecology, engineering and life cycle analysis. Political components need to have at the very least regional and stakeholder representation. Legal compliance with international agreements would be a necessity.
2. There need to be pre-set criteria for environmental and social acceptability
3. Actual geo-engineering should be prohibited except for research agreed through the international governance arrangements. No payments should be considered through, e.g. CDM, before sign off by these committees.

Criteria in (2) need to recognize that not every proposition is necessarily environmentally damaging, but there are features of the risks associated with their implementation.

1. Ideas which remove $CO_2$ and other gases from the atmosphere by physical means are less interventionist that those which use existing ecosystems, and deliver more effective change than those which try to 'reflect' heat. In addition to climate change, $CO_2$ also causes ocean acidification which will potentially have serious impacts on the marine ecosystems and on coastal communities. Ocean fertilization as a mitigation strategy, whether with iron or other nutrients, could exacerbate this problem, damage marine ecosystems and even result in increased emissions of other, biogenic greenhouse gases. A Note published on iron fertilization published last year by the Greenpeace International Science Laboratory is submitted as an appendix.
2. Large scale intervention in natural ecosystems is generally perturbing systems that we do not understand with the potential for widespread, unpredictable and long-lasting adverse consequences. It should be subject to the precautionary principle.
3. There needs to be a thorough understanding of the life-cycle impacts of any propositions.

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[4] http://www.exxposeexxon.com/
[5] http://www.euractiv.com/en/transport/meps-side-carmakers-co2-cuts/article-175032
[6] http://www.euractiv.com/29/images/Turmes%20European%20Spring%20Council%202008-Background_tcm29-170918.doc
[7] http://www.greenpeace.org/raw/content/international/press/reports/toxic-lobby-how-the-chemical.pdf
[8] http://euobserver.com/9/26901
[9] http://en.wikipedia.org/wiki/Moral_hazard

This approach and criteria are suggested because of the context in which geo-engineering ideas are being raised. It is a much better option for society as a whole to use *existing* technology and policy to reduce emissions rather than attempt the potentially dangerous approaches that geo-engineering propositions represent. Public money and policy focus is better spent on this than on speculative and potentially risky geo-engineering ideas.

Doug Parr & David Santillo
11/12/08

**HEAT ISLAND GROUP, LAWRENCE BERKELEY LABORATORY**
**Author:** Hashem Akbari

Dear Andrew,

Attached please find

1. a paper titled: Akbari, H., S. Menon, and A. Rosenfeld, "Global Cooling: Increasing World-wide Urban Albedos to Offset CO2," Climatic Change, DOI 10.1007/s10584-008-9515-9, 2008.

2. A short summary of the paper.

In your solicitation, you request a summary (not to exceed 4 pages).

I am wondering if you could review these attached documents and let me know about any additional information that I can provide so that an "International Cool Cities" program will be selected on top of the list of Royal Society for global geo-engineering.

White roofs save energy in air conditioned buildings and improve comfort in non-conditioned buildings.

White roofs and reflective pavements improve urban comfort and reduce urban smog.

Using white roofs and reflective pavements in urban areas can cool the world equivalent to offsetting 44GT of CO2 emissions.

White roofs and reflective pavements typically do not incur any additional cost.

White roofs and reflective pavements have been tested for thousands of years.

What are we waiting for? It is time to mobilize the world under this white flag.

Respectfully,
Hashem

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**Research Highlights**
**LBNL Heat Island Group**
September 20, 2008
**White Roofs Cool the World, Offset CO2 and Delay Global Warming**

As the threat of global warming becomes widely recognized, scientists have proposed using geoengineering (manipulation of the Earth's environment) to quickly respond to this threat. Most proposed geo-engineering techniques are novel and unproven. Two simple technologies that have been around for thousands of years, cool roofs and cool pavements, should be the first geoengineering techniques used to combat global warming.

Increasing the solar reflectance of urban surfaces reduces their solar heat gain, lowers their temperatures, and decreases their outflow of thermal infrared radiation into the atmosphere. This process of "negative radiative forcing" counters global warming. In a recent study to be published in journal *Climatic Change*, Akbari, Menon and Rosenfeld have calculated the CO2 offset, or equivalent reduction in CO2 emission, achieved by increasing the solar reflectance of urban surfaces[10].

Most existing flat roofs are dark and reflect only 10 to 20% of sunlight. Resurfacing the roof with a cool white material that has a long-term solar reflectance of 0.60 or more increases its solar reflectance by at least 0.40. Akbari *et al.* estimate that so retrofitting 100 m2 (1000 ft2) of roof offsets 10 tonnes of CO2 emission. Emitted CO2 is currently traded in Europe at about $25/tonne, making this 10-tonne offset worth $250.

It is fairly easy to persuade (or to require) the owners of buildings to select white materials for flat roofs, and in California this has been required since 2005.[11] However, the demand for white *sloped* roofs is limited in North America, so California compromises by requiring only "cool colored" surfaces for sloped roofs. (This rule takes effect in July 2009.) Use of cool-colored surfaces increases solar reflectance by about 0.20 and yields a CO2 offset of about five tonnes per 100 $m^2$, or about half that achieved with white surfaces. The solar reflectance of pavement can be raised on average by about 0.15, offsetting about four tonnes of CO2 per 100 $m^2$.

Over 50% of the world population now lives in urban areas, and by 2040 that fraction is expected to reach 70%. Pavements and roofs comprise over 60% of urban surfaces (roofs 20 to 25%, pavements about 40%). Akbari *et al.* estimate that permanently retrofitting urban roofs and pavements in the tropical and temperate regions of the world with solar-reflective materials would offset 44 billion tonnes of emitted CO2, worth $1.1 trillion at $25/tonne.

How can the reader visualize this *one time* offset of 44 billion tonnes of CO2? If the average car emits 4 tonnes of CO2 each year, permanently increasing the solar reflectance of urban roofs and pavements worldwide would offset 11 billion car-years of emission. This is equivalent to taking the world's billion cars off the road for 11 years. The offset provided by cooling urban surfaces affords us a significant delay in climate change during which we can take further measures to improve energy efficiency and sustainability.

Akbari *et al.* propose an international campaign to use solar reflective materials when roofs and pavements are initially built or resurfaced in temperate and tropical regions. They point out that such an international "cool cities" program is a win, win, win proposition. It is well known that cool roofs reduce cooling-energy use in air conditioned buildings and increase comfort in unconditioned buildings (win #1). The authors have also shown that cool roofs and cool pavements mitigate summer urban heat islands, improving outdoor air quality and comfort (win #2). Now, their latest research shows that cool roofs and cool pavements can cool the entire globe (win #3).

Installing cool roofs and cool pavements in cities worldwide does not require delicate international negotiations about capping CO2 emission rates. An international cool cities program can be used as a model to organize the world's efforts to mitigate global warming.

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[10] Akbari, H., S. Menon, and A. Rosenfeld. 2008. "Global cooling: increasing solar reflectance of urban areas to offset CO2," In press, *Climatic Change*. Hashem Akbari is a senior scientist (email H_Akbari@lbl.gov, phone +1-510-486- 4287) and Surabi Menon (email SMenon@lbl.gov , phone +1-510-486-6752) is a scientist with the Lawrence Berkeley National Laboratory. Arthur Rosenfeld is a commissioner with the California Energy Commission (email Arosenfe@energy.state.ca.us, phone +1-916-654-4930).

[11] California has justified cool roofs based on cooling energy saving alone. White roofs save building's cooling-energy use by about 20% (and hence directly reduce CO2 emissions from power plants). The estimated U.S. potential savings for white roofs are in excess of $1 billion per year in net annual energy bills (cooling-energy savings minus heatingenergy penalties). Cool roofs also reduce the summertime urban temperatures leading to an improved urban air quality.The combined effect of the energy and air-quality savings from increasing the solar reflectance of urban surfaces in the U.S. alone can exceed $2 billion per year. For urban dwellers worldwide savings would be huge.

Figure 1. Cool roofs (clockwise, Bermuda, Dallas, and Santorini) offset CO2 emissions and delay global warming. One hundred square meters (1000 ft2) of a white roof, replacing a dark roof, offset the emission of 10 tonnes of CO2.

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**IMPLICC STEERING COMMITTEE, MAX PLANCK INSTITUTE**
**Author:** Hauke Schmidt

**Statement on geoengineering, its potential uses, costs and side effects**

By the IMPLICC steering committee:
**Hauke Schmidt1, Asbjorn Aaheim2**, **Jon-Egill Kristjansson3**, **Mark Lawrence4**, **Michael Schulz5**, and **Claudia Timmreck1**
**1**: Max Planck Institute for Meteorology, Hamburg, Germany
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**IMPLICC: Implications and risks of engineering solar radiation to limit climate change**
IMPLICC is a small collaborative project that will be funded by the European Commission within the Framework Programme 7 (FP7) to study implications and risks associated with engineering solar radiation to limit climate change. The project is likely to start early in 2009.
This text is intended to answer the request of the UK Royal Society for views on the topic of geoengineering (also known as "novel options" for climate change mitigation).

In the following, we will
· provide a short introduction to the topic,
· discuss reasons why we think it is necessary to study the physical aspects of geoengineering with respect to effectiveness and side effects of different proposed methods,
· argue that for the proper understanding of effects and side effects of geoengineering, basic research on feedbacks in the climate system has to be continued,
· give a short overview on the status of research on three proposed methods to manipulate the Earth albedo, and
· make the point that a broad international discussion is necessary to address legal, ethical and economical aspects of geoengineering.

With the Kyoto protocol the United Nations took a first step to limit the anthropogenic increase of the atmospheric content of green house gases (GHGs) and thereby the projected climate change. Despite these attempts, carbon dioxide concentrations in the atmosphere have continued to rise. In order to prepare for possible failure of emission reduction measures put in place through international agreements, or other unexpected consequences such as an acceleration of climate change, the public and scientific communities begun more earnestly discussing the possibility of "geoengineering", meaning *the deliberate manipulation of the Earth system to manage the climatic consequences of human population and economic expansion* (Schneider, 2001). This discussion has been further intensified following an article by Crutzen (2006), in which he suggested considering and investigating methods of geoengineering Earth's climate in order to provide, if the need arises, sound scientific support to policy makers.
As pointed out by the UK Royal Society, geoengineering schemes may be grouped broadly into two categories: a) greenhouse gas reduction schemes, and b) albedo modification schemes. As the IMPLICC consortium has proposed to study only the latter category of schemes, we will also focus our discussion here on them. This does not imply we prefer these schemes over greenhouse gas reduction schemes.
Suggestions to modify the albedo have been criticized heavily because they try to cure some symptoms of global climate change and not its cause. By engineering incoming radiation it might be possible to limit global temperature increase; however, the acidification of oceans as a consequence of increasing CO2 levels would not be stopped. Another problem is the long lifetime of atmospheric CO2 that would make it necessary to sustain geoengineering for periods of hundreds to thousands of years if no other technical way to remove CO2 from the atmosphere were to be found.
On the positive side, part of the long-term perturbation of the carbon cycle might be suppressed by geoengineering if positive feedbacks between global warming and the carbon cycle are as important as

suggested in the recent IPCC report. Through such feedback mechanisms, the CO2 concentration might actually be reduced by geoengineering.
However, it is also possible that other, as yet unknown feedbacks could result in an increase in CO2 as a result of geoengineering. Substantial scientific research is needed to better understand such possibilities.
Political and psychological concern exists that the discussion of geoengineering options might distract or prevent societies from investing in technological developments, or behavioral changes, that will reduce the emission of GHGs in the first. We acknowledge this concern, and strongly support that priority is given to emission reduction. However, we should not limit the scope of research addressing itself to these critical issues, because we can not exclude that a geoengineering option may be required at some point; for instance to buy time in the phase of unforeseen but catastrophic changes to the climate system. As pointed out by Lawrence (2006): "if we do not conduct careful research now, we will not be prepared to advise politicians on how to best approach large-scale geoengineering applications – including providing sound information on the various risks involved." Scientific advice on a new technology with broad consequences such as geo-engeneering can not be expected to be available on short notice. The research should try to determine the efficacy and costs, but in particular the range and magnitude of anticipated side effects connected with different geoengineering schemes.
The IMPLICC consortium plans to perform numerical studies of the effectiveness, side effects and economical implications of three geoengineering schemes:
a) space borne reflectors (placed at the Lagrangian point between the Earth and sun);
b) sulphur injections into the stratosphere; and
c) engineering of low level marine clouds through sea salt injections;
which we discuss in turn below.

Over the last few years, a small number of groups have started to study the impact of geoengineering solar irradiance to limit climate change, using numerical simulations of the response of the atmosphere or the climate system to albedo modification schemes. However, numerical studies have mostly been performed with models that may be too simplified to fully assess important possible risks. Several studies have been performed by simply reducing the incoming solar radiation (e.g. Matthews and Caldeira, 2007). This would be the effect of space borne reflectors. Crutzen (2006) suggested studying the injection of large amounts of sulphur dioxide in Earth's stratosphere. Sulphate aerosol would build up, subsequently reflecting part of the solar radiation, thus changing the atmospheric energy budget and decreasing the temperature at the Earth's surface. This is analogous to the climate effect associated with big volcanic eruptions. The advantage of this scheme is that big volcanic eruptions may have similar climate effects, and in particular the relatively well observed Mt. Pinatubo eruption in 1991 may be considered as a test case. Studies have shown that an increased stratospheric sulphate aerosol loading leads to an enhanced loss of polar ozone (e.g. Tilmes at al., 2008) and impacts the hydrological cycle (e.g Robock et al., 2008). While the radiative and chemical effects of volcanic (or geoengineered) stratospheric sulphate aerosols seem to be quite well understood, possible dynamical effects, are less clear.
Another suggestion is the modification of low level marine cloudiness via the injection of additional condensation nuclei (e.g. Latham, 2002; Bower et al., 2006) that should lead to a brightening of the clouds. It is debated whether an enhancement of cloud albedo can be deliberately introduced that is sufficient to counteract current and future global warming.
Cloud-climate feedbacks belong to the most uncertain processes in our current understanding of climate change and introduce therefore a large source of uncertainty in numerical climate models.
These examples show that research on geoengineering requires a deep understanding of the functioning of the climate system. Therefore, not only studies specifically designed with respect to geoengineering are needed but also a continuation of the efforts to improve the basic understanding of the climate system. The other side of this coin is that research on the effects of geoengineering, if properly conducted, can advance our understanding of the climate system as a whole.
Numerical climate models are presently the only tools available for studying the climate evolution of the future under different emission and geoengineering scenarios. They will thus play an important role in future geoengineering research. They can, however, at best reflect the current state of knowledge on the climate system. Bengtsson (2006) has raised concern about inaccuracies of current numerical models that limit our capability to predict climate and to adequately study the consequences of geoengineering. Some of these deficiencies (different models show for instance different climate sensitivities), can be ameliorated by using a

coordinated multi-model approach by a larger community as it is currently already being done in the case of future climate projections for which the IPCC provides the framework. Nevertheless, we should be aware that even the most thorough numerical study does not guarantee an error-free climate projection. In plain terms, history has examples of the physical system responding to imposed perturbations in ways that are not anticipated by any of our models; the rapid and unanticipated decline of arctic sea-ice being a recent and familiar one.

The possible application of geoengineering schemes raises not only questions concerning the physical climate system, but also carries economical, legal, political and ethical implications.

The current basis for economic evaluations of geoengineering schemes is thin. A report from the National Academy of Sciences (1992) is one of very few references with suggestions about the costs of some alternative geoengineering options. Furthermore, implications for the costs and benefits have been discussed with reference to certain properties of geoengineering, but we have found no attempts to actually estimate the benefits in terms of climate change impacts. An apparently common view among economists that actually have dealt with geoengineering is that *costs are low*. This statement is based primarily on the abovementioned report from the National Academy of Sciences from 1992 but has been echoed in more recent publications (e.g. Nordhaus and Boyer, 2000). Barrett (2008) emphasizes that the perception of low costs gives countries a strong incentive to start experiments with geoengineering on their own; hence there is some urgency to the task of more fully considering the costs, including those attributable to the response of the physical system, associated with various geoengineering proposals.

Although it is not our field of expertise we think it should be mentioned that the issue of geoengineering raises vital questions about global governance, like the following: *Is any nation or group of nations allowed to intentionally modify climate on a global scale, since these modifications may be beneficial for some and detrimental for others, and since many of the side effects of such modifications cannot be predicted with any degree of certainty? Is there a political entity legitimated to decide on the application of the proposed novel options?*

These questions can only be discussed in an international framework that is as comprehensive as possible. Of course, similar questions relate to the unintended global effects of increased greenhouse gas concentrations to which different nations have contributed to a very different degree.

In the end, the question as to what to do cannot be separated from the broader international debate on climate; as many of the questions raised echo those that have long been considered in this broader context. And as is the case for the climate change discussion more broadly, our task as scientists is to ensure that such a discussion is based on the most complete understanding of the system that we are able to master. It is in this sense that we hope IMPLICC can make a contribution.

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**INSTITUTE FOR RESEARCH ON ENVIRONMENT AND SUSTAINABILITY AT NEWCASTLE UNIVERSITY**
**Author:** David Manning

**Geoengineering Climate**

**Response from the Institute for Research on Environment and Sustainability, Newcastle University**

**Engineering soils for climate change.**

*Contact: Professor David Manning, Director, Institute for Research on Environment and Sustainability, Newcastle University; david.manning@ncl.ac.uk*

In the context of the consultation, this response focuses on the role of managing the coupled plant-soil system as a way of removing $CO_2$ from the atmosphere. We are contributing to a second response from the UK Biochar Research Centre, based at Edinburgh University.

Both responses draw upon a common scientific theme.

**Summary.**

1) The coupled soil-plant system annually removes almost 10% of the carbon present in the atmosphere, returning that amount as photosynthetically-fixed C is mineralized during plant decay.
2) Artificial interception of this component of the carbon cycle is feasible, through adaptation of existing land management techniques.
3) Biochar addition to soils is one such process, with tremendous potential (see submission from UK Biochar Research Centre).
4) Carbonate mineral (especially calcite) precipitation in soils is a second process that takes place especially on urban soils rich in waste from demolition, but also on soils developed on calcium-silicate rich bedrock and superficial deposits derived from such bedrock.
5) The cement manufacture emissions cycle in principle can be closed by allowing concrete waste from demolition to carbonate in soils as a normal process within land remediation schemes.
6) Carbonate mineral precipitation in natural soils on calcium-silicate rocks can be encouraged through appropriate planting, in the UK as well as in more arid climates.
7) Research is needed to quantify the amount of carbonate that forms naturally in UK soils (rural and urban), so that this can be understood, managed and encouraged artificially.
8) Soils, managed appropriately, can be regarded as analogous to reedbeds for the passive remediation of polluted waters.
9) Soil management is inherently low risk compared with geoengineering that involves intervention in ocean and atmosphere chemistry and processes, and is likely to be readily acceptable by the public.
10) Soil management is the hallmark of human civilization; it is something we know how to do.

*1. What do you consider to be the current state of knowledge regarding the feasibility, efficacy and predicted impacts of climate geoengineering schemes?*

How can soils act as long term sinks for carbon? Each year, plants remove approximately 60 GT of carbon from the atmosphere through photosynthesis. On entering the soil system, decomposition of photosynthetically-fixed carbon returns a very similar amount to the atmosphere. It is striking that plants are capable, globally, of removing almost 10% of the 720 GT carbon that is in the atmosphere annually. Thus if we wish to geoengineer climate, one of the means to do that has to be by interception of the plant-soil carbon cycle to greatly enhance soil stocks of immobile carbon.

Carbon in soils turns over at different rates depending on the stability of organic matter and other hosts. Within soils, there are two forms of carbon that are stable on exceedingly long (geological) time scales:

i) Charcoal – a refractory form of carbon, produced naturally in forest fires since land plants first evolved (and found in coals; Scott and Glasspool, 2007), or produced artificially as a by-product

of bioenergy production (when it is known as biochar – see UK Biochar Research Centre submission).

ii) Calcium carbonate – precipitates of calcium carbonate within soils are known as pedogenic carbonates and are well known from soils in arid areas. Recent EPSRC-funded research has found pedogenic carbonates to occur in the UK in urban soils rich in dusts derived from concrete crushing, and in artificial soils formed by blends of compost and calcium-silicate bearing rocks (dolerite of the Whin Sill; Manning, 2008). Additionally, approximately 40% of the input carbon within putrescible matter going to landfill is fixed as calcite, much to the inconvenience of landfill site operators because of the disruption it causes to internal drainage systems (Van Gulck et al, 2003; Manning, 2001).

Human beings know how to manage soil – it is the mark of civilization. Thus if we are to find a way that offers quick, cheap, wins in the battle to compensate for the combustion of fossil fuels then as one of the tools at our disposal we should focus on land management that is designed to maximize carbon capture as charcoal or carbonate minerals.

Focusing on carbonate precipitation in soils, we are handicapped in the UK by deficiencies in the scientific information recorded for our soils. The calcium carbonate content is not rigorously recorded in analysis of soils of England and Wales, whereas it is to a much greater extent in Scotland. Thus a given soil series that crosses the border from Northumberland into Scotland has calcite north of the border, but none reported south of the border. At a time when we need to know much more about our soils than their ability to support crops, we are at a great disadvantage compared with those countries that use the USDA classification, which routinely has abundant chemical information.

Soil carbonate precipitation occurs at depths that increase with increasing rainfall (Jenny, 1980). In the UK, in areas that can support wheat, calcite precipitation might be expected at depths of around 1 meter, well within the reach of wheat roots. But we have only surveyed soils to 1m depth routinely. There is an abundance of information concerning soil function from greater depths of which we are ignorant, especially at the zone of interface between rock materials and soils.

Plant roots exude carbon into the soil system, Although controversial in terms of the amounts that plants produce individually (Ryan et al., 2001), very elegant work by Moulton et al (2000) in Iceland has shown that woodland can pump approximately as much carbon into the soil-groundwater system as is fixed annually in biomass. If sufficient calcium is also present, calcite will precipitate. Thus the problem with geoengineering soils to maximize calcite precipitation lies in ensuring that enough calcium is present.

*2. How do you think research into climate geoengineering should be taken forward, and by whom?*

Given the need for a multidisciplinary approach to the management of soils to promote carbon capture, research needs to be carried out by both universities and institutes. Only the universities have ready access to the different disciplines that are required, involving the sciences and the humanities (because social constructs define land-use just as much as technical factors). The monodisciplinary institutes (such as the British Geological Survey, the Soil Surveys of England and Wales, and Scotland) have a vital role to play in mapping soils from the point of view of quantifying carbon capture as carbonates (or char). Research institutes (such as Rothamsted) have an essential role to play in long term experimentation, and with the universities provide access to a diverse set of soil and cultivation types for experimental work.

Funding of research of this type falls across research council boundaries. Current work at Newcastle is funded mainly by EPSRC, partly because the focal point is investigation of urban soils produced artificially as a consequence of civil engineering operations. BBSRC could be regarded as an appropriate host for work on carbon capture in farmed systems. NERC focuses on natural environmental processes, and funds the survey work of the BGS. NERC has a role to play in investigating carbon capture in non-farmed soils, and especially on the interface between parent materials and soil processes that produce carbonate.

Because of the breadth of disciplinary inputs needed, a joint research council initiative within the context of *Living with Environmental Change* could be a suitable way forward. Because soil-plant interactions need several years to explore experimentally, the programme of work should last for at least 5 years. This is likely to require investment of at least £10 million over that period.

*3. What factors need to be considered before deploying any climate geoengineering schemes? Who should be responsible for any deployment?*

Clearly safety and efficacy are vital factors. The public needs to be satisfied that whatever is proposed is safe, to people and to the environment. Work with soils is likely to be highly acceptable to the public, because of the beneficial impacts to the rural environment that come through greater awareness of soil function. Additionally, recognition of the value of carbon capture within urban soils will enhance redevelopment of sites with a previous use (for example, the London Olympic site, at no extra cost, has the potential to capture as much carbon as a year's expensive injection of $CO_2$ into Sleipner). In addition, existing risk assessment methodology is held by the Environment Agency and DEFRA.

Deployment could be carried out in a number of ways:

i) Urban developers could be encouraged to design soil restoration/landscaping plans to maximize carbonate precipitation, in the same way that they are encouraged to maximize energy efficiency.

ii) Rural landowners/users could be encouraged to plant to maximize carbonate precipitation under existing guidance used by DEFRA.

*4. What do you consider to be the most important political, social, legal or ethical issues raised by climate geoengineering?*

It is completely unethical to ignore climate geoengineering. This approach provides the only means we have of removing a proportion of the $CO_2$ from the atmosphere that we have put there through the combustion of fossil fuels.

But climate geoengineering needs to be undertaken in ways that are wholly acceptable to the public. It should not place in jeopardy parts of the Earth system that we have no track record of controlling, including the oceans and ocean chemistry. We simply have no idea how the ocean will respond to artificial intervention on the scale that might be necessary. In contrast, we know very well how soils react to human intervention, and we know it is possible to correct mistakes made in soil management.

*5. What do you see as the main barriers to, and opportunities offered by, climate geoengineering?*

Barriers to climate goeengineering vary according to what is planned. Some techniques, such as land-use change are available for immediate action now. Others face barriers because they are still distant from practical use, and public confidence in them needs to be built.

The opportunities are enormous for soil-based geoengineering – in terms of sustaining or increasing employment in rural areas, in raising awareness of the dynamic interaction between soils, plants and the atmosphere, and in literal greening of the environment.

*6. Where do you feel that climate geoengineering fits in the greater scheme of climate research and action to mitigate and adapt to climate change?*

Climate geoengineering can be regarded as an extension of environmental engineering, which is well established as the practical interface between human society and the natural world – providing clean water

and cleaning up our liquid, solid and gaseous wastes. So climate engineering is part of the larger paradigm of Earth System Engineering – on a truly global scale. It is a solution to compensate for mankind's past use of fossil fuels. We need to act now to redress the problem of increased atmospheric $CO_2$ levels, but in order to address the cause of climate change we need to continue research to understand its geological history, its modern causes, and their sensitivity to human actions.

*7. Are there any other issues related to climate geoengineering that you consider to be important?*

None in addition to the above.

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**INSTITUTE OF PHYSICS**
**Author:** Peter Main

Dear Mr Parker
**Geoengineering climate**
The Institute of Physics is a scientific membership organisation devoted to increasing the understanding and application of physics. It has an extensive worldwide membership and is a leading communicator of physics with all audiences from specialists through government to the general public. Its publishing company, IOP Publishing, is a world leader in scientific publishing and the electronic dissemination of physics.
The Institute welcomes the opportunity to respond to the Royal Society's call for submissions to inform its study on geoengineering the Earth's climate. This response was prepared with input from the Institute's Energy Sub-group, which includes a range of leading physicists working across the energy sector. The Sub-group reports to the Science Board of the Council.
The attached annex highlights the Institute's response to the questions listed in the call for submissions.
If you need any further information on the points raised, please do not hesitate to contact me.
Yours sincerely
**Professor Peter Main**
Director, Education and Science

**Geoengineering climate**
The Institute welcomes the Royal Society's initiative to make an objective assessment of the scientific basis for the expected efficacy of and the possible undesired consequences of a range of concepts aimed at offsetting the effects of increases in levels of atmospheric carbon dioxide. In doing so, the Institute does not imply that current national and international efforts to reduce carbon dioxide emissions should thereby be reduced or delayed. The Institute does, however, consider that the world is ill-prepared for a conceivable situation in which global warming substantially exceeds the projections of present climate models or in which we find we are approaching a catastrophic climatic tipping point. The projected study should clarify the options that might be available in such eventualities and provide the beginnings of a basis for developing international contingency plans.

**1. What do you consider to be the current state of knowledge regarding the feasibility, efficacy and predicted impacts of climate geoengineering schemes?**
Currently, geoengineering as a subject has not received the wide and serious examination necessary for informed and critical assessment. In 2004, the Tyndall Centre and Cambridge-MIT Institute Symposium held an invitation-only meeting in Cambridge on macro-engineering options for climate change management and mitigation which was attended by an international group of prominent scientist and engineers. The proceedings of this meeting have not been published and the projected follow-up meeting does not appear to have been held. It is timely that the November issue of the Philosophical Transactions of the Royal Society is dedicated to this theme and hopefully it will stimulate interest in resolving the issues.

**2. How do you think research into climate geoengineering should be taken forward, and by whom?**
Research on some of the new proposals, for example, biological or chemical carbon-to-fuel recycling could be undertaken within the UK university sector with funds earmarked for it. The research must include the secondary impacts, especially to ecological systems. As another example, the assessment of cloud albedo modification, however, would require improved knowledge of aerosol and in-cloud physical processes which are also critical to the reliable calculation of negative cloud feedback in climate modelling. This research would require extensive new measurements of in-cloud physics in conjunction with targeted terrestrial and satellite observations in cooperation with climate modellers. An international collaboration would be necessary, with the UK and the USA as leading partners.

**3. What factors need to be considered before deploying any climate geoengineering schemes? Who should be responsible for any deployment?**

No scheme should be deployed before careful analysis and modelling of all the impacts to establish the potential efficacy of the intervention and the scale and potential seriousness of any undesired effects. Following this, pilot-scale trials can be considered, with clearly limited undesired risks. The spatial extent of the pilot trials should be within national boundaries, so the relevant government can take responsibility, after consultation with the international community and the scientific academies.
Larger-scale deployment must be contingent on widespread consultation and a satisfactory safety case, taking into account the results of the pilot trials, in which the duration and reversibility of the intervention are rigorously demonstrated and measures to counter and limit any undesired effects are incorporated. Where the spatial extent is international, technical consultation should include the major scientific academies worldwide. A new framework for this could possibly be established through the International Council for Science (ICSU). Other factors, particularly those impinging on sovereign rights and legal liabilities might require a new international convention and oversight body.

**4. What do you consider to be the most important political, social, legal or ethical issues raised by climate geoengineering?**
Climate geoengineering at scale must be considered only as a last resort. There should be no lessening of attempts to otherwise correct the harmful impacts of human economies on the Earth's ecology and climate. Therefore, the capability to deploy any geoengineering scheme should be seen as a prudent precautionary measure in case all other attempts to control dangerous climate change fail or are inadequate – for whatever reason.

**5. What do you see as the main barriers to, and opportunities offered by, climate geoengineering?**
The main barriers to many of the schemes will not be technical. One barrier will be objections, on principle, that any such precautionary insurance will weaken the international resolve to reduce carbon dioxide emissions. Another may be the difficulty of establishing sufficiently accurately the ecological and environmental consequences associated with any particular scheme. Another may be the cost of some schemes. For the albedo modification schemes, the opportunities include, along the way, a fuller understanding of the relevant climate processes and the development of new technologies and new industries.

**6. Where do you feel that climate geoengineering fits in the greater scheme of climate research and action to mitigate and adapt to climate change?**
Uniquely it offers the possibly of an ultimate insurance policy against a 'worst fears' case. We note that some of the schemes in the first category involve recycling extracted carbon dioxide into carbon-neutral fuels. These could add substantially to our portfolio of carbon recycling options and could be very important in reducing the projected reliance on large-scale carbon sequestration.

**7. Are there any other issues related to climate geoengineering that you consider to be important?**
Research into albedo modification by schemes in categories 2a, 2b and 2c of the call for submissions should lead to improved knowledge of processes central to the reliable calculation of positive and negative albedo contributions in climate modelling and thus reduce the present range of uncertainty in the modelling of these effects.

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4) *Presently-Feasible Albedo-Control Approaches to Prevention of Both Types of Climate Change* presented at the Tyndall-MIT conference 2004 by a team from Livermore and Stanford.
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**OCEAN NOURISHMENT CORPORATION**
**Author:** Martin Lawrence

To: Royal Society
Please find attached a submission addressing the place of ocean fertilization with macronutrients in the suite of potential geoengineering approaches to mitigating climate change. Ocean Nourishment Corporation welcomes the opportunity to make this submission to the important review being undertaken by the Royal Society.
Ocean Nourishment Corporation (ONC) has been established with the objective of conducting research and development, with the view to possible eventual commercialization of ocean fertilization. The specific technical focus of ONC is fertilization the ocean with macronutrients.
The achievement of this final objective is, of course, subject to an appropriate regulatory arrangement (which is in turn dependent on assessment of technical risks by bodies that establish regulations). Further, the objective is subject to an economic financial return being available from the commercialized activity.
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## Ocean Fertilization with Macronutrients

Submission to the Royal Society by: Ocean Nourishment Corporation, www.oceannourishment.com
Contact: Martin Lawrence, martin.lawrence@oceannourishment.com December 2008

### Summary

This submission discusses ocean fertilization with macronutrients as a geoengineering method to mitigate climate change. Some essential features of this method are briefly addressed, in some cases with comparison to related technologies. Space precludes dealing with all issues related to ocean fertilization with macronutrients. The aim of the submission is to show that macronutrient ocean fertilization is a contender for greenhouse gas mitigation and thus should be targeted for research. Key Points:

- Macronutrient ocean fertilization has the potential to sequester up to 0.8 GtC/yr, using nitrogen fertilization alone. With the addition of phosphorous to the fertilizer, the potential is much larger.
- Macronutrient ocean fertilization has a number of potential advantages in comparison with micronutrient fertilization. Further research is needed to clarify.
- Macro and micronutrient ocean fertilization are applicable in complementary parts of the ocean.

### Introduction

The problem of rising levels of carbon dioxide in the atmosphere is addressed in many documents. Biosequestration of carbon by fertilization of the ocean is one of the geoengineering approaches that have been proposed to help mitigate the problem. Ocean fertilisation has the ability to drawdown CO2 from the atmosphere. This technique is technically relatively simple to implement. It shows promise of being inexpensive, in comparison with existing and expected future prices of carbon credits. To date, much of the emphasis of research and discussion has gone into the use of the micronutrient iron as the fertilizer. However, we believe that fertilization of the ocean with macronutrients, such as nitrogen and phosphorus, holds even greater promise of providing sequestration of large quantities of carbon.

### Macronutrient Fertilization

Nitrogen is an essential ingredient for macronutrient fertilization of the oceans. The concentration levels of phosphorous (another macronutrient) are important for consideration of ocean fertilization. The macronutrient balance in the world's oceans (Figure 1), averaged over the annual cycle, is such that 80% of the surface area has an excess of phosphorous above the Redfield ratio for nitrogen. (The Redfield ratio is the elemental ratio applicable to growth of phytoplankton in the ocean.) The remaining 20% of the world's ocean corresponds approximately to the region that has a shortage of the micronutrient iron. For a threshold of 0.2 µmol/l phosphorous excess, 50% of the ocean is available for fertilization by nitrogen only. For 0.4

µmol/l phosphorous excess, 16% of the ocean is available. These values are calculated using data from the World Ocean Atlas (2005) for nitrate and phosphate levels, on a 1° grid, in the surface ocean.

*Figure 1: Excess of phosphorous over nitrogen in the surface ocean expressed in µmol/l. Zero is at the Redfield ratio. Plotted values are limited to range 0.0 to 0.5 µmol/l excess phosphorous. Values outside this range are set to the limiting values. (Data are from World Ocean Atlas 2005).*

The quantity of carbon that could potentially be sequestered by fertilization with nitrogen alone is estimated to be 0.8 GtC/yr (which corresponds to 2.9 GtCO2/yr). To achieve greater levels of sequestration, phosphorous would need to be added to the nitrogen fertilizer. The above potential sequestration limit is determined by first calculating the quantity of carbon that is the (Redfield) equivalent to the excess phosphorous in the 80% of the ocean with excess phosphorous. This quantity of carbon is 8.0 GtC. To obtain a sustainable annual sequestration value this must be divided by the replenishment time of the phosphorous. Surface water remains above the seasonal thermocline for order of a decade (Broecker and Peng 1982). Using this estimate of replenishment time leads to the estimate of 0.8 GtC/year for the upper limit of ocean biosequestration by nitrogen (alone) fertilization. Clearly the above sequestration values are not precise, nor do they account for various inefficiencies that might arise in the process. However, they do serve to provide the current best estimate of the size of benefit that might be available by this technology, using nitrogen alone. Reactive nitrogen can be produced in required quantities in the same way used for agriculture on land. Any CO2 produced in manufacture of fertilizer is easily accommodated in the overall carbon accounting of ocean fertilization. The total cost involved in producing and delivering nitrogen fertilizer from ships is favourable compared with the current price of carbon credits. To achieve even greater levels of sequestered CO2, phosphorous could be added to the ocean along with nitrogen. The economics of this approach will depend on the price of phosphorous which has been fluctuating considerably in recent times. However, this approach also appears to be economically viable, based on selling carbon credits.

**Aspects of Ocean Biosequestration**

It is known that ocean fertilization will convert CO2 into organic form and sequester some fraction of it for long periods of time. The recent review by Lampitt et al. (2008) covers ocean fertilization in general. The article by Jones (2004) addresses macronutrient ocean fertilization.

The following discussion attempts to bring out issues of technical relevance for ocean fertilization with macronutrients, contrasting with micronutrient fertilization where appropriate.

- Ocean Regions: The proportion of the world's surface ocean that is primarily limited by the lack of micronutrients (primarily iron) is approximately 25% of the world's ocean (Lampitt et al. 2008), with the remaining 75% being limited by lack of macronutrients.
- Sequestration Efficiency: On adding fertilizer to the surface ocean, new primary production will convert inorganic carbon into organic carbon. After the timescale of the life of individual phytoplankton (about one week), some of this organic carbon will be exported out of the surface layer. Remineralisation of the dead organic matter remaining in the surface layer then occurs, providing nutrients for the next generation of phytoplankton. Provided the area has not been over fertilized, the process repeats until the added nutrient has left the surface layer. In the case of macronutrients, it is expected that all of the added macronutrient will take carbon with it as it moves to deeper waters, leading to a very high efficiency in sequestering carbon. In the case of iron fertilization, there is considerable uncertainty as to the expected efficiency of sequestration (Lampitt et al. 2008).
- Sequestration Period: Some carbon that is exported from the surface zone will enter the mid water levels and from there come back to the ocean surface. Some will enter the deep waters before returning to the surface, while another fraction will reach the sea floor and remain there for a very long time. More study is required of the fractional distribution of sequestration periods. For example, for a given fertilization process, how much carbon will be sequestered for in excess of 100 years and how much for in excess of 1,000 years?
- Atmospheric drawdown of CO2: As pointed out by Lampitt et al. (2008), it takes time for CO2 to move from the atmosphere to the ocean, after fertilization reduces the level of dissolved CO2 in the surface ocean. CO2 depleted water must stay in contact with the atmosphere for sufficient time for this exchange to take place. Again, from Broecker and Peng (1982), surface water remains above the seasonal thermocline for order of a decade. This is a substantial period in which the surface water depleted in CO2 level (by fertilization) will be in contact with the atmosphere, thus assisting atmospheric drawdown.
- Nitrous Oxide Production: Any production of N2O, a powerful greenhouse gas, will reduce the efficiency of the ocean biosequestration process. It has been suggested (Duce et al. 2008) that for ocean biosequestration by addition of reactive nitrogen, much of the effect of CO2 sequestration could be negated by N2O production. However this analysis did not consider all relevant effects. It is also necessary to take into account the relative longevity of the N2O gas in the atmosphere as against the sequestration lifetime of the CO2 in the ocean. The nitrous oxide stays in the atmosphere for 114 years (IPCC Report: Denman et al. 2007), while the carbon dioxide is sequestered in the ocean for 1,000 years (Duce et al. 2008). Taking this into account leads to a loss of efficiency of the macronutrient ocean biosequestration process of approximately 5%. Jin and Gruber (2003) have considered the issue of N2O emissions from ocean iron fertilization.
- Nutrient Stealing: Advection of fertilized water can lead to "nutrient stealing", in which the benefits from adding nutrient in one location results in a lack of nutrient in another location. Modelling has predicted that this could be a problem with iron fertilization due to macronutrient limitations in temperate waters (Dutkiewicz et al. 2005). In contrast, fertilization with macronutrients should not be greatly impacted by advection of fertilized water. However this issue requires more study. Macronutrient fertilization will consume trace nutrients. This may not be a problem as there are no areas of the ocean currently recognized as having limiting trace nutrients (with the exception of iron in certain locations). Nitrogen only fertilization would lead to reduced phosphate levels. What are the implications of this, e.g. for diazotrophs? If there are problems arising with nitrogen only fertilization, it may be prudent to fertilize with a combination of nitrogen and phosphorous.
- Unknown Risks: Because ocean fertilization has not previously been practised on a large scale, it has been suggested that some unknown or unexpected negative effect might eventuate. The technical issues need to be investigated to clarify whether there is an actual risk. There may be a different level of risk for each type of ocean fertilization. There is unlikely to be much progress on the issue of unknown risk without large demonstrations of the techniques. This concern can never be completely allayed solely by theoretical considerations and laboratory testing.

**Future Research**

It is clear that there will be need for a geoengineering solution in the near to mid-term. This is true even if the most optimistic international agreements are concluded and implemented. For this reason it is essential for there to be a rapid increase in the resources dedicated to scientifically exploring the various options for geoengineering. It is only when the science is clear that policy makers will be able to make an

informed decision. We strongly advocate that scientific research into ocean fertilization should include both macronutrient and micronutrient fertilization. The two types of fertilization have sufficient differences that one may be more attractive than the other from a technical viewpoint. Further, the two types of fertilization are applicable in different regions of the world's ocean.

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**PLYMOUTH MARINE LABORATORY**

**COMMENTS ON ROYAL SOCIETY GEO-ENGINEERING CLIMATE STUDY**

The great majority of geo-engineering proposals for combating climate change address the issue of global warming caused by increased concentration of greenhouse gases and its effect on radiation (solar shades, sulphur addition, etc). Others may attempt to increase the natural carbon sinks, for example, through ocean fertilisation with iron or urea. Iron fertilisation has been the focus of substantial scientific study over the last two decades, with a handful of *in situ* experiments. PML has been involved in many of these experiments and in general these experiments show an increase in ocean productivity after iron fertilisation and a net drawdown of carbon dioxide from the atmosphere, at least over the short term. However, there is still much uncertainty as to whether the carbon drawn from the atmosphere into the surface ocean remains in the ocean for sufficient time to have an impact on atmospheric concentrations. To do this, the carbon fixed by the primary producers must be transported into the deep ocean and remain there for hundreds of years. This is where the uncertainty lies and therefore the cost effectiveness of this activity (in terms of dollars and carbon). There are also many concerns from scientists actively involved in this field that stimulated ocean productivity could cause an imbalance in marine food webs and stimulate production of other climate active gases. Without a doubt further, larger scale research is required to reduce these uncertainties. The London Convention has recently stated that ocean fertilization on a geo-engineering scale should not be allowed by member nations but that scientific experiments may be permitted on application.

The issue of ocean acidification is usually not addressed by geo-engineering solutions, so those that do not involve a reduction in atmospheric CO2 still allow ocean acidification to continue. Whether ocean fertilization geo-engineering proposals enhance or remedy ocean acidification is debatable but clearly a future research question. Ocean pumps (Lovelock's) proposal may enhance ocean acidification by upwelling water rich in CO2 but again this requires further research. The uncertainties around liming the ocean are even greater and in the very early days of desk top assessment

**RCUK**

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Any future correspondence on this submission should be sent to:

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Best regards,

Dan

**MEMORANDUM FROM RESEARCH COUNCILS UK (RCUK) TO THE ROYAL SOCIETY GEOENGINEERING CLIMATE STUDY**

**Bulleted summary**


- Geo-engineering is seen by some as having the potential to counteract global climate change; however, the feasibility of different conceptual options has yet to be rigorously examined, and it will be important to guard against unintended effects on the environment.
- The further development of geo-engineering ideas will require a combination of engineering, environmental and socio-economic expertise
- Whilst sophisticated model-based simulations are essential for feasibility assessments, there may be important differences between model climate behaviour and that of the real world at both regional and Earth system scales
- NERC and EPSRC support a wide range of research that is relevant to geo-engineering, particularly in the areas of climate dynamics and CCS (carbon capture and storage). New activities could build on this to explore the potential for geo-engineering development.


1. Research Councils UK is a strategic partnership set up to champion research supported by the seven UK Research Councils. RCUK was established in 2002 to enable the Councils to work together more effectively to enhance the overall impact and effectiveness of their research, training and innovation activities, contributing to the delivery of the Government's objectives for science and innovation. Further details are available at www.rcuk.ac.uk.

2. This evidence is submitted by Research Councils UK (RCUK) on behalf of the Natural Environment Research Council (NERC), the Engineering and Physical Sciences Research Council (EPSRC) and the Economic and Social Research Council (ESRC) and represents their independent views, developed in consultation with the Biotechnology and Biological Sciences Research Council (BBSRC). It does not necessarily reflect the views of the Department for Innovation, Universities and Skills.

3. NERC, EPSRC and ESRC fund and carry out impartial research and training in the sciences of the environment, physical and engineering sciences and economics and social research respectively, within their own remits. Funding is through support to universities and in the case of NERC, also to its Research and Collaborative Centres. Details are available at www.nerc.ac.uk, www.epsrc.ac.uk and www.esrc.ac.uk.

4. In preparing this submission, discussions were held with NERC-funded research centres, including the British Geological Survey (BGS); the Centre for Ecology and Hydrology (CEH); the National Centre for Atmospheric Sciences (NCAS); the National Oceanography Centre, Southampton (NOCS); Plymouth Marine Laboratory (PML) and the UK Energy Research Centre (UKERC).

**Comments on the scope of the Royal Society study**

5. We note the Terms of Reference of the study and the information provided on its scope, as given in the call for submissions. Table 1 summarises issues relating to a number of geoengineering options RCUK is aware of, alpha-numerically labelled according to the Scope guidance. Although this list is by no means exhaustive, comments from RCUK should be interpreted as pertaining to these examples.

6. The exclusion of carbon capture and storage (CCS) at the point of emission is consistent with the approach taken by the House of Commons Innovation, Universities, Science and Skills Committee (IUSSC) in the context of its recent geoengineering case study. There would, however, seem potential ambiguity in the Royal Society's exclusion of CCS at the point of emission since Method 1b)ii explicitly includes chemical engineering approaches to prevent $CO_2$ and other greenhouse gases from entering the atmosphere or oceans.

**[Q1] What do you consider to be the current state of knowledge regarding the feasibility, efficacy and predicted impacts of climate geoengineering schemes?**

1.1 Climate geoengineering is an activity that is essentially hypothetical: whilst many ideas have been raised, none have yet been subject to rigorous feasibility analyses, cost-benefit calculations or proof-of-concept demonstrations. Whilst geoengineering is seen by some as having the potential to counteract global climate change, it will be important not only to guard against unintended effects on the environment but also to fully consider socio-economic issues relating to public acceptability, financing, cost-effectiveness, ethical considerations, verification and international governance.

1.2 NERC and EPSRC currently support a wide range of research that is relevant to climate geoengineering which may be used to inform future, more focussed developments. Information on relevant research currently funded by NERC and EPSRC (and sometimes involving other Research Councils) is summarised in Table 2. Known future projects and programmes, currently in the planning stage, are also shown.

1.3 Relevance to geoengineering is assessed in Table 2 as either low, medium or high. Whilst no high category is used for current work, EPSRC is considering holding a 'sandpit' (Ideas Factory[12]) activity that is explicitly directed at exploring geoengineering feasibility in an interdisciplinary context.

1.4 As indicated in (6.) above, there is a close link between CCS and the proposed geoengineering option of air capture of carbon dioxide ('artificial trees'; option 1ai, Table 1). Both initially involve energy-demanding techniques to remove the $CO_2$, and subsequently require its safe long-term storage. Whilst chemical removal processes are currently favoured for CCS, biological processes may be possible (e.g. involving oil-producing algae). Thus genetic engineering may have a role to play at the interface between geoengineering and CCS.

1.5 For climate geoengineering to achieve its intended benefits, it must have a direct or indirect effect equivalent to diminishing radiative forcing by around 1W $m^{-2}$ (as noted in the Royal Society's call for submissions). However, interventions on this scale – other than by a geographically well-distributed air capture system – are near-certain to have complex, far-reaching and potentially undesirable consequences.

1.6 In particular, atmospheric or surface-based geoengineering schemes relating to shortwave reflection are most effective in tropical regions (where incoming radiation is greatest); however, anthropogenic global warming has greatest effects in polar regions, where increased levels of $CO_2$ and other greenhouse gases reduce planetary heat loss by absorbing longwave radiation. As a result of this spatial mis-match, an atmospheric or space-based albedo modification that achieves a global average cooling of, say, 1°C will not directly reverse a global average warming of 1°C due to greenhouse gases: weather patterns will be different, with the result that some countries and regions will be winners and others losers.

[12] http://www.epsrc.ac.uk/ResearchFunding/Opportunities/Networking/IDEASFactory/WhatIsASandpit.htm

1.7 Ocean acidification can be considered a more fundamental impact of albedo-based geoengineering, since (unless coupled with strong mitigation measures), atmospheric $CO_2$ will continue to increase.

1.8 Geoengineering schemes based on greenhouse gas reduction avoid that problem. Nevertheless, if ecosystem-based, changes in land use or ocean biology over large areas are necessarily involved. If chemically-based, relatively large quantities of raw materials (including water) and energy are likely to be needed for feedstock and infrastucture, and there also may be need to dispose of large quantities of waste, e.g. as sequestered carbon. Significant economic and environmental impacts would therefore seem inevitable, requiring careful cost-benefit analyses, on a full lifetime ('cradle to grave') basis.

**[Q2] How do you think research into climate geoengineering should be taken forward, and by whom?**

2.1 As indicated above, the further development of geoengineering ideas (if considered desirable) will require a combination of engineering, environmental and socio-economic research. The UK government view, as expressed in written and oral evidence by Defra, DIUS and DECC to the IUSSC, is that the national interest is currently best served by focussing research and policy effort on mitigation, i.e. CCS and other measures that directly reduce the problem.

2.2 RCUK shares that view; nevertheless, such an approach is not incompatible with modest spend to obtain additional scientific information on the pros and cons of geoenginering, without any commitment for follow-through. Indeed, improved knowledge of the efficacy and potential impacts of geoengineering may be politically necessary to dissuade other countries from unilaterally implementing ineffective approaches, or to influence UN regulatory mechanisms (e.g. via carbon credit schemes), or to develop independent verification arrangements should climate geoengineering be carried out by others.

2.3 If more substantive research effort were considered to be scientifically and politically desirable, this should, ideally, be taken forward with international partners. The UK already has close engagement with governmental and non-governmental organisations with interests, in climate-related assessment, regulation and research (e.g. IPCC, UNFCCC, WMO, WCRP and IGBP); no new mechanisms or institutions would seem to be needed.

2.4 There is currently little, if any, direct engagement between UK researchers and industry with regard to geoengineering. At the current stage of development that is unsurprising; short-term (or even medium-term) return on private sector investment is unlikely, and governments have to ensure that they have access to independent advice on proposed geoengineering schemes. Nevertheless, there is non-governmental interest through philanthropic trusts, foundations and similar (e.g. the US Carnegie Institution; Richard Branson's Virgin Earth Challenge) and if western governments were to decide that geoengineering should proceed, the private sector might be made responsible for its implementation via schemes similar to carbon trading, subject to verification.

**[Q3] What factors need to be considered before deploying any climate geoengineering schemes? Who should be responsible for any deployment?**

3.1 Before deployment, the proposed geoengineering option must provide a measurable benefit that unambiguously outweighs the impacts arising from the full lifetime energy costs, carbon emissions and other adverse environmental consequences involved in establishing, maintaining and decommissioning the relevant technologies.

3.2 Sophisticated model-based simulations of relevant engineering and environmental processes are essential for feasibility assessments. However there may be important differences between model behaviour and that of the real world, particularly for climate processes at both regional and Earth system scales. Experimental studies and observational-based analyses will therefore also be required, over a range of scales

3.3 For both experimental work and actual deployment, the magnitude of the manipulation should be controllable, with the ability to switch off the effect relatively easily in the event of significant unforeseen adverse consequences.

3.4 In addition (yet more fundamentally) there must be public trust, long-term political commitment and international agreement on the acceptability of geoengineering activities that are financially rewarded through international arrangements, and/or those that may have adverse, as well as positive, effects on globally-shared resources.

3.5 It would seem essential that responsibility for deployment is at the governmental and inter-governmental level, ideally under UN auspices and fully subject to international law.

**[Q4] What do you consider to be the most important political, social, legal or ethical issues raised by climate geoengineering?**

4.1 The socio-economic agenda in relation to geoengineering is unpredictable given the imprecise understanding of what geoengineering interventions may be in the future. However, it is clear that the socio-economic effects of such large scale, complex and presumably resource-intensive investments are potentially huge, and social science has much to contribute to informed assessments of these problems.

4.2 There is a critical need for a clear understanding of what constitutes 'human benefit' prior to commencing geoengineering. Which humans, where and in what way will they benefit? Negative implications also need to be explored and questions of equity and ethics considered: who, if any, will suffer and how will they be compensated and by whom? The large-scale manipulations involved in geoengineering will undoubtedly require considerable investment. Cost benefit and risk assessment will therefore be essential.

4.3 The acceptability of associated infrastructure is also likely to be an important issue, in relation to land and ocean use, ownership, activity displacement, equity and security. Evidence in relation to installing power generation facilities (whether based on renewable or nuclear energy) demonstrates the need for policy and planning development in the context of need at all levels. For example, findings from the ESRC Sustainable Technologies Programme cite the strong influence of both local opinion and of local and national landscape and environmental protection groups in the refusal of planning for large scale facilities. In the geoengineering context this would include supra- and international, national, regional and local communities of interest covering issues as diverse as international law, regulation, and social acceptability (which may differ by any range of sectors or socio economic groups). Broader 'ownership' of large-scale projects, in the sense of engaging with affected communities at an early stage can provide an opportunity to mobilise support.

4.4 At the level of the development, planning and delivery of complex systems and products the social sciences are able to offer considerable insight into to how to best to take these forward. The ESRC Centre for Complex Products and Systems Research has provided critical insight to such problems (e.g. work with Boeing on aircraft development). Lessons learnt and best practice tools developed though this research is expected, at least in part to be transferable to other large scale activities such as geoengineering.

4.5 There are also considerations of cultural responses in relation to religious and other belief systems should geoengineering lead to large-scale and purposefully-created changes in the environment. For land-based geoengineering options, the value attached to landscape can vary both within and between different countries, and may be an important factor in terms of where interventions are to be sited.

4.6 Note that Table 1 identifies some socio-economic issues associated with specific geo-engineering options, although this is not intended as a definitive assessment.

**[Q5]. What do you see as the main barriers to, and opportunities offered by, climate geoengineering?**

5.1 The unambiguous demonstration of net benefit (see 3.1) – is likely to be highly demanding, with major investments needed to scale-up from proof-of-concept to pilot trials and full deployment. The use of state-of-the-art climate models, including a range of biogeochemical feedback processes, is clearly necessary for 'safe' global-scale testing, to quantify potential benefits and assess the risk of undesirable impacts. A secure assessment of the full impact of geoengineering solutions requires a comprehensive Earth System Model.

5.2 Earth System Models (which must include for example the land surface, atmospheric chemistry, and biogeochemical processes occurring throughout the ocean) are still in their infancy but are in active development within NERC (in collaboration with other bodies such as the UKMO). Currently such models do not adequately represent regional climate and its variability. High resolution regional models will be needed to complement field trials, to verify that intended effects did not arise for other reasons. It is a priority research area to improve and assess these models. But model behaviour can never fully replicate real-world behaviour; at full scale-up, it would be prudent to expect the unexpected. Hence the importance that the manipulation is controllable, and can be easily stopped if net benefits are not achieved.

5.3 'Global planning permission' will undoubtedly be needed for schemes of sufficient scale to be climatically effective. As yet, the ethical and legal frameworks for purposeful climatic manipulation do not exist, and their development is unlikely to be straightforward. Any scheme would require international approval/verification (through a form of carbon credits, via UNFCCC or similar) for it to proceed; it is unlikely – although not impossible – that any single country would otherwise be willing to meet the financial cost.

5.4 The 'opportunity' offered by geoengineering is essentially preventive: avoiding dangerous (and potentially catastrophic) climate change, should mitigation measures be insufficient to prevent climatic tipping points being breached. Global temperature increases in the range 5-10°C and sea level rise of many metres are not beyond the bounds of possibility within our grandchildren's lifetimes.

**[Q6]. Where do you feel that climate geoengineering fits in the greater scheme of climate research and action to mitigate and adapt to climate change?**

6.1 The feasibility of geoengineering warrants attention on the basis that such an approach might 'buy time' or provide a future safety net. However, geoengineering *alone* is inherently unlikely to provide a sustainable, long-term solution to climate change. That is because: i) the scale of geoengineering interventions would need to be increased year-by-year to keep up with increased emissions (currently rising at more than 3% pa); ii) several schemes are limited in the scale of their effects, or constrained by other factors (e.g. storage capacity for captured carbon); and iii) ocean acidification would continue unabated if no measures are taken to limit the increase in atmospheric carbon dioxide.

6.2 RCUK is aware of concerns that over-optimistic reliance on geo-engineering might prove to be chimeric and diversionary. Thus attention given to 'technological fixes' could attract resources and effort away from more fundamental ways of tackling the problem of global warming, through a rapid transition to a low-carbon economy.

6.3 The 5$^{th}$ Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) may provide an opportunity for the UK research community to assist in establishing international consensus on the viability of geoengineering options. However, IPCC's 4$^{th}$ Assessment Report (2007) considered that "geoengineering options ... remain largely speculative and unproven, with the risk of unknown side effects".

**[Q7]. Are there any other issues related to climate geoengineering that you consider to be important?**

7.1 The main issues of concern and interest to RCUK are covered above and in Tables 1 and 2. The tabled information is similar to that provided by RCUK to the House of Commons Universities, Innovation, Skills and Science Committee.

**Table 1.** Summary information on key issues for some geo-engineering options that have been proposed to counteract climate change. Options are alpha-numerically labelled in accordance to headings in the Scope section of the Royal Society's Terms of Reference for this study. Note: we do not provide any examples of 1aiii) or 1bi) and ii). Additional detail in Launder & Thompson (2008) "Geoscale engineering to avert dangerous climate change" *Phil Trans Roy Soc A* vol 366 (No.1882) and Vaughan & Lenton (review, in prep).

| 1) Greenhouse gas reduction schemes | | | |
|---|---|---|---|
| **Geo-engineering option** | **Engineering issues** | **Environmental issues** | **Socio-economic issues** |
| a)i Air capture of carbon dioxide | Development of efficient devices to remove $CO_2$ from (ambient) air; long term storage; links to CCS | Ensuring safe long term storage of captured carbon; assessment of energetic cost-effectiveness | Assessment of economic cost-effectiveness |
| a)i Enhanced carbon sequestration on land through biochar burial in soil | Obtaining bulk biochar; scale of (re-)forestation required to achieve globally-significant effect; use of biochar based on agricultural waste will require change in agricultural systems | Uncertain timescale and magnitude of soil storage capacity; need for major land use/ land cover changes; soil fertility effects; questions over whether biochar leads to enhanced mineralization of labile soil carbon | Possible limited duration of effect, dependent on soil conditions/type of biochar (may be stable for 100's - 1000's of years); impacts on food production; once started has to be maintained |
| a)ii Increasing open ocean productivity through micro- or macro-nutrient addition | Obtaining and delivering nutrients, such as iron or urea | Uncertain timescale and magnitude of carbon sequestration; ecosystem effects; possible release of climate-reactive gases | UN moratorium on such work (by Convention on Biodiversity); once started has to be maintained |
| a)ii Increasing ocean productivity and surface cooling through increased mixing (ocean pipes) | Design, deployment and maintenance of mixing devices | Likely to be small or zero net effect on carbon budget ($CO_2$ from deep water released); cooling trivial on global scale? | Assessment of cost-effectiveness; interference of mixing devices with shipping and fishing |
| **2) Albedo modification (short wave reflection/deflection) schemes** | | | |
| a) Increasing land surface albedo by physical means (paint in urban areas, plastic surface on deserts) | Production, deployment and maintenance of surface covering – large area required for global effect | Potential for urban areas; less feasible for natural surfaces. Loss of desert dust would affect ocean productivity | Public acceptability of changes to visual landscape; assessment of cost-effectiveness |
| a) Increasing land surface albedo by biological means (changing vegetation) | Changing crop and/or grassland albedo, without affecting yield (via GM?) | Impacts on biodiversity, productivity, hydrological cycle and regional weather; scale of change needed for global effect | Public acceptability of changes; assessment of cost-effectiveness; regional losers |
| b) Increased cloud albedo in lower atmosphere (e.g. using seawater spray) | Design and auto-operation of spraying devices; satellite-based verification of effect | Would effect be large enough? Need to model and monitor chemical impacts | Changes likely in regional weather patterns, with reduced rainfall downwind |
| c) Increased aerosols in upper atmosphere (using sulphur compounds) | Design of delivery vehicles and dispersion mechanisms; supply of sulphate; energy costs | Uncertainty in climatic effects - models suggest regional changes and overall decrease in precipitation; risk of ozone depletion and acid rain | Assessment of cost-effectiveness; public/ political acceptability likely to be low (losers as well as winners) |
| d) Global shading in space (using mirrors, discs or reflective mesh) | Need for novel materials; design of delivery vehicles; problem of energy- | Actions not easily reversible, hence high reliance on models to predict climate impacts – | Assessment of cost-effectiveness; public/ political acceptability likely to be low (losers |

| | | | |
|---|---|---|---|
| | intensive start-up; opportunity for energy to be collected in space? | these suggest regional changes and overall decrease in precipitation; problem of space debris. | as well as winners) |

**Table 2** Summary of current and planned research by NERC, EPSRC and other Research Councils considered relevant to geoengineering. Relevance rating: X, low; XX, medium; XXX, high. Annual cost estimates (where given) are averaged over programme lifetime and may not accurately represent current spend. *Note that figures are for the entire activity, not just the component relevant to geoengineering.* Surce-based carbon capture and storage (CCS) is not here regarded as geo-engineering.

***CURRENT WORK (December 2008)***

| **Activity** | **Rele-vance** | **Duration; annual cost** | **Main links to geo-engineering** | **Support arrangements** | **RC(s) providing support** |
|---|---|---|---|---|---|
| Research Councils Energy Programme: *www.epsrc.ac.uk/ResearchFunding/Programmes/Energy/Funding/default.htm* | | | | | |
| • UK Energy Research Centre | X | 2004-09 £2.6m pa | Energy systems and modelling | Consortium (10 institutions) led by Imperial College | EPSRC, NERC, ESRC |
| • Carbon management and renewables: carbon capture and storage | XX | 2005-10 £3.0m pa | CCS including potential for carbon sequestration by soils | Current CCS grants include consortia, smaller projects and capacity building activities | NERC, EPSRC BBSRC |
| Other programmes and projects | | | | | |
| Tyndall Centre for Climate Change Research *Themes include constructing energy futures; integrated modelling; engineering cities; informing international climate change policy* | XX | 2006-09 (Phase 2) £2.0m pa (total) | Overview; policy implications | Consortium of 6 core partners, led by UEA | NERC, EPSRC ESRC |
| Living with Environmental Change (LWEC) *Details in development* | X | 2008 - 18 | Mitigation and adaptation; socio-economics | Networking and enhanced collaborations | NERC, ESRC, EPSRC, BBSRC, MRC & AHRC |
| British Geological Survey (BGS) *Themes include climate change, energy, land use and development, marine geoscience* | XX | Ongoing | CCS, land use, element cycling | NERC Centre | NERC |
| Oceans 2025 *Themes include marine biogeochemical cycling; next generation ocean prediction* | XX | 2007-12 £24.0m pa (total) | Ocean carbon uptake/release; acidification risks from CCS | Coordinated programme at 7 NERC-supported marine centres, including NOCS, PML and POL | NERC |
| National Centre for Atmospheric Science (NCAS) *Themes include climate science and climate change; weather, atmospheric composition, and technologies* | XX | Ongoing £9m pa | Regional and global atmospheric behaviour; climate predictions using state-of-the-art high resolution | NERC Collaborative Centre involving 7 centres and facilities | NERC |

| | | | | | |
|---|---|---|---|---|---|
| | | | models; cloud physics; aerosol behaviour and properties | | |
| Centre for Ecology and Hydrology (CEH) *Themes include land/ climate feedbacks and biogeochemical cycling* | XX | Ongoing £2-3m pa | Land surface modelling and linkage to Earth System Models to predict impacts. | Core programme of NERC Research Centre | NERC |
| Quantifying and Understanding the Earth System (QUEST) | XX | 2003-09 £3.8m pa | Modelling climate impacts | 70 grant and fellowship awards; Core Team at Bristol | NERC |
| Aerosol properties, processes and influences on the Earth's climate (APPRAISE) | XX | 2005-11 £1.1m pa | Atmospheric dynamics and albedo | Directed programme: 7 awards at 5 institutions | NERC |
| Surface ocean – lower atmosphere study (UK SOLAS) | X | 2003-10 £1.5m pa | Ocean carbon uptake/release; atmospheric chemistry | Directed programme: 28 awards at 14 institutions | NERC |
| UK contribution to VOCALS (VAMOS Ocean-Cloud-Atmosphere-Land Study) | XX | 2008 -11 ~£0.3m pa | Cloud formation (via sulphate aerosol) and their albedo effect | Consortium | NERC |
| Participation in German-led ocean iron fertilisation experiment | XX | Jan – March 2009; ~£10k | Study of fate of Fe-enhanced primary production in Southern Ocean | National Oceanography Centre Southampton (research cruise led by AWI Bremerhaven) | NERC |
| Sustainable agriculture and land use | X | Ongoing | Land-based carbon sequestration | Support via Rothamsted Research, other Centres and HEI awards | BBSRC |

***PLANS FOR FUTURE WORK (December 2008)***

| **Activity** | **Rele-vance** | **Duration; cost** | **Main links to geo-engineering** | **Support arrangements** | **RC(s) providing support** |
|---|---|---|---|---|---|
| National strategy for Earth system modelling | XX | tba | Modelling climate impacts | Capacity building/start-up initiative | NERC |
| CCS: capture, transport, storage, whole systems and sustainability of carbon capture and storage | XX | tba | CCS | Wide ranging activities including consortia support, capacity building and start-up initiatives. Some E.ON co-support | EPSRC, NERC, ESRC |
| Ocean acidification | X | tba | Ocean carbon uptake/release; CCS | Large-scale research programme | NERC |
| Earth System Engineering IDEAS Factory (='Sandpit') | XXX | tba | Focus on geo-engineering | tbc | EPSRC |
| Doctoral training in CCS | XX | ~£5m total | CCS | 10 students pa for 5 yr | EPSRC |

*RCUK, December 2008*

**ROYAL SWEDISH ACADEMY OF SCIENCES**

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**Geoengineering Climate - Input from the Royal Swedish Academy of Sciences**
Kevin J. Noone

## Summary of the main points


- Future research on geoengineering must be carried out in an Earth System context; it is not sufficient to engage in analyses of individual components or manipulations (e.g., ocean fertilization, cloud seeding, stratospheric aerosol injections) in isolation. These must be analyzed looking at the entire coupled human-environmental Earth System.
- The most pressing issues associated with geoengineering are not technical ones; rather they concern the ethical aspects of global manipulations, the governance, management and legal structures needed to administer and adjudicate the schemes, and the need to imbed analyses of geoengineering in an Earth System perspective.
- It is critically important to distinguish between *research* on geoengineering and *implementation* of geoengineering schemes. *Research* cannot be avoided, but *implementation* must wait until all the issues – especially the ethical ones – are satisfactorily resolved.
- Geoengineering research should be coordinated through international, interdisciplinary, accredited scientific organizations.


## Responses to questions

1) What do you consider to be the current state of knowledge regarding the feasibility, efficacy and predicted impacts of climate geoengineering schemes?

Our level of knowledge is very low – particularly from an Earth System-level perspective. While there are many possible examples, I will use two schemes to attempt to make this point: cloud seeding and stratospheric aerosol injections.

It has been known for many years that humans can modify the reflectivity and life cycles of clouds ((Twomey et al., 1968), (Albrecht, 1989)). Large-scale investigations into the processes behind these effects have been carried out (e.g., (Durkee et al., 2000)), but generally not within an Earth System framework. One of the proposed geoengineering schemes involves generating sea salt particles, which would presumably increase the reflectivity of low-level marine stratocumulus clouds, causing a net cooling effect. While it is possible to estimate some of the local microphysical effects associated with this kind of manipulation, there are several broader aspects that have yet to be analyzed in any detail. The chemical consequences of sea salt generation for the cloudy marine boundary layer have not been assessed. What would be the effects on oxidant concentrations, and on the in-cloud oxidation of sulfur, nitrogen, and organic carbon compounds? Furthermore, recent calculations using a state-of-the-art coupled atmosphere-ocean climate model show that geoengineering clouds in the South Pacific and South Atlantic regions can induce changes temperature and precipitation patterns that resemble La Niña and El Niño conditions, respectively (Jim Haywood, personal communication). According to these calculations, precipitation in South America could decrease as much as 15% due to these manipulations. This is an excellent example of the realization that manipulating one part of the planetary system can have serious consequences elsewhere in the system.

Injecting aerosols into the stratosphere has been suggested as a potential way to decrease the amount of shortwave solar energy reaching the Earth's surface, thus cooling the planet ((National Academy of Sciences (NAS) Committee on Science, 1991),(Crutzen, 2006)). A main argument supporting this scheme is the fact that volcanoes do this naturally, albeit intermittently. The Mt. Pinatubo eruption of 1991 was estimated to have resulting in a decrease in surface temperature of 0.5°C in the year following the eruption ((Lacis and Mishchenko, 1997)). While volcanoes do on occasion cause increases in stratospheric aerosol loading, using this scheme in a geoengineering sense would require continuous injection of aerosols – which does not resemble a natural process. (Wigley, 2006) calculated the surface temperature

changes resulting from stratospheric injections of aerosols, but did not estimate other possible effects like changes in heterogeneous chemistry in the stratosphere. Furthermore, aerosols injected into the stratosphere do not remain there forever. Eventually they are transported back into the troposphere. It is possible that this increased, quasi-permanent stratospheric aerosol layer could have an influence on clouds in the upper troposphere. It is entirely possible that the particles could act as ice nuclei as they are transported from the stratosphere into the upper troposphere. This could lead to an increase in optically thin ("subvisible") cirrus clouds. Since these clouds tend to warm the planet, it is possible that the net result of stratospheric injections of aerosols could actually be increased surface warming – exactly the opposite of the desired result. There is very little known about optically thin clouds in the upper troposphere, and this interaction is only one of many that needs to be fully investigated in the context of this geoengineering scheme.

Perhaps most importantly, none of these schemes protect against the effects of ocean acidification. The only way to avoid this potentially catastrophic biogeochemical tipping point is by reducing $CO_2$ emissions.

2) How do you think research into climate geoengineering should be taken forward, and by whom?

Because geoengineering is by definition a planetary-scale endeavor, it requires a global approach to organizing and coordinating research. Because research into geoengineering involves scientific, ethical, legal, governance and many other aspects, it requires the participation of many disciplines across the natural and social sciences, as well as the humanities. Our current educational and funding systems are not well equipped to meet this challenge. They are organized largely along disciplinary lines, which is not what is needed in the case of geoengineering research.

(Clark et al., 2006) evaluated the influence of global environmental assessments and came up with three main criteria for success: credibility, salience and legitimacy. While credible science can be done by individuals organized along disciplinary, salience and legitimacy in the context of global environmental issues are better served by a different organization. There are a number of recognized global environmental change (GEC) programs in place under the auspices of the International Council for Science (ICSU) that could serve as a starting point for a proper organization of geoengineering research. The four ICSU-sponsored GEC programmes DIVERSITAS (an international programme of biodiversity science), the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP) and the Worl Climate Research Programme (WCRP) together formed the Earth System Science Partnership (ESSP) in 2001. The ESSP provides a credible and legitimate platform covering primarily the natural and social sciences. While the ESSP could be an excellent starting point for taking forward geoengineering research, it lacks structural links into the engineering community, and into the political and private sectors. Stakeholder involvement is critical to the success of geoengineering research; however, to be legitimate, the research needs to be organized by scientifically credible, international, interdisciplinary bodies.

The Intergovernmental Panel on Climate Change (IPCC) provides a good example of a successful global environmental assessment process – but the IPCC does not organize or carry out independent research. In addition to the need for international, interdisciplinary organization of geoengineering research, an assessment process like the IPCC would be a necessary component.

3) What factors need to be considered before deploying any climate geoengineering schemes? Who should be responsible for any deployment?

As mentioned previously, the technical aspects of geoengineering are perhaps the least of our concerns regarding implementation. The major consideration must be to develop an internationally accepted set of principles and terms of reference in which the ethical, legal, governance and management issues are clearly stated. The historical example of the development and use of nuclear weapons in advance of international agreements is one that is worthwhile to study. While the context for geoengineering is entirely different than the development of nuclear weapons during a devastating world war, still valuable lessons can be learned by this comparison. One of the principles should involve the necessity for comprehensive, Earth System-level analyses of any geoengineering scheme that conclusively show acceptably small risks of unintended negative consequences as a first step before any geoengineering scheme could be implemented. A transparent, global-scale governance and management structure needs to be first established, with clear guidelines for liability, responsibility and distribution of any profits accrued by geoengineering schemes.

4) What do you consider to be the most important political, social, legal or ethical issues raised by climate geoengineering?

Equity issues are central to geoengineering. We need to clearly understand and account for how the positive and negative consequences of geoengineering will be distributed. We need to guarantee Pareto equality[13] as a minimum criterion for geoengineering. Anthropogenic climate change itself is predicted to have the largest negative impacts on already vulnerable parts of society – those who have thus far had the smallest contribution to causing climate change. We need to ensure that any geoengineering schemes that are implemented lead to a global society that is more equitable and better able to pursue the common human endeavor that our present society.

5) What do you see as the main barriers to, and opportunities offered by, climate geoengineering?

Economic gain would appear to be an opportunity offered by geoengineering. Reducing the emissions of greenhouse gases will be expensive compared with the anticipated cost of many of the geoengineering schemes that have been discussed ((Barrett, 2008)). However, most simple cost-benefit analyses for geoengineering use models in which ecosystem services and natural resources are "externalities", and there is considerable disagreement on what a proper discount rate would be. The main barriers would appear to be a) the lack of a global governance and management system up to the task of controlling and regulating geoengineering; b) the lack of an agreed set of principles and terms of reference for geoengineering; and c) the lack of Earth System-level understanding of the processes (natural and societal) controlling the outcomes of geoengineering schemes.

The main opportunity would be to begin working on eliminating these barriers while at the same time pursuing the transformation of our energy production, transportation, agricultural and other infrastructures towards renewable, sustainable means. A wonderful possible result would be for us to create these institutions and then discover that we did not need them.

6) Where do you feel that climate geoengineering fits in the greater scheme of climate research and action to mitigate and adapt to climate change?

Research on mitigation, adaptation and transformation (please see the response to question 5) must be the primary efforts for the international research community. While research on geoengineering cannot be avoided, geoengineering itself should be viewed as a temporary method for emergency use only.

7) Are there any other issues related to climate geoengineering that you consider to be important?

The temptation to apply quick-fix, whiz-bang solutions to complex global environmental problems is very large. Experience in interfacing with the international community that funds global environmental change research has shown that the vast majority of funding agencies are under pressure to move resources from research into how the Earth System works (and consequently how our actions influence the function and character of the the Earth System) into solutions for the problems associated with climate change.

We must learn how to effectively make the argument that truly informed decisions about issues such as geoengineering are not possible without a comprehensive framework of basic, discovery science research into how the Earth System works.

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**SCIENCE FOR HUMANITY TRUST**

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**Responding on behalf of:** Science for Humanity Trust
**Date received**: 01 November
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Summary: The following comments have been sent to the Royal Society in response to the subject Call from http://royalsociety.org/page.asp?id=2556. The schemes described below have recently been, or will shortly be, presented in international conferences (see item 1). Items 3, 4, and 5 below have not yet been written in a publishable form. Therefore, no details will be available until mid- to late-January 2009.

1. Introduction to Science for Humanity Trust
2. Solar power from LEO
3. Solar shade/reflector at LEO
4. Solar Windmill
5. Extended Twilight
6. Mass lifter
7. Barriers to acceptance and implementation

1. Introduction:

The Science for Humanity Trust (Bangalore India) and Science for Humanity Trust, Inc. (Tucker, Georgia, USA), have a primary goal to explore alternative energy sources. While, if successful, these would all have an impact on global warming by reducing the world dependence on fossil fuels, some of the ideas being explored by the Trusts actually fall into the category of Geoengineering.

So far, only one set of these ideas has been developed to the stage of getting into the public domain. A subset of these concepts has been presented recently by two of my students at the 59th International Astronautical Congress (Glasgow (IAC-2008), Scotland, Sept. 29 – Oct. 3, 2008). These papers are included as references in the extended abstract (attached) for a third paper accepted for presentation at ENVIROENERGY 2009: International Conference on Energy and Environment, Chandigarh INDIA, March 19 - 21, 2009. This third paper, "Solar Power from Leo," is the one that is the basis for Geoengineering.

2. Solar power from LEO

Most present concepts for a Space Power System (SPS) depend on construction at geostationary earth orbit (GEO). Our proposal is for a system at much lower altitudes (LEO). If the tradeoff between microwave-power transfer from LEO vs. that from GEO were to be won by GEO, there are still benefits of the LEO system that cannot be matched. These benefits result from a need to control global warming that was not perceived during earlier SPS-concept development. For a fraction of the cost envisioned for $CO_2$ sequestering alone, solar shades that would have the same thermal impact can be placed in LEO. This would provide the infrastructure for a LEO SPS (or new civilization) essentially for free. By the end of the century, the fossil fuel requirements for the majority of humanity could be eliminated.

3. Solar shade/reflector at LEO (albedo modification from space)

The timeline for the SPS development may be too slow for the long-range global-warming concerns. Therefore, the LEO thin-film-reflector program would be required. Within 50 years, the solar flux at the earth's surface could be reduced by 1%. [While the specific albedo modification envisioned exceeds 100 W/m$^2$, the 1% coverage reduces the average modification to the 1 W/m$^2$ goal for controlling global warming.] The mass requirement in space for such a project is huge. The climate impact of such a mass transfer cannot be ignored, even if the major cost factor in this new environment may be. This issue is addressed below in item 6.

Since the Polar Regions are most important and vulnerable in the present crisis, the circum-terra rings supporting the reflectors would be rotated to polar orbits. This would have a disproportionate affect[14] and would allow some "tailoring" of the global temperature distributions.

[14] The shadow cast by the reflector ring is the same width at the equator and at the Arctic Circle. However, the Arctic Circle is less that ½ the length of the equator. Thus, the shadow width-to-circumference ratio is doubled at the polar

As the SPS output grows and the excess $CO_2$ from fossil fuel usage decreases, the need for shadowing the earth decreases and the LEO assets may be converted to other uses. One such use is power generation from a solar "windmill" and a variant thereof.

4. Solar Windmill

This concept[15] is only somewhat more sophisticated than the reflector rings planned for global thermal control. On the other hand, it is so close to the same structure[16] that it becomes a natural "follow-on." Furthermore, there are some significant differences in capabilities between 1983, when light-sail windmills were proposed by Paul Birch, and the present. The ability to store energy in the ring itself and to "tap" that stored energy at will, via electrodynamic tethers, adds dramatically to the appeal of the system. Since such a system could provide hundreds of terawatts[b] of continuous, clean power, it should (by itself) be able to provide for the earth's needs, even at the end of the century. The major limitation seen is the required transfer of such immense levels of power from space to earth.

5. Extended Twilight

With a relatively minor adjustment to this solar windmill concept, a major change in this planet's light cycles could also be induced. This modification to the solar mill involves an adjustment to the angle of the thin-film panels. By reflecting the visible light, from the specially treated film surfaces, to the earth's surface rather than into space, an extended (by 1 – 2 hours) or "brightened" twilight could be adjusted and permanently bestowed on the earth. The savings in electricity from the now-redundant lighting requirements during these hours could be significant. If imposed over a decade or more, the ecological impact would not be a major problem since most life would have time to adapt. The beneficial impact of such a change goes far beyond the economic. Nevertheless, this is the type of Geoengineering that would need to be examined closely for unintended consequences.

6. Mass lifter

One problem with many of the concepts for the use of space for terrestrial benefits is the cost (financial and ecological) of the large number of rocket launches required for any significant project. Proposed solutions to this problem involve a "space elevator" (or mass-lifter) of one form or another. Unfortunately, such a development has required demonstration of either a large step-function in fiber tensile strengths and/or the production of operational hyper-sonic aircraft before the project can even be considered.

In reference 4 of the attached abstract, we have described a mass-lifter, based on the best of the previous proposals, which has better prospects and can be started immediately. This system promises nearly an order-of-magnitude reduction in cost-per-pound delivered to orbit and an environmental impact equivalent to air traffic between two small cities.

The system could be making its first trial mass transfers from an aircraft at 40,000 ft to LEO within 5 years of initial funding. Therefore, the potential for near-term space-based schemes is real – and should be considered seriously in the Royal Society Geoengineering Climate Study.

7. Barriers to acceptance and implementation

The Science for Humanity Trust was established in India because this country has long-term energy requirements that must be satisfied and it has no petroleum reserves or industry of its own to fight competition from alternative energy sources. It has a growing space program, major manpower and financial resources, and has its own launch facilities and the potential for a more-nearly equatorial launch site. Furthermore, the schemes proposed above require international agreement and cooperation. India has not alienated a large segment of the world's population.

<u>Conclusion</u>

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circles and gets greater rapidly as one moves pole ward. The actual reduction in average sunlight intensity falling on the ground is no different, but the percentage change is much greater in the Polar Regions.

[15] Paul Birch, "Orbital Ring Systems and Jacob's Ladders – III," Journal of the British Interplanetary Society, Vol. 36, pp. 231-238, 1983

[16] It is a sun-stationary polar-orbiting polar array, rather than being a polar array normal to the solar mill. That is to say, all of its components are in sunlight 100% of the time, rather than casting a near-maximal shadow on the earth 100% of the time.

While several of the items discussed above may not be climate-geoengineering schemes, they address the advantages and disadvantages of those items that are (Items 3 and 5). They are specifically responsive to the stated goals and scope of the Geoengineering climate: call for submissions, in that they are required for the proper context of the schemes identified. It is hoped that this new material, in some cases revisiting and updating concepts that were "rejected" more than a decade ago, will be useful to the Royal Society's Study.

## SOLAR POWER FROM LEO

Andrew Meulenberg,[17] Rahul Suresh, [18] Shivram Ramanathan,[16] and Karthik Balaji P. S.[16]

This paper deals with a Low-Earth-Orbit-based solar-power-generation system. Starting with an assumption that an equatorial "circum-terra" ring can be deployed in LEO,[19] a solar-power generation system is proposed that would take advantage of an equatorial ring structure to provide mechanical stability, power transfer, and dynamic power storage.

Solar Power from space has been proposed since the 1970's. These systems, based in geostationary earth orbit (GEO) and with microwave beaming to earth, have never been funded beyond the exploratory stage because the large expense involved in such a system would make the costs of provided energy non-competitive. With the costs of energy increasing steadily over time, these systems might be revisited. However, other factors can make space solar power even more attractive. Foremost of these is the impact of global warming. This introduces two reasons for space solar power. First is the obvious reduction of fossil fuel use (not previously of concern); second is the possibility of using massive solar reflectors in LEO to reduce solar input to the earth. Relative to the massive estimated costs of sequestering $CO_2$ (or other greenhouse gases), solar "shades" in LEO are inexpensive. This option establishes the infrastructure and material framework for space solar power on a massive scale. Over time, the reflectors would be replaced by solar collectors and a major cost factor of space power would be eliminated.

Another factor to make space solar power attractive is the proposed development of a new system to transfer mass from earth to LEO.[20] This system, based on the proposed ring system, would greatly reduce the major launch costs and environmental impact inherent in deployment of a space solar power system.

These solar-power rings would consist of circum-terra, conductive fibers, along with the solar-power "stations" and microwave antennas for space-to-earth, space-to-space, and even earth-to-space power transfer. Each power-station would consist of arrays of solar concentrators and thermal radiators, coupled with high-efficiency thermal-to-electrical converters (e.g., Stirling engines, or Microgap ThermoPhotoVoltaics, MTPVs) and RF antennas (phased-array or directed-beam). The conductive-ring system provides for power transfer between the power stations and the active-transmitter sites (load sharing). Terrestrial rectenna farms are deployed at many locations beneath the ring (perhaps initially near the equator and later spread across the globe as the ring system expands). They would be large enough to provide efficient collection of RF power from ring stations 30° above the horizon and to keep the RF-power densities low at the earth's surface.

The details, advantages, options, and economics of the proposed LEO-based solar-power generation system relative to existing, future, and alternative energy sources (both renewable and non-renewable, space and Terrestrial) are described.

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[18] National Institute of Technology Karnataka, Surathkal, India

[19] Andrew Meulenberg, Rahul Suresh,[19] and Shivram Ramanathan, "Leo-Based Optical/Microwave Terrestrial Communications," Proceedings of the 59th International Astronautical Congress Glasgow, IAC-2008, Scotland, Sept. 29 – Oct. 3, 2008.

[20] Andrew Meulenberg, Karthik Balaji P. S., Rahul Suresh, and Shivram Ramanathan, "Sling-On-A-Ring: A Realizable Space Elevator to Leo?" Proc. of the IAC-2008, Scotland, Sept. 29 – Oct. 3, 2008.

**UK BIOCHAR RESEARCH CENTRE**

**Author:** Simon Shackley

03 December 2009

Dear Mr Parker

**Re: Geoengineering Climate: The Role of Biochar in Reducing $CO_2$ Emissions in the UK and Internationally**

We are pleased to submit the following evidence to your enquiry on 'Geoengineering climate'. The University of Edinburgh, working with Newcastle University and Rothamsted Research, has established a major new centre on biochar – the UK Biochar Research Centre (UKBRC), which is actively growing. This will integrate climate change and soil science, energy systems and policy analysis and bio-energy engineering. The aim is to undertake leading-edge multi-disciplinary research on the role of biochar as a carbon storage and sustainable energy technology, and to provide an understanding of the agronomic and socio-economic impacts of biochar. UKBRC is funded by the Engineering and Physical Sciences Research Council (EPSRC).

We would be pleased to come and talk to the Working Group or to individual members in order to provide more information on what is currently known about biochar and what we need to know in order to better evaluate the deployment of biochar. We would also welcome discussion on how to bring the biochar option to the attention of policy makers and investors, in the UK and internationally.

Yours sincerely

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**See also:** www.geos.ed.ac.uk/sccs

**Biochar, reducing and removing $CO_2$ while improving soils: A significant and sustainable response to climate change?**

UK Biochar Research Centre, hosted by the School of GeoSciences, University of Edinburgh, in partnership with Newcastle University and Rothamsted Research

**Summary**

1. The focus of this response is evaluation of a single option – that of biochar for carbon storage in soils.
2. Biochar is primarily a response to climate change. Carbon savings come from carbon sequestered for the long-term (100's to 1000's years) in biochar, and from avoided emissions (from substituting fossil fuels and fertiliser; and through suppression of methane and nitrous oxide emissions).
3. A conservative estimate is that 1 gigatonne of carbon per year can be stored in biochar by 2050, and probably by 2030, mostly produced from agricultural residues and organic wastes. More ambitious proposals, which progressively use dedicated biomass stocks, could increase this to 5 – 9 gigatonnes C per year by 2100, and probably much earlier, though careful evaluation of the environmental and socio-political implications of such a scenario is necessary (e.g. to ensure that it does not simply lead to a massive expansion of unsustainable agri- and silvicultural plantations).
4. Whilst biochar is readily produced from a wide range of organic feedstocks and wastes, the efficient 'closed-system' slow pyrolysis technology is still at a relatively early stage of development and is consequently still relatively expensive. As experience grows, several dominant designs should emerge and unit costs and maintenance & operation costs should come down.

5. Biochar has been shown to improve productivity of crop growth in many different soil and agronomic conditions, though there is a lack of scientific understanding of what explains this effect. Biochar has also been reported to suppress $CH_4$ and $N_2O$ emissions from soil and to improve water retention.
6. The UK's universities and research institutes are ideally placed to take biochar RD&D forward. A coordinated approach by the Research Councils will, however, be necessary.

**Question 1: What do you consider to be the current state of knowledge regarding the feasibility, efficacy and predicted impacts of biochar schemes?**

**What is biochar?** Biochar is a black carbon material produced from the decomposition of plant-derived organic matter (biomass) in a low- or zero-oxygen environment (i.e. pyrolysis or gasification) to release energy-rich gases which are then used for producing liquid fuels or directly for power generation. The carbon atoms in biochar molecules are strongly bound to one another, and this makes biochar resistant to attack and decomposition by micro-organisms. By contrast, the carbon in most organic matter is rapidly (between 1 and 5 years) returned to the atmosphere as $CO_2$ through respiration. Consequently, biochar is a potentially highly valuable way of stabilising carbon and storing it in soils and is one of very ways of removing $CO_2$ from the atmosphere. There are a very wide range of potential biochar feedstocks: e.g. wood waste, timber, agricultural wastes, manure, leaves, food wastes, straw, paper sludge, green waste, distillers grain, bagasse and many others.

The main technologies for producing biochar are fast, moderate and slow pyrolysis and gasification. Pyrolysis produces between 12 and 35% biochar (dry basis), with slow pyrolysis (at about 500$^{o}$c and with a very long vapour residence time of between 5 and 30 minutes) giving the best biochar yields. Gasification occurs at a higher temperature of at least 750$^{o}$c with a moderate vapour residence time of 10 to 20 seconds (Brown, 2009) and generates approximately 10% biochar (dry basis). Biochar has a unique porous structure and chemical composition which enhances soil fertility and allows for a more sustainable use of some soils. Biochar is first and foremost, however, a response to the problem of climate change. This is through the long-term storage of carbon in soils in a stable form as biochar, with additional carbon offsetting arising from the avoided emissions from fossil fuel combustion, fertiliser application and field operations.

**Longevity of Biochar Carbon Storage:** Biochar from forest fires has existed in some soils for 10,000 years, whilst radiocarbon dating of the *terra preta* soils of Amazonia show that the carbon can persist in the soil for between 500 and 7000 years before present (Lehmann et al., 2009). One conservative estimate is that the Mean Residence Time (MRT – the average time that biochar remains in the soil) is between 1000 and 2000 years for dryland conditions of northern Australia. A recent study confirmed that the MRT for black carbon in two Australian savannah regions was between 1,300 and 2,600 years (Lehmann et al., 2008). The half-life of biochar found in coastal temperate forests in western Vancouver has been calculated as 6623 years (Lehmann et al., 2009). There are, however, some other studies which show a much faster turn-over time for biochar. A study of fires in the Russian steppe concluded that the turn-over time of biochar was only 293 years. Meanwhile, biochar stocks formed after savannah burning in Zimbabwe had a MRT of only a few decades. Lehmann et al. (2009) suggest that these much lower residence times might be explained by processes other than mineralization alone (such as leaching or erosion).

The longevity of biochar in soils should not be overestimated: an unknown but large-scale mechanism for removing black carbon appears to exist. We know that more black carbon is produced than is found in possible long-term sinks (e.g. ocean sediments and the soil organic carbon pool) (Woolf 2008). Over-accumulation of black carbon in soils is also inconsistent with empirically-validated models of the response of carbon in soils. One of the critical research needs is better understanding of such processes on different timescales. In summary, whilst there are major scientific questions to be addressed regarding longevity, there is good evidence that biochar, if managed correctly, will remain in soils for at least 1000 years and possibly much longer. These timescales look sufficient for biochar to qualify as a viable option for atmospheric $CO_2$ reduction (since, to be effective in tackling anthropogenic climate change, the carbon must be removed from the atmosphere for hundreds to a thousand years) (Shackley and Gough 2006).

**How Much Carbon Can Biochar in Soils Store?** The amount of biochar that can be stored in soils is a function of the concentration of the material in the soil and the depth to which it is incorporated. To date, we have the evidence of the *terra preta* soils of Amazonia, which contain approximately 50 tonnes of black carbon per hectare to a one meter depth (Glaser et al., 2001). Applications of up to 140 tonnes of biochar per hectare on weathered soils in the tropics resulted in crop yields, and without reaching a point at which yield increases ceased (Lehmann et al. 2006). Several trials with particular crops have shown a threshold effect, and Lehmann concludes that: "crops respond positively to bio-char additions up to 50MgC $ha^{-1}$ and may show growth reductions only at very high applications." Biochar is a variable substance whose properties are determined by feedstocks, conversion processes and the soils into which it is applied. Exactly how much biochar can be applied in different agricultural and land-use contexts, and on what timescales, is not well understood at present.

Lehmann et al. (2006) estimate that current global *potential* production of biochar is 0.6 ± 0.1 gigatonnes per year ($10^9$ tonne or $PgCyr^{-1}$). They estimate that by 2100 production of biochar could reach between 5.5 and 9.5 gigatonnes per year. There are very large uncertainties attached to these numbers, however, arising from competition for land-use, competition for use of biofuels and agricultural wastes and a huge divergence (of nearly 1000%) in different expert estimates of the potential future global supply of biomass for bioenergy purposes. Woolf (2008) estimates that if all existing agricultural crop residues were used to produce biochar, this would constitute 1 gigatonne of carbon storage. A reasonably conservative assumption would be that biochar has the potential to offset global atmospheric carbon emissions at the gigatonne per year scale by 2050 (and probably by 2030 if a concerted effort were made) - one of the climate 'wedges' in Pacala and Socolow's (2004) schematic, hence comparable to other major mitigation activities ($CO_2$ Capture and Geological Storage (CCS), renewables, efficient vehicles, etc.).

**Positive Impacts of Biochar Upon Soils:** Studies of biochar-rich *terra preta* and *terra mulata* soils in Amazonia have stimulated interest in the agricultural benefits of incorporating biochar into soils. Crop fertility appears to improve in many situations where biochar has been incorporated, whilst such soils appear to retain water more effectively, as well as possibly reducing run-off of agricultural inputs and, in some circumstances, limiting nitrous oxide and methane emissions. In tropical environments, biochar has sometimes increased crop yields 2- or 3-fold, although at the moment the impact is not predictable. Biochar can also reduce the number and intensity of field operations, thereby reducing diesel use. And biochar addition appears to stimulate the net primary productivity of many agri- and ecosystems, thereby resulting in a net uptake of carbon.

Reviews of the agronomic impacts of biochar have been undertaken by Woolf (2008) and Blackwell et al. (2009). The reason why soil productivity is improved appears to be related to the following factors: reduction in soil acidity, improvement in the cation exchange capacity, an improved habitat for soil microorganisms and better water holding capacity. The pore size allows beneficial microorganisms to find suitable shelter from predatory soil fauna. Meanwhile, water retention in biochar occurs because water molecules collect in the voids, though chars can be hydrophobic so there is some uncertainty on whether water retention will be a universal property of biochar (Woolf, 2008). Whilst most greenhouse- and field-trials generally show the beneficial impacts of biochar upon agronomic performance, there is a high degree of variability in the response - hardly surprising considering the diverse sources of biochar and the highly variable soils and agronomic systems into which biochars have been introduced.

**The Efficacy of Biochar as a Form of Carbon Storage:** Evaluating the efficacy of biochar requires consideration of the energy and carbon balance of the full life-cycle. What is the energy yield (i.e. energy inputs compared to the energy outputs) for pyrolysis biochar systems (PBS)? What is the net carbon benefit (i.e. avoided greenhouse gas emissions plus carbon that is sequestered in the long-term) of PBS and how does this compare to other ways of using biomass for sustainable energy (such as combustion for electricity or heat, Combined Heat and Power, anaerobic digestion, fermentation, etc.). Is it better in carbon terms to use biochar as an energy source rather than applying it to soils as a long-term carbon store?

Fowles (2007) found that in terms of carbon balance, it is better to use biomass for PBS than for straight combustion if the reference case (i.e. what is being replaced) is natural gas or the national grid mixture. On the other hand, if coal combustion is being replaced, then more carbon emissions are avoided by using the biomass for conventional electricity generation than to use PBS. Fowles assumed that 30% of the material is converted to, and permanently stored as, carbon as well as a 33% efficiency for biomass

combustion. Furthermore, if biomass combustion is utilised with a Combined Heat and Power system (which typically reaches 80% efficiency), then use of biomass in such a way is preferable to PBS, except when the reference case is natural gas at 80% efficiency. Fowles did not include the avoided $CO_2$ emissions arising from the use of pyrolysis syngas or bio-oils, or suppression of non-$CO_2$ GHGs, so his estimate of the carbon value of biochar is almost certainly an underestimate.

As yet, very few Life Cycle Assessments (LCA) of pyrolysis + biochar have been undertaken so we cannot currently answer several key questions. Gaunt and Lehmann (2008) compared growing winter wheat with the production of bioenergy crops (BECs) (Miscanthus, switch grass and corn) and also explored the use of crop wastes (winter wheat straw and corn stover) to produce biochar. Their findings can be summarised in the key points below:

- The energy output is greater than the energy input by 2 to 7 times in the case where slow pyrolysis is optimised for biochar rather than for energy production (with a consequent 30% reduction in energy output). This energy balance compares favourably with comparable technologies such as ethanol from corn (which yields 0.7–2.2 MJ $MJ^{-1}$).
- The $CO_2$ emissions arising from pyrolysis are in the range 91 to 360 kg $CO_2$ per MWh (with no account taken of carbon sequestered in char, or other impacts of char on GHG emissions when applied to soils). This compares with emissions of 390 to 880 kg $CO_2$ per MWh for gas and coal respectively (in the UK).
- Including all the carbon avoided and sequestered, PBS accounts for 4 to 8 tonnes carbon avoided per hectare per year when PBS is optimised for energy generation; and between 12 and 19 tonnes avoided per ha per year when PBS is optimised for biochar production. Hence, optimising for biochar production rather than bioenergy avoids between 3 and 5 times more carbon. The carbon stored in biochar accounts for 41 to 64% of the overall carbon avoided, whilst avoided fossil fuel emissions, reduced fertiliser use and reduced non-$CO_2$ GHG emissions account for the remainder.

**2. How do you think research into biochar should be taken forward, and by whom?**

UK universities and research institutes are very well positioned to take forward RD&D on biochar. There are core competencies in the life sciences, soil and other geosciences, sustainable energy engineering, and systems analysis. The UK Biochar Research Centre will endeavour to play a coordinating and facilitating role to UK research activities, in addition to undertaking leading-edge research.

**3. What factors need to be considered before deploying any biochar schemes? Who should be responsible for any deployment?**

To our knowledge, there are no evident negative impacts arising from applying biochar to soils. According to Gaunt and Lehmann (2008), use of slow pyrolysis avoids the production of dioxins and polyaromatic hydrocarbons, which can be persistent organic pollutants. If biochar is deemed to be a by-product that is being disposed-of, then it is classified as a waste and the pyrolysis process and disposal of the biochar is subject to the onerous requirements of the Waste Directive. There are also regulations controlling what is put on to agricultural land in the UK and it is clear that a detailed environmental impact assessment will be necessary prior to any deployment of biochar, to ensure that there are no adverse impacts. Biochar projects in developing countries that are aiming to secure carbon credits, will be subject to evaluation under the Clean Development Mechanism. It is important that appropriate environmental impact assessment methodologies are developed and adopted internationally and the UK Government could play an important role here.

**4. What do you consider to be the most important political, social, legal or ethical issues raised by biochar?**

The use of PBS need to be carefully evaluated to ensure that there are no adverse impacts on land-use, potential conflict with food production or biodiversity protection. As is the case for biomass for bioenergy in general, if biochar becomes one of the principal carbon reduction 'wedges', there are inevitable implications for land-use change globally on a large-scale. Such land-use change raises important questions at a number of levels: environmental impacts from (potentially) intensive land-use; carbon emissions from forest clearing which may take years to 'pay back'; land ownership and equity issues regarding who benefits and who loses out from large-scale plantations; ethical issues regarding whether

large-scale, intensive biomass cultivation is consistent with moves to a more sutainable zero-carbon society (e.g. see Ernsting and Rughani (2008) for a critical NGO perspective on biochar). If PBS is to contribute constructively to a sustainable response to carbon reduction, it is vital that the lessons of the past regarding the adverse environmental and socio-economic and political impacts of intensive plantations are learnt and acted upon.

**5. What do you see as the main barriers to, and opportunities afforded by, biochar?**

Biochar provides an opportunity for involving farmers and landowners as participants in carbon markets; this is important to rural livelihoods and diversification in all countries, and lends itself particularly well to poverty alleviation in developing countries. Creative approaches to certification and verification of biochar under the Clean Development Mechanism (CDM) could permit a much-needed step-change in the engagement of small farmers from developing countries in the CDM. There is, furthermore, an opportunity for biochar to contribute to low-carbon food chains, i.e. if the carbon stored in biochar (derived from crop residues) can be accounted for in the carbon footprint of foods. PBS may also provide important low- or negative-carbon alternatives to existing and emerging waste technologies.

A key barrier at present is the lack of reliable off-the-shelf pyrolysis technologies at a suitable price. Technology development is proceeding rapidly but there is, as yet, no 'dominant design' in the market, and it is likely that a variety of competing designs will be available to developers over the next few years before the market settles on a few preferred designs. At this stage of the technology cycle, costs per unit are likely to remain high and performance, reliability and operability parameters are still being formalised. Partly as a consequence of technological uncertainties, economic analyses of biochar are at present in their infancy. Gaunt and Lehmann (2008) found that the cost of reducing a tonne of $CO_2$ in the PBS they examined was between \$9 and \$16 (relative to maximising the plant for energy production). This is considerably less than the average cost of a tonne of $CO_2$ under the EU ETS over the past several years. The authors do not, however, provide a full economic costing of their PBS, so the abatement cost is not comparable with commonly quoted values for other technologies. McCarl et al. (2009) have undertaken a full economic costing of biochar for US conditions and find that the use of maize residue using fast or slow pyrolysis is not profitable. They do find, however, that the economic value of carbon storage in biochar is slightly greater than its value as an energy source, especially at the summer 2008 carbon price on the EU ETS (\$40 $tCO_2^{-1}$). For slow pyrolysis to be economic, however, would require the carbon price to double to \$79 $tCO_2^{-1}$.

**6. Where do you feel that biochar fits in the greater scheme of climate research and action to mitigate and adapt to climate change?**

PBS has a relatively low-capital intensity and a short lead-time. This means that, once good technology designs are available in the market at the right price, deployment could take place rapidly at the global scale. Herein lies an important advantage of biochar compared to low-carbon energy projects which are capital-intensive and have a long lead-time - such as CCS and nuclear power. More research is needed to explore the interactions between deploying biochar on a gigatonne scale and other elements of a c. 10 GtC reduction strategy to 2050. For example, is it consistent with other bioenergy and biofuels policies and ambitions? What would be the implications of an aggressive biochar strategy for land-use, food production and rural livelihoods? Biochar may also help in adapting to climate change through its role in water management, mitigation of erosion and creating a more resilient agricultural system.

**7. Are there any other issues related to biochar that you consider to be important**

Deploying PBS is complex because of the range of sectors and policy domains which are affected: energy & climate, soils, waste, agriculture & food, water, rural development, and so on. PBS is vulnerable to price fluctuations in products and services in a number of these different markets. Hence, PBS deployment would require recognition of multiple benefits and appropriately designed policies.

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**UK MET OFFICE**

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**Met Office submission to the Royal Society call on "Geoengineering the Earth's Climate"**

This submission represents the institutional position of the Met Office.

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**Summary**

- It would be unrealistic to believe that the climate effects of geoengineering schemes can be predicted to a better accuracy than predictions of climate change itself.
- Because of the long lifetime of carbon dioxide in the atmosphere, geoengineering the planet with an albedo modification scheme would have to be implemented for hundreds of years to offset a delay in reducing $CO_2$ emissions of a few decades.
- If sea-salt production increases cloud droplet number concentration as assumed, seeding large scale stratocumulus cloud decks in the South Atlantic, South Pacific and North Pacific can produce a significant radiative forcing that can partly offset global warming.
- Cloud seeding over the ocean is likely to result in a inhomogeneous radiative forcing. The climate response to a inhomogeneous radiative forcing is inhomogeneous. While some areas benefit from geoengineering stratocumulus decks, there are significant areas, including the Amazon rainforest, where the climate response could be very detrimental, thus questioning the reversibility of such a scheme.
- Artificial fertilisation of the ocean may only achieve a limited carbon uptake and could lead to the degradation of the oceanic ecosystems. The long-term impacts are not known.
- Both oceanic and terrestrial ecosystems would respond to a geoengineered climate where the atmospheric $CO_2$ concentration keeps increasing but the global-mean surface temperature does not, with both positive and negative impacts. The impact of ocean acidification on the marine biology remains largely unknown.
- Earth System models such as those developed at the Met Office Hadley Centre can be used to study the positive and negative impacts that geoengineering schemes would have on our climate and environment.

**Report**

This report focuses on albedo modification schemes but briefly addresses some aspects of greenhouse gas reduction schemes as well. It brings general points that are valid for all geoengineering schemes as well as specific points that are valid only for a particular geoengineering scheme. Rather than addressing each of the 7 questions, we categorize this submission in different sections and indicate the relevance to the 7 questions and scheme categories as appropriate.

## a) Timescales of geoengineering and climate change (Q1, Q6, Q7; category 2)

It is of paramount importance that geoengineering schemes are not assessed against their cost effectiveness for achieving a particular radiative forcing at a particular time in the future. Instead a cost-benefit analysis of geoengineering schemes should consider the reduction in radiative forcing achieved over a long timescale (commensurate with our target for climate stabilisation) and the implications that a termination of the geoengineering scheme would have in the future. Using a too short time horizon to assess a geoengineering scheme is like ignoring the cost of decommissioning a nuclear power plant at the planning stage.

Boucher et al. (2008a) showed that geoengineering the planet with an albedo modification scheme (e.g. through the direct and indirect effects of aerosols) would have to be implemented for hundreds of years to offset a delay in reducing $CO_2$ emissions over a few decades. Alternatively much larger emissions reductions would be required to compensate for the emission overshooting once the geoengineering is

stopped. This arises because $CO_2$ has such a long lifetime compared with the short term interventions. Boucher et al. focused on stabilisation scenarios at 550 ppm (as a low-end but realistic mitigation scenario) and 750 ppm (as a high-end mitigation scenario). They specifically investigated the consequences of delaying the $CO_2$ emissions reductions by 1 to 4 decades before coming back either to the desired emission pathway or the desired concentration pathway.

**b) Climate response to stratocumulus decks brightening (Q1; category 2b)**

One suggestion (Bower et al., 2006; Latham et al., 2008) is to increase the albedo of low-level marine clouds by injecting large amounts of sea-salt aerosol into the marine boundary layer in certain regions using a fleet of cloud-seeding ships (Salter et al., 2008). The suggestion is that the sea-salt aerosol would act as cloud condensation nuclei and so increase the reflectivity of the modified cloud via the first (albedo) and second (precipitation efficiency) indirect effect. Such clouds, being low-level, act to cool the climate system, and the suggestion is that modifying them would enhance this cooling. We have not attempted to address issues regarding the plausibility and detailed aerosol-cloud microphysical aspects of this geoengineering scheme, but have assessed the geographic impacts of such a scheme if the mechanism works as suggested by its proponents.

The Met Office Hadley Centre has performed an idealised study of the climate response of deliberately seeding large scale stratocumulus cloud decks in the South Atlantic, South Pacific and North Pacific thereby invoking a cooling via the first and second aerosol indirect effects. Atmosphere-only, fully-coupled atmosphere/ocean, and atmosphere/mixed-layer ocean versions of the Met Office Hadley Centre HadGEM2 model are used to investigate the radiative forcing, climate efficacy, and the response of regional temperature, precipitation and net primary productivity to such geoengineering. The radiative forcing simulations indicate that seeding all of the three stratocumulus areas offsets approximately 35% of the radiative forcing due to current levels of greenhouse gases. Transient simulations of the climate response reveal that this approach could delay the simulated global warming scenario by about 25 years. These simulations suggest that while some areas experience increases in precipitation and net primary productivity, sharp decreases are noted in South America, with particular detrimental impacts on the Amazon rainforest. Further simulations with the atmosphere/mixed-layer ocean model where each of the three stratocumulus sheets is modified in turn reveals that the most efficient cooling per unit radiative forcing occurs when the South Pacific stratocumulus sheet is modified. These results suggest that **while some areas benefit from geoengineering, there are significant areas where the response could be very detrimental** with implications for the practical applicability of such a scheme.

It has already been argued that these experiments do not correspond to the suggestion by Latham et al. (2008) to seed larger geographic areas than solely the three predominant stratocumulus areas initially suggested by Salter et al. (2008). We accept that our experiment is idealised but it would be wrong to think that cloud seeding could result in a homogeneous radiative forcing. Cloud seeding by sea-salt particles is likely to be enhanced in regions of stratocumulus decks. This is because these regions exhibit persistent cloud regimes; they have a high fraction of low-level non-precipitating cloud with little overlying high-level cloud, and generally have fairly low cloud droplet number concentration (CDNC) values, making them susceptible to modification by the addition of sea-salt aerosols. In addition, calculations have been made to assess the lifetime of sea-salt aerosol injected in the storm track regions as suggested by Latham et al. (2008). The lifetime of the sea-salt aerosol when injected in such regions is too low for injection in these areas to be effective (less than 1 day) owing to the significant wet-deposition of aerosol in rainout (unpublished results). Moreover, being located near continents, these stratocumulus cloud sheets are readily accessible, which would facilitate deployment and maintenance of the cloud-seeding ships.

**c) Climate response to injection of stratospheric aerosols (Q1, Q2; category 2c)**

Volcanic aerosols are a good analogue to a stratospheric aerosol geo-engineering scheme. Research at the Met Office Hadley Centre has explored climatic change caused by the injection of aerosols into the stratosphere following large volcanic eruptions either as such (Jones et al., 2005) or as part of transient climate simulations of the 20$^{th}$ century.

The effects of volcanic eruptions are not just limited to lowering surface temperatures. Changes of heating in the stratosphere influence tropospheric circulation patterns. There are changes to the hydrological cycle, which cause decreases in global and other changes to regional precipitation. The

carbon cycle is also influenced by the impact changes in radiation, temperature and precipitation have on vegetation and surface fluxes (Mercado et al., 2008). These and other climatic impacts are being explored for volcanic eruptions and may provide analogues to the impacts that may follow a stratospheric aerosol geoengineering approach.

Rasch et al. (2008) examined the pattern of climate change associated with stratospheric injection of sulphur. Their model indicates that during winter mid-latitude and polar regions do not cool as much as the rest of the world in response to stratospheric aerosols. Rasch et al. also showed that the increased mass exchange between the stratosphere and troposphere under a warmer climate shortens the residence time of stratospheric aerosols and requires a larger injection rate of sulphur. Finally they pointed out to the importance of the aerosol size in determining the radiative efficiency of stratospheric aerosols. Tilmes et al. (2008) showed that large artificial injection of sulfur in the stratosphere would cause significant Arctic ozone depletion and would delay the recovery of the Antarctic ozone hole.

The Met Office Hadley Centre had not yet performed simulations of the climate response to emissions of sulphur dioxide in the stratosphere using its latest Earth System model. However, in collaboration with universities, we will soon have the capability to perform such experiments with a modified version of our HadGEM2-ES climate model that would include the UKCA stratospheric chemistry module coupled to the UKCA-MODE aerosol scheme. Such a model would be appropriate to study the response of climate and stratospheric ozone to anthropogenic perturbations to stratospheric aerosols

**d) Reversibility and irreversibility of geoengineering schemes (Q1, Q3, Q4; category 2)**

It has been argued that surface- and troposphere-based schemes are easily reversible while upper atmosphere schemes are less reversible and space-based schemes may be irreversible. While this is true from the point of view of the lifetime of the perturbation introduced in the troposphere or stratosphere, it should not be assumed that the effects of surface-based and troposphere-based geoengineering schemes are necessarily all reversible. Specifically, Jones et al. (2008) show that intervention to brighten clouds in some regions would give reduced rainfall in other regions, such as the Amazon rainforest, possibly causing a dieback. Such impacts on the biosphere would be effectively irreversible, which affects the concept of pulling out of geoengineering if it has nasty effects. Moreover, if geoengineering has been used to relax planned $CO_2$ emissions reductions, the additional $CO_2$ emissions that occurred before the geoengineering scheme is stopped cannot be reversed.

**e) Oceanic carbon sequestration (Q1, Q2, Q3, Q4, Q5; category 1a ii))**

Oceanic carbon sequestration schemes aim to reduce ocean surface $CO_2$ (and thus draw more $CO_2$ from the atmosphere) by stimulating the growth of phytoplankton. These single-celled plants take up carbon when they grow, and some of the fixed carbon sinks in particles before being recycled into solution again. The phytoplankton growth is proposed to be stimulated by artificially fertilising the ocean with a micro-nutrient (iron, needed in trace quantities), or a macro-nutrient (nitrate and/or phosphate) or by bringing naturally nutrient-rich water up to the surface from depth.

Most of the required technology is available, but the logistics of operating the schemes on the scale required are formidable, especially if, as modelling studies indicate, the most efficient area is at high latitude around Antarctica. Small-scale experiments have shown that artificial fertilisation can produce a bloom of phytoplankton. However long-term effects and those over a wider area are not clear from experiments. Model studies (Marinov et al., 2006, and references therein) have repeatedly shown that even if the theoretical maximum efficiency of carbon uptake is achieved the reduction in atmospheric pCO2 is only a relatively small part of the projected 21$^{st}$ century increase (70ppm in Marinov et al., 2006). However this maximum efficiency is unlikely to be achieved, because even if all the required nutrients are available phytoplankton growth can still be limited by light or by zooplankton grazing. The studies also indicate that if growth is increased at high latitudes (where the carbon uptake is more efficient) then less nutrient is available at low latitudes, so growth decreases there. Finally, the extra carbon taken up is stored close to the surface, and can swiftly return to the atmosphere (over a few decades). Even worse, if the scheme involves bringing naturally nutrient-rich water up from depth then because such water is usually also carbon-rich the flux of $CO_2$ out of the ocean will increase.

The big uncertainty with all the suggested schemes is how the ecosystem will respond; this is not well understood at present, and such predictions are beyond the competence of current ocean biological

models. If taken forward at all, more detailed modelling studies are needed before any large-scale practical trials are undertaken as the potential to seriously degrade marine ecosystems is significant. Ecosystem degradation is a key issue, as many people's livelihoods depend on food and other services from the ocean. Different phytoplankton species respond in different ways to fertilisation. Sometimes toxic plankton can bloom, sometimes the increased growth at the surface leads to anoxia at depth. The food web could be disrupted, reducing the transfer of energy to the higher trophic levels that we use as food (of course, there could be an increase). It is possible that for some areas the effects could be worse than those of global warming. A better understanding of the long-term response is also needed.

### f) Climate response to increasing the air-sea DMS flux (Q1, Q3, Q4; category 2b)

Wingenter et al. (2007) suggested that by fertilizing a large area of the Southern Ocean, a significant amount of recent global warming could be offset through increased flux of DMS from the fertilized area. The hypothesis is that increased DMS emissions would increase the concentration of sulphate aerosols, thereby having an impact on the number of cloud condensation nuclei (CCN) and cloud optical properties. This suggestion was investigated by Woodhouse et al. (2008) with the GLOMAP-MODE model. A patch that mimicked the one envisioned by Wingenter et al. was added to the model, increasing DMS surface concentration by a factor of 5 over 5% of the Southern Ocean for a month of December. The subsequent impact on CCN was compared to a baseline model case, and the predictions made by Wingenter et al. (2007). The impact on CCN predicted by GLOMAP-mode is almost an order of magnitude less than that projected by Wingenter et al., so that the impact on climate is likely to be minimal. The actual impact on climate, and feedbacks resulting from altered fluxes of DMS could not be calculated in the GLOMAP-MODE model, but might be worth investigating in an online global climate model such as HadGEM2 coupled to the UKCA-MODE aerosol microphysical model.

### g) Impacts of elevated concentrations of atmospheric $CO_2$ (Q1, Q2, Q3, Q5; category 2)

#### Ocean acidification

A certain consequence of moderating global warming by engineering an increase in planetary albedo, whilst allowing atmospheric $CO_2$ levels to continue to rise, is the continued, and even potentially enhanced, acidification of the world's oceans. Rising levels of atmospheric $CO_2$ are already impacting the chemistry of the oceans, and this effect is predicted to increase significantly with further anthropogenic emissions over the coming decades and centuries (Feely et al., 2004; Orr et al., 2005). The impact of ocean acidification (the term now commonly used to describe the reduction in pH of the surface ocean in response to increased absorption of atmospheric $CO_2$ and its dissociation to carbonic acid) on marine biology, and the potential feedback on atmospheric $CO_2$ concentrations, represent a major area of ongoing research. Despite the chemical response of the oceans to increasing levels of atmospheric $CO_2$ being relatively well constrained (Feely et al., 2004; Orr et al., 2005), the complexity of the biological response is only just being realised.

A major focus amongst the community has been on the consequences of a reduction in seawater pH on calcium carbonate shell, or reef, building organisms. There is compelling evidence that corals and foraminifera (a major component of the zooplankton) will experience a reduction in calcium carbonate precipitation in response to elevated $CO_2$ levels (Barker and Elderfield, 2002; Bijma et al., 2002, Langdon et al., 2000), and with more delicate skeletal structures are likely to undergo increased grazing, with implications for all associated ecosystems. The third major marine calcifier -coccolithophores- appears to exhibit a more complex response to elevated $CO_2$ levels. Preliminary results suggested that coccolithophores too would experience reduced calcification under lower pH conditions (Riebesell et al, 2000), however recent culture experiments, backed up by sedimentary analysis, suggest that certain coccolithophore species might actually calcify more heavily under conditions of elevated $CO_2$ (Iglesias-Rodriguez and Halloran et al., 2008; Halloran et al., 2008).

The focus on calcifying organisms has occurred because, beyond the impact on marine ecology, calcification plays a vital role in carbon cycling in the ocean. A reduction in calcification, without a concomitant reduction in organic carbon production (e.g. Riebesell et al., 2000) would result in increased carbon export from the surface to the deep ocean, and allow the ocean to 'soak up' more $CO_2$ from the atmosphere. Conversely, an increase in calcification without an increase in organic matter production (e.g. Langer et al., 2006) would result in a reduced surface-oceanic capacity to store $CO_2$. If a purely albedo-based approach were to be taken to climate-geoengineering, the sign and strength of this $CO_2$ feedback must first be understood.

In the Met Office Hadley Centre we are currently implementing a scheme to investigate the consequences of ocean acidification on the marine carbon cycle and air-sea C fluxes. This will first be investigated in an ocean-only model, but there is interest in incorporating this feedback into a full earth-system model. Such a model would be ideally suited to explore the, to our knowledge as yet unexplored, carbon feedbacks associated with the unique situation where the oceans remained cool (and therefore capable of absorbing additional C), but the atmospheric $CO_2$ concentrations continued to rise.

**Land fertilisation**

Increased atmospheric $CO_2$ concentrations will also affect terrestrial ecosystems through an increased in plant productivity and a reduction in runoff (Gedney et al., 2006; Betts et al., 2007). The fertilisation effect is expected to be larger if not associated with an increase in surface temperature (as it would be the case under a geoengineered planet). However it should be noted that the $CO_2$ fertilisation effect itself leads to a small increase in surface temperature through decreased evapotranspiration (e.g., Boucher et al., 2008b; Doutriaux-Boucher et al., 2008).

**h) Uncertainties in climate prediction (Q1, Q3, Q4; category 2)**

It is noteworthy that a number of geoengineering schemes rely on the injection of aerosol or aerosol precursors in the atmosphere. Yet they are still large uncertainties in the direct and indirect radiative forcing by aerosols despite recent progress (Haywood and Schulz, 2007). It would be unrealistic to believe that we can predict the climate effects of such geoengineering schemes to a better accuracy than we can predict climate change itself. Yet one can argue that, from ethical and legal points of view, our level of confidence in climate predictions need to be higher before undertaking intentional climate change than before taking precautionary measures against inadvertent climate change.

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