# Geoengineering the climate: Science, governance and uncertainty

## Responses to call for evidence

## Part II

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***Global Temperature Regulation through man-made aerosol***
**(Geoengineering Climate: Royal Society Call for Submissions)**

**Summary**

1. **Geoengineering schemes are a possible stopgap if dangerous climate change occurs and more time is needed to meet global energy demands through non CO2 producing forms of energy**

2. **Such schemes should be investigated to establish their likely effectiveness and reducing or stabilizing global temperature but only implemented if absolutely necessary**

3. **It is important that research involves groups of engineers, physical scientists and climate modelers to enable the practicality of schemes to be investigated along with their effectiveness and likely impact on regional as well as global climate.**

4. **It is essential that such schemes and their effects can be rapidly terminated after implementation in the event of damaging changes in global circulation and regional weather that were not anticipated.**

This submission is a personal statement but written in my capacity as Head of the School of Earth Atmospheric and Environmental Sciences at the University of Manchester.
In the sections below I will briefly respond to each of the questions posed:

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

I am confining my response to schemes that alter the radiative balance of the troposphere or stratosphere by injecting atmospheric aerosol to directly scatter solar radiation or alter cloud properties so that their albedo is enhanced or lifetime extended.

It has been demonstrated that such schemes are in principle capable of offsetting global warming and at least stabilizing temperatures. These schemes are discussed in a recent special issue of Philosophical Transactions of the Royal Society A, and I am a co-author of one paper concerning cloud albedo enhancement. There is much uncertainty, however, about the engineering required to get the aerosol material into the right place the quantitative effects of the aerosol both in reducing global temperature and also in producing possible unwanted effects due to changes in global circulation and precipitation patterns.

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

I believe that detailed modeling, laboratory and limited field trials need to be performed by consortia of engineers (producing the aerosol) physical scientists (investigating the impact of the aerosol produced) and climate modelers to investigate the likely beneficial and potentially harmful impacts the global and regional climates

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

1. It must be clear that dangerous climate change is inevitable and imminent
2. The impacts of the scheme must be clear both globally and regionally across the globe

3. It must be possible to stop the scheme quickly and remove its forcing effect in the event of unexpected dangerous impacts

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

Two issues:

1. Geoengineering must be understood to be an emergency stopgap to reduce the impact of greenhouse gases, whilst we develop new clean technologies. We must resist the temptation to attempt make it a permanent fix
2. Regional climate change induced by circulation changes resulting from geoengineering may adversely affect the regional climate in parts of the globe. These changes may impact on agriculture, tourism and other weather related activities in a damaging way. It is important that every effort is made to predict these impacts and reach international agreement before proceeding. However, the need for the rapid termination of geoengineering and its impacts is given is essential in the event that unexpected consequences occur.

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

The main barriers are technological, getting the dissemination systems to work on a large enough scale, the cost and understanding the full impact of geoengineering on the climate system. The main opportunities are increased understanding of the climate system and time to develop new forms of energy and refine and develop nuclear power.

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?

Geoenginnering is a short term fix and not the solution to the problem, it has many dangers but we need to examine it as a possible way forward in the short term if the worst case scenarios in projected climate change manifest.

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

I believe the key issues are summarized above.

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**Submission to the Royal Society's Geoengineering Climate Study**

This response is a personal position of the authors

**Summary**

Geoengineering is a key component of humanity's effort to recover into an environmentally stable, economically viable future.
It can probably only operate effectively if it is embedded into systems that humanity requires for economic reasons, rather than operating as a stand-alone 'save the environment' process.
Two specific examples are given of how geoengineering can be combined synergistically with electrical power generation.
Heat sources (thermal emissions) and sinks within the global climate system will play an important role in the assessment of geoengineering benefit.

**Replies to questions**

1. The current state of knowledge is incomplete, particularly with respect to the range of alternative schemes that can achieve a reduction in projected global temperature.

5. The main barriers to geoengineering are economic cost, environmental impact, and, in some types of scheme, negative impact on (or absence of synergy with) other infrastructure and economic activities such as energy generation and food production. In order not severely to drain humanity's capacity for development, geoengineering schemes must complement essential economic activities and at their most successful will be an *integral part of these activities*. Examples of high synergy are electricity generation schemes that inherently produce a negative temperature forcing, thus having the dual function of energy supply and climate mitigation. This submission points out two such schemes that may achieve this at the level of 0.5-1.5 W/m$^2$ by 2100, given appropriate funding.

6. Climate geoengineering is, or should be, an integral component of climate research and mitigation actions, provided the focus is on synergistic schemes as discussed in the response to question 5, in preference to 'stand-alone' geoengineering schemes.

7. A key issue is to understand the baseline climate evolution upon which mitigation has to act. This submission argues that this baseline actually includes:

   (i) Changes in greenhouse gas (GHG) levels and resultant temperature forcing under plausible assumptions on GHG emissions control (e.g. scenarios discussed in Ref. **[Kharecha**] and evaluated by the IPCC).

   (ii) Thermal emissions and resultant temperature forcing that will occur under plausible projections of economic activity during the next century and beyond **[Cowern]**.

It is likely that item (i) will peak and subsequently decline slowly from midcentury onwards while item (ii) will increase almost exponentially. Viewed on timescales relevant to geoengineering this makes thermal

emissions a key element of the baseline. Consequently *thermal sources and sinks within the climate system*, as well as albedo engineering, should be considered when assessing quantitative benefits of alternative geoengineering schemes.

**Discussion**

Ref **[Cowern]** argues for the use of selected power generation schemes that perform the dual function of energy supply and geoengineering within a single technology. Two schemes are put forward. The first is a modification of a recent proposal for a Solar Grand Plan for energy generation dominated by photovoltaic (PV) technology **[Zweibel]**, which it was claimed could provide the USA's (and we infer by a proportional extension, most of humanity's) energy supply by 2100. In the modified scheme, wide band-gap thin-film PV technology is used to generate electricity from the energetic 'blue' end of the solar energy spectrum while lower energy photons are reflected back out of the PV surface. This raises the albedo of the PV surface, so that for a system of the proposed magnitude, global forcing may be reduced by ~0.5 $W/m^2$ by 2100 with respect to that occurring with zero-carbon energy sources such as nuclear energy or fossil fuels with carbon capture and storage. The reduction in forcing may be somewhat attenuated if surface cooling engendered by albedo increase and electrical energy transmission causes temperature inversion to clear cloud cover over large PV arrays – however such an effect would increase electricity output, enabling solar generation to forestall more rapidly the use of $CO_2$ emitting power systems.

The second scheme proposed in **[Cowern]** emphasizes the large-scale implementation of a form of Ocean Thermal Energy Conversion (OTEC) technology **[Vega]** that uses deep ocean water as coolant. Current feasibility studies on OTEC are effectively looking at the transfer of heat energy from surface waters (which are close to a quasi steady state with atmospheric temperature) to 1 km deep ocean waters. This will provide the capacity to cool surface waters over timescales of hundreds of years before a significant return flux of heat enters the surface ocean-atmosphere sub-system. Deeper OTEC systems might provide even longer time delays. The magnitude of the effect is about 0.04 $W/m^2$ per TW of electrical power output , or > 1 $W/m^2$ by 2100 if OTEC could provide all global energy needs by that time. Since OTEC is already the focus of energy-related research funding, it could be a highly effective policy to support such research work for geoengineering purposes as well.

While this latter scheme does not lie within the strict boundaries of GHG mitigation or albedo engineering, it does appear to be important enough to merit consideration by the Geoengineering Climate study.

These examples illustrate the vital importance of connecting geoengineering research with the wider science, engineering and societal communities, especially those involved in climate and energy studies, so that efficient, affordable geoengineering can be built into the flow of future economic development.

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## Summary

Greenhouse gas emissions are unlikely to decrease fast enough to mitigate the more damaging impacts climate change. It therefore seems logical that the scale of the response should be proportionate to the problem we face – making geoengineering appear to be an attractive option. However, the potential scale of unintended consequences of attempts to re-engineer the Earths climate system advocates caution. The environment must be protected as a whole, balancing climate change mitigation with other needs.

## Background

As emission mitigation efforts make limited progress, many politicians and scientists are taking a serious look at re-engineering the climate system to create anthropogenic cooling as a counter to anthropogenic warming. Proponents of geoengineering, the large-scale modification of the Earth's system to bring a desired end, often point out that civilisation itself is one large unplanned geoengineering scheme that brought unintended consequences that we may alleviate through well-planned targeted geoengineering.

## Emerging schemes

From the body of evidence we have collected in the last four years, we see geoengineering approaches in two areas. The majority of proposed schemes focus on countering the temperature effects of climate change through either albedo modification (increasing sunlight reflection) or greenhouse gas reduction, but a small number of schemes are beginning to address other features of climate change. So far only experimental projects have been undertaken. The main developments from our evidence-base are described below.

- ***Albedo modification***

Albedo – the extent to which sunlight is reflected – plays a significant role in the climate system. As such, modification of planetary albedo to reflect more solar energy back into space is seen as one mechanism to counter the warming caused by greenhouse gases.

- **Atmospheric injection** uses particulates – usually either sulphur (1, 2, 3) or water droplets (4) – to enhance natural cloud formation, thus increasing cloud cover which increases the reflection of sunlight back to space. The theory is grounded in observations of atmospheric cooling after volcanic eruptions, which release sulphate aerosols into the atmosphere, and the 'global-dimming' phenomenon resulting from 20$^{th}$ Century industrial air pollution. An injection of 10 million tonnes of sulphur could cool the Earth by 0.5°C for a year or two (1). Yearly injections could provide a 20 year

grace period before carbon emissions need to be reduced (5). Injection will require energy intensive delivery systems such as jets, naval rifles or stratospheric balloons.

- **Sun shades** use hardware rather than the enhancement of natural processes. Reflection from trillions of tiny discs (6) or lenses and large mirrors (7) or shields (8) set in space between the sun and the Earth counters warming by limiting solar input. If atmospheric $CO_2$ doubles, 1.8% of the sun's heat would need to be blocked to prevent severe climate change impacts. This would require a massive 100,000 km long shield. Placement of such large pieces of hardware in space will be energy intensive and polluting.

- **Vegetative albedo** can be increased though direct planting; however, more recent research suggests some possible geoengineering approaches. These include enhancing the amount of leaf hair on certain super hairy plants (9), and doping trees with nitrogen (10). Some relationship has been found between leaf albedo and nitrogen content in trees; however, the mechanism is not yet understood. Tests with super hairy soya plants show they reflect between 3 and 5% extra sunlight back into space from latitudes between 30 and 60°; enough to cool these regions by an average of 1°C (9). Changing the albedo of plants could alter habitats or even impact local climate. Doping with nitrogen carries all the risks associated with fertilisers including groundwater contamination, increased water needs and the formation of nitrous oxide in soils.

- **Surface reflection** can be enhanced physically by laying reflective plastic on glaciers (11), oceans or deserts (7). One estimate puts the decrease in radiative forcing needed to counter global warming at 2.8 $Wm^{-2.}$ This would require covering a total of 4 million square miles (an area larger than the United States) with a material that increases reflectivity to 0.8 (12). Any physical modification of the Earth's surface is likely to alter habitats and place considerable strain on land resources.

- ***Greenhouse gas reduction***

In contrast to albedo enhancement, which counters warming with cooling, these methods act to directly reduce greenhouse forcing through removal of the gases.

- **Ocean fertilisation** uses nutrients, usually delivered through iron enrichment (13, 14) but also through nitrogen enrichment (15, 16) or piping of cold bottom waters up to the surface (17, 18), to enhance primary productivity in the oceans. Plankton remove carbon dioxide from the atmosphere by incorporating it during growth, incorporating it into skeletons (e.g. diatoms) or excreting carbon rich pellets (e.g. sea salps) that sink to the bottom of the ocean. Iron is most often the deficient nutrient needed to enhance plankton blooms. Each kilogram of iron can fix 83,000 kg of $CO_2$. Carbon sequestration efficiencies resulting from ocean iron fertilisation experiments range between ~4,300 mol C per mol Fe and 668,000 mol C per mol Fe (19). Pumping cold water to the surface would require 134 million pipes in order to sequester one-third of the carbon dioxide produced by human activities each year, according to US company, Atmocean Inc (17). Stimulating primary productivity could lead to increased harmful algal blooms, deep ocean oxygen depletion or anoxia and disrupted ecosystems.

- **Agrichar** is a soil improving charcoal technique produced through pyrolysis of biomass, typically agricultural waste. Emerging evidence suggests application of agrichar removes carbon from the atmosphere and locks it into healthy soils that do not need further tilling or fertilising following application (20, 21, 22, 23) and produces fuel as a by-product (24). At full potential, agrichar could sequester more $CO_2$ by the end of the century than is currently emitted from the use of fossil fuels (25). Models of UK potential using forestry residues, purposely grown biomass, non-wood waste and wood waste showed potential for sequestration of 14 MtC/yr, which is 9% of current UK carbon emissions (26). However, agrichar will only sequester carbon if applied properly in the correct kinds of soil – a ten year study found that charcoal mixed with leaf litter actually releases carbon because of the increased presence of micro-organisms. It is this type of detail that makes geoengineering risky. Use of agrichar is limited right now by a lack of pyrolysis plants (27). New Zealand company

Carbonscape are pioneering microwave technology for agrichar, claiming that it is more efficient than traditional pyrolysis even if using fossil fuels (28).

- **Engineered soils and plants** can enhance natural carbon removal. If soils are supplemented to contain high-levels of calcium silicates which lock up $CO_2$ released from plant roots, 5 to 10% of the UK's carbon reduction goals could be met (29). In addition, the plants themselves can be genetically engineered to enhance the formation of silica plantstones which lock away bits of plant matter (30). Genetic modification companies are looking at a number of different ways to enhance natural carbon uptake and sequestration. Actual environmental impacts of genetic modification have not yet been detailed (31); however, widespread opposition to the technology remains in Europe.

- **Mineral precipitation** can be enhanced in perdidotite (32) or basalt (32, 34) by fracturing the rock and pumping in $CO_2$-enriched water or supercritical $CO_2$. The UK has relatively limited igneous rock formations, but use of this process in places like India (~150 $GtCO_2$, 33), Oman (~100,000 $tCO_2$/yr, 32), the US (~50 $GtCO_2$, 33) and the ocean floor would aid global $CO_2$ removal. Large scale drilling in rock, whether on land or the seabed, will disrupt ecosystems and could directly harm wildlife. Permanent sequestration is not guaranteed because of the potential for leaks and re-volatisation by the heat stored in volcanic rocks.

- **Passive atmospheric removal** of $CO_2$ is usually proposed in the form of towers or 'synthetic trees' that can be placed around the landscape to filter $CO_2$ out of the air. These mechanisms are thought to be an effective way to capture $CO_2$ from processes that aren't given to CCS at the point of emissions, such as transport. Estimates of effectiveness range from 20 $tCO_2$/yr for a square metre of scrubbing material (35) to 90,000 $tCO_2$/yr for one full size tree (36). The towers themselves may disrupt habitats; however, the real risk from these systems will stem from the subsequent need to transport and store the captured $CO_2$.

- ***Other schemes***

In addition to albedo enhancement and $CO_2$ reduction to address temperature change, geoengineering schemes have been proposed to counter some of the other impacts of climate change.

- **Spraying icesheets** with freshwater could counter the slowdown on thermohaline circulation in the North Atlantic by accelerating freezing in winter and melting in spring to stabilise the freshwater to saltwater ratio. The most cost-effective means of investigated methods is the use of 8,000 barges a year (37). This method could harm the fragile Arctic environment or alter the water cycle causing disrupted precipitation patterns.

- **Lime** could be added to oceans to both reduce the record-breaking acidity and allow more absorption of $CO_2$. If the lime is sourced from areas of so-called 'stranded energy' – such as limestone deserts – the $CO_2$ emitted in extraction will be half that absorbed when the lime is added to seawater (38). Acidification is also harming calcifying organisms, so increasing the alkalinity of the ocean will help these creatures recover; however, it could have unintended consequences for both the organisms and the global ocean-atmosphere system.

- **Hurricane taming** could be done using 1.6 million wave-powered pumps to bring cold seawater to the surface to reduce sea surface temperatures as storms approach (39) or by seeding storms with carbon particles (40). Pumping seawater will alter natural ocean circulation and spraying into hurricanes will kill any organisms that happen to be sucked up. Adding carbon particles to the atmosphere will add to the global carbon load.

**Risks**

The risks of geoengineering are beginning to be documented. One analysis (41) by meteorologist Alan Robock outlines the twenty main concerns, including moral and ethical issues, for which we also hold a variety of evidence. We have grouped Robock's concerns into those which are emerging from studies and models and those that are more speculative.

Modelled impacts:

- Effects on regional climate (42)
- Continued ocean acidification (43, 44)
- Ozone depletion (2, 45)
- Effects on plants (46)
- More acid deposition (2)
- Whitening of the sky (2)
- Less sun for solar power
- Environmental impacts from the physical means of implementation
- Rapid warming if deployment stops (42, 46)
- Cost (2, 6, 47, 48, 49)
- Commercial control of technology (50, 51, 52, 53)

Speculative impacts:

- Effects of cirrus clouds
- There's no going back (46)
- Human error
- Undermining emissions mitigation
- Military use of the technology
- Conflicts with current treaties
- Control of the thermostat
- Questions of moral authority
- Unexpected consequences

To these we add:

- **Disrupted global water cycle.** Modelling studies have shown that both reducing sunlight and sequestering $CO_2$ have global effects on the water cycle leading to changes in precipitation, evaporation and evapotranspiration (42, 43, 46, 52, 53). The hydrological cycle is more sensitive to changes in albedo than it is to greenhouse gases. Although regional drought is addressed by Robock, we feel that the consequences for the global water cycle that result in these regional droughts is worth noting separately.

- **Ineffectiveness.** Although many proposed geoengineering projects are theoretically sound, in practice they may be unable to achieve the modelled impacts. For example, a number of studies have demonstrated that the effectiveness of plankton to counter global warming may be lower than expected. The proportion of plankton that sink to deeper waters during the summer is half that of other times of year (54). In addition, the idea that more plankton could produce more cloud cover through dimethyl sulphide (DMS) emissions was shown to be unworkable because shading from the resulting cloud slows subsequent DMS production (55). Moreover, plankton are known to suffer nutrient stress even where iron is abundant (56).

- **The devil is in the details.** Geoengineering projects will be so large scale that risk assessments will inevitably miss some details that will result in environmental harm.

- **Opposition.** NGOs and other supporters of the precautionary principle are likely to strongly oppose geoengineering because it will never be proven safe beyond any doubt (14, 15).

**Needs**

In regard to geoengineering, the futurist Jamais Cascio has noted that when time is the only solution, you have to either act faster or create more time (57). Cascio and an increasing number of scientists feel that geoengineering may be one way to buy time while the research, development and mindset needed for a carbon free world are being worked at and eventually established. If this is to be the case, then the following needs must be addressed before geoengineering is attempted to ensure that the environment is protected.

- **Research** Geoengineering research should establish which approaches "might look attractive at first, but have devastating results" (45). Research programmes have been widely discussed (7, 8, 13, 20, 52), but we need to be sure that feasibility studies simultaneously look at environmental risks. Those planning the projects and those assessing the impact are too often studying separate models which are then compared. Assessing one model for both feasibility and risk may be more effective for protecting the environment.

- **Regulatory review** Certain aspects of geoengineering are unlikely to be covered by existing regulation and unwanted schemes may go forward without international approval simply because no authority has yet been specified. In November 2008, delegates from 85 nations at a meeting of the London Convention Treaty, which regulates pollution in international waters, agreed to set scientific guidelines for geoengineering projects that aim to sequester carbon dioxide by fertilising ocean waters to encourage algal growth (58) and, in June 2008, 191 countries at the UN Convention on Biological Diversity called for a ban (59). However, both of these actions took place after Planktos and Climos attempted commercial fertilisation to sell carbon offsets to consumers (51, 60).

- **Mindset** We need to ensure that geoengineering does not highjack the climate change agenda. An acceptance that greenhouse gas reductions are still needed even if geoengineering is undertaken must be fostered. Tom Wigley of the National Center for Atmospheric Research (NCAR) has shown that the combined use of geoengineering and emissions reductions is more effective than either used separately (5).

- **A sense of proportion** Philip Ball compared the cost estimate for reversing global warming with a giant sunshade to the estimated cost of mitigating climate change (if we start now) presented in the Stern review on the economic risks of climate change (47). The estimates are nearly equal negating geoengineering as a means to spare the economic impact of greenhouse gas reductions. Estimated costs are 25 to 50 billion US Dollars for sulphur injection and a few trillion US Dollars for multi-disk sunshades (6).

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**PROFESSOR J.R.G.EVANS**

**Enhancement of Cloud Albedo: Technical Challenges**
**A submission to the Royal Society Geo-engineering Climate Study**
11th December 2008
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**Summary**
I propose that the climate engineering intervention that is safest, most forgiving in terms of rapid reversal, most likely to gain WHO approval and easiest in terms of securing international agreement is the inoculation of the troposphere with seasalt particles in the sub-micron region at rates approaching 30 tonnes/s globally. This intervention, proposed by John Latham is designed to increase the droplet number concentration of marine stratocumulus clouds thus increasing optical depth and cloud albedo. The essence of the problem is technical but crucial and it is this; atomization methods that produce <5μm droplets consume high specific energy and deliver at low rates per nozzle and hence involve high capitalisation. We propose the systematic comparison of seven atomization strategies. A crucial part of the investigation must be the coagulation dynamics whereby plumes of droplets travelling with similar velocity coarsen and precipitate. We also suggest exploring the bubble bursting method by which nature herself launches marine cloud condensation nuclei from whitecaps.

**Background to this submission**
The author, along with colleagues in UCL (Ian Ford; Physics aerosol science, Mohan Edirisinghe, Mechanical Engineering; electrosprays and David Andrews, Mechanical Engineering; marine engineering) began meetings in early 2007 to discuss the technical requirements for implementation of the Latham plan to increase the number density of cloud condensation nuclei in marine stratocumulus clouds and hence increase cloud albedo through the Twomey effect. Cloud albedo is often reported as a sensitive input in climate models. This document is a summary of our judgement.

**Reasons for our focus on exploitation of the Twomey Effect**
Our thinking is predicated upon the inductive argument that social and economic inertia will preclude fuel change (FC)/ carbon capture and sequestration (CCS)/ demand reduction (DR) strategies from taking effect in the requisite timeframes to meet the 80% reduction target for CO2 emissions by 2050. All are technically possible but require either long lead times (CCS), long product diffusion times (FC) or exploitation of elasticities through politically sensitive tax interventions (DR). The financial community has now become aware of the implications of climate change: in February 2008, the CERES group of 40 largest institutional investors (http://www.ceres.org), demanded reductions in greenhouse gas emissions of 90% by 2050. These concerns echo the collective message from environmental scientists through the IPCC reports. In contrast, a National Audit Office report suggests that the UK has failed even to approach the modest Kyoto targets because of carbon accountancy errors. We therefore take it as an axiom that [CO2] will rise to and exceed 450 ppm and that there will be a period of 1-2 decades with adverse consequences. These may initially include fresh water shortages and associated disease on a large scale, particularly affecting third world countries. We regard climate engineering as a stop-gap measure but are acutely aware that its successful implementation could relieve pressure for long-term effective amelioration.
We have assessed the portfolio of interventions [1] in the following way. We are concerned that the leadtime for the construction and launch of space-based 'parasols' will be extended by failure to obtain international agreement because of the potential for their abuse. We have rejected the lofting of partially metallised balloons because polymer degradation under UV and cosmic radiation may sink them into air traffic corridors. Our assessment is that the *intervention of last resort* will be that proposed by Nobel Laureate Paul Crutzen [2], namely the injection of sulphur and consequent formation of sulphate aerosol in the stratosphere, where it would have a residence time 60-90 Ms. This would emulate the natural effects of volcanic activity: the aerosol would scatter solar radiation and counter greenhouse gas warming. We anticipate that international agreement for this intervention will be achieved *in extremis.* There is an alternative, toned-down, stratospheric intervention namely the inoculation of dispersed mineral powder such as alumina.

Our view is that tropospheric interventions will precede the long residence time experiments with the upper atmosphere primarily because the former have short residence times and are easily correctable. They involve benign materials such as seasalt. We therefore encourage laying the foundations of a *penultimate* climate intervention that will be environmentally acceptable to the international community, based on the suggestions of John Latham [3,4]. It is the development of sea-level inoculation of the troposphere with fine salt particles. The injection of seasalt can increase and stabilise tropospheric marine cloud, thereby having a strong effect on cloud albedo by the Twomey effect [5] and providing global cooling. A meeting of the Aerosol Society at which Latham was present was devoted to discussion of this and similar interventions; we focused our discussion on the technical challenges [6]. This procedure could be adopted *now* to slow global warming and allow time for greenhouse gas emissions to be reduced and associated socio-economic changes to take place. The intention would be ultimately to remove such intervention, certainly not for it to remain in place for ever. It is a cautious intervention and its adoption should not provoke strong opposition.

Seasalt is both benign and short-lived, being deposited or rained out in ~ 500 ks. This means that if unacceptable consequences of the procedure arise, the status quo can quickly be re-established. It is our opinion that seasalt inoculation would pass a WHO assessment and we foresee fewer impediments to reaching international agreement than for all other interventions.

Central to the success of this intervention is the control of seasalt particle size and particle size distribution, in order to promote activity as cloud condensation nuclei (CCN) and the demonstration of workable, robust delivery technologies and platforms. The technological challenge is thus delivery of very fine seawater droplets (<5 μm) at high rates (30 tonnes/s globally). In some senses, it is a humble challenge; atomization and sprays command little headline-grabbing glitz but as shown below it is far from simple. Below, I address the basic contradictions that make this a challenge and outline potential strategies and their limitations.

The UK has positioned itself as a leader in environmental stewardship and it seems wholly appropriate that the UK should take the lead in preparing for climate interventions that may become unavoidable if existing carbon mitigation schemes do not succeed. There is also an historical reason: the UK, which led the world into the industrial revolution, should position itself in the vanguard of the defence against the consequences of climate change.

**Increasing Cloud Albedo: cloud condensation nuclei**

Sea salt already provides a significant proportion of CCN responsible for marine cloud [7]. Sulphate particles also play a role, formed by oxidation of *inter alia*, SO2 and dimethyl sulphide, generated locally or transported from higher altitudes. The oxidation of sulphur compounds on the surface of soot particles [8], makes them hydrophilic and they act as additional, natural or man-made CCN. This emphasises the unwelcome fact that pollution, both man-made and volcanic, can promote optical thickness and cloud nucleation (as demonstrated by the creation of ship-tracks) and therefore contributes to global cooling. This point is made by Crutzen [9] who notes that recent achievements in pollution control may have enhanced global warming. All aerosol species are effective in scattering or absorbing radiation and act as CCN to varying degrees. Nevertheless almost all marine aerosols larger than 0.13 μm (i.e. potential CCN) contain some seasalt [10] and the properties of this species are the key to cloud stability and optical depth.

This climate intervention is largely based on control of particle size and dispersion. Three main factors influence the choice of particle size; contribution to light scattering, to cloud droplet nucleation and to lift. Raes et al. [11] are among those who recognise the importance of transport for effective nucleation and provide a general circulation model for cloud-forming aerosol. Mapping of marine aerosol has been underway for about 30 years [12] so that meridional differences and locations of atmospheric updraught are known and will determine the optimal geographical positions of injection rafts. Water soluble particles (mainly chloride and sulphate) have the advantage of reducing the vapour pressure over the droplet solution and therefore reducing the supersaturation needed to stabilise the nucleus. Large particles are more difficult to loft, needing higher windspeeds [13] and so the CCN tend to be in the 100nm to 1μm region, the socalled accumulation mode. For high windspeed conditions, seasalt aerosol provides the primary source of cloud nuclei [7,14]. The important physical principle here is that an increase in droplet concentration both enhances cloud albedo and improves cloud stability because it suppresses droplet growth [15]. Artificially injected CCN in the micron region containing 10-14 g salt, typically giving nominal dry diameters in the 200 nm region, produced at a rate of 300g/hr/km2 are needed. Based on an equivalent sphere radius ratio for salt/droplet of 0.25, the nominal upper limit for droplet diameter is ~5μm. In order to prevent the promotion of high level clouds (which absorb long wave radiation from earth, a warming effect), Latham suggests the CCN injection

should be deployed in regions typically lacking low level maritime clouds, namely off the west coasts of Africa and the South America, to increase the optical depth and stability of marine clouds and increase their reflectivity of incident sunlight.

**Increasing cloud albedo: the technical challenges**

It is necessary to estimate the likely fate of a plume of seasalt aerosol after emission from a relatively compact source. Only part of the emitted aerosol will survive to nucleate fresh cloud droplets. Deposition and coagulation are likely to be limiting processes, especially in a plume in which a high concentration of fine droplets are ejected with the same velocity. Plume simulation, incorporating models of aerosol dynamics and coagulation kinetics must be conducted as this will constrain the possible implementation schemes.

Among atomization technologies in general, those that deliver high throughputs at low specific energy, produce large droplets and *vice versa* [16]. **This is the essence of the contradiction we face.**

*Hydraulic atomization* using moderate pressures (up to 100 Bar) tends to deliver droplet distributions with only a small fraction less than 10 μm. If the nozzle diameter is reduced, there are two consequences: seawater filtration demands are exacerbated and pump capitalisation and energy consumption rise dramatically. *Rotary atomisation*, low in specific energy consumption requires exceptional and probably impractically high speeds to deliver fine droplets. A range of *two fluid atomisation* methods, namely *impingement atomization* [17] and *effervescent atomization*, a result of the work of Lefebvre [18] are both forms of twin fluid pressure atomisation involving the introduction of a small amount of gas into the liquid before injection are claimed to deliver a higher proportion of droplets below 10 μm and deserve to be investigated further. The inter-nozzle distance and consequently the proximity of plumes, is anticipated to have a profound effect on coagulation and hence coarsening of the distribution. Building a system of possibly ~107-108 nozzles well spaced on a sea-faring platform raises particular engineering problems. The methods proposed must function with different water types and survive conditions of corrosion between maintenance periods.

*Ultrasonic atomization* can produce fine (1-5μm), narrow distributions of droplets at high frequencies (1-2.5 MHz) [19] but presently with very high specific energies. Combined jet and standing ultrasonic wave methods (e.g. [20]) also deliver in the specified size range but with added complexity. A recent method of producing ~5μm diameter droplets is *flow focusing* [21] in which a liquid stream is drawn through a coaxial orifice by a gas flow. This two-fluid method is derived from work on *electrostatic atomization* with the electrostatic opposition to surface tension replaced by a local high speed gas stream. This simple design of jets lends itself to manufacture of multiple nozzle plates. Direct and air-assisted *electrospraying* of aqueous electrolytes [22] can deliver nearly monodisperse drops in the desired size range below 5μm. Establishing electrospraying in a humid environment replete with a conducting liquid requires the design and construction of insulating electro-hydrodynamic spray rigs. A derivative of electrospraying is *microbubbling* [23] which has been used to produce 1-2μm diameter hollow microcapsules. In this case, air is pumped through the inner nozzles and microbubbles are generated in the drawn ligament in the electrospray process. This offers the possibility of delivering hollow seasalt particles ideally suited to lofting in lower wind speeds. There is another potential advantage of electrohydrodynamic atomization; in the early stages, when the plume is dense, mutual repulsion will act against coagulation and stabilize the aerosol until charge is lost by interaction with atmospheric ions.

The main natural source of seasalt particles is *bubble burst* in marine whitecaps and detailed measurements of particle size distributions, concentrations and fluxes in different windspeeds have been made. Large salt particles (>10 μm) have low atmospheric residence times and their circulation dynamics are well known while the transport behaviour of small salt particles (~0.2 μm) is less clear [24]. The simplest particle generator would mimic this natural process and could just involve submerged nozzles and compressed air.

This approach benefits from a recent study [25] using glass sinters immersed in artificial seawater producing dried particles between 10 and 450 nm. *Bubble burst* launches fine particles in the 100 nm region from film retraction and larger 'jet' particles one tenth bubble diameter from flow recovery. The use of pipes, platforms and air compressors has the advantage of great technical simplicity but rigs covering large areas would be needed. These rigs would need to be constantly on the move because oxygenating the surface waters will change marine ecology, probably reducing surface tension and increasing viscosity as a result of organic excretions; both changes affect bubble burst.

An important aspect is the dispersion of the aerosol. Even if near-monodispersity is achieved at delivery,

for example by electrospray, atmospheric mixing of aerosol does not easily lead to a uniform concentration of aerosol particles because the diffusivity of the particles is very small. The aerosol coagulation rate depends on the local number concentration, and is affected by fluctuations in these concentrations at very small length scales, such fluctuations potentially leading to non-uniform and hence short residence clouds.
The topic of fluctuations and spatial uniformity is under-researched in aerosol science, but commands considerable attention in this application.
Once the atomization method is chosen, the task is to design a system that can deliver the required numbers and sizes of potential CCN in an efficient and controllable manner from seawater. It is estimated that ~1000 CCN delivery platforms might be needed globally, each feeding ~100 tonnes seawater/hr into the marine boundary layer. It is important that at the concept exploration phase a wide range of engineering possibilities are investigated. These are expected to range from conventional small vessels (possibly supported by mothership akin to whale factory vessels to give them sustainability), through larger more dispersed, more self-sufficient ships (able to operated for sustained periods), right through to very large mobile floating platforms. One issue to be explored alongside scale and density of coverage is that of global coverage and regional positioning as the choice here will influence the attractiveness of particular vessel types and sizes.

**Summary**

Inoculation of marine stratocumulus with seasalt represents the most acceptable procedure for climate modification. It requires much preparation because of the technical contradiction presented by the demand for large delivery rates of very fine droplets. Coagulation in plumes from adjacent sources is a major issue in determining the spatial arrangement of nozzles. Feasibility studies should be begun now even if projected implementation is some decades away. This project may well end up using simple technology but at astonishing and hitherto unimaginable scales.

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**ALAN GADIAN*(1), ALAN BLYTH(1), LAURA KETTLES(1), JOHN LATHAM(2)**

**Geoengineering Climate: Royal Society Call for Submissions**
**Research into the Marine Cloud Albedo Enhancement Geoengineering Scheme**

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**Summary.**
This submission briefly presents a description of our current research activities in the subject area of the geoengineering scheme (Latham 1990, Bower et al. 2006, Latham et al., 2008, Salter et al. 2008) which proposes to increase the Earth's planetary albedo by seeding marine stratus clouds so as to increase their droplet number concentration, and thus their reflectivity (and possibly longevity). We describe our research plans for both the near future and the longer term. In the final section some of the specific questions raised in the call are addressed.

**Current modelling activities.**
Current research in the University of Leeds group has focused on the use of climate models to simulate the effects of modification of marine stratocumuli cloud droplet number concentration on the cloud albedo and associated negative forcing over the entire globe. This work is presented in Latham et al (2008) Climate simulation of impacts scenarios have been examined. Using the global UK MO HADGaM atmosphereonly climate model, further computations to those presented in the paper, have consistently yielded increased albedo values as the droplet concentration is increased. Figure 1, (Fig 3 in the paper), indicates that a global average cooling of -8 Wm-2 can be obtained by increasing the cloud condensation nucleus (CCN) concentration in the low level stratuscloud to 375 cm-3 If such a level of negative forcing could be achieved technologically, the Earth's temperature could be stabilised for at least several decades, in the face of increasing atmospheric carbon dioxide levels.

***Figure 1.*** *Five-year mean difference in radiative forcing (Wm-2) at TOA. between the control simulation and that with Nd = 375 cm-3 in all regions of low-level maritime cloud.*

**The VOCALS project**.
Computational studies of our cloud albedo enhancement geoengineering scheme are fairly well developed and continuing (Latham et al. 2008), but it is vital for a thorough assessment of the scheme for field experimental studies related to it to be made. Three separate experimental studies (two involving satellite measurements and the other flights in and around marine clouds) provided data supportive of the scheme, and are described in Latham et al., (2008). Ultimately it will be necessary to conduct a comprehensive field experiment dedicated exclusively to examining the scheme, but the recently conducted major, international

VOCALS experiment, described below, has yielded huge quantities of high-quality data which should permit trustworthy quantitative assessment of important, currently unresolved questions (defined by Latham et al., 2008) regarding the properties and behaviour of marine stratocumulus clouds. Resolution of these questions will greatly enhance our understanding of these clouds and identify ways of improving our modelling of the cloud albedo enhancement scheme.

VOCALS, see Figure 2, is an ongoing large international project, with five participating aircraft (two from the UK), and two ships. It aims to examine the cloud properties of low level marine stratus clouds. The observational phase, with over 200 hundred participants, occurred during October and November 2008. There were 40 UK participants, including the two aircraft ground crews, and was based in Arica, Chile.

A NERC consortia grant, led by the University of Manchester, with significant contributions from the Universities of Leeds and Reading, as well as the UK Met Office, participated in the field project. Results from it will provide important information about the cloud structure and development, the formation of pockets of open cells (POCs), and the radiative and microphysical properties of these clouds. More details can be obtained from http://www.eol.ucar.edu/projects/vocals/

*Figure 1: Key features of the SEP climate system.*

***Figure 2*** *Schematic diagram showing the extent of the stratocumulus cloud deck observed in VOCALS*

**VOCALS and Large Eddy Modelling.**

One of the prime objectives is to examine the microphysical, dynamical and radiative properties of the stratocumulus clouds. Specific observational periods are being examined. In particular the UK Met Office Large Eddy model, is being used, initially to simulate the clouds, their structure, the formation of drizzle within them and the processes that cause the clouds to dissipate. As these studies progress, we hope to be able to quantify the sensitivity of the radiation balance to CCN and cloud droplet number concentration enhancement For different values of droplet concentrations, Nd , we hope to determine associated albedo changes. It is expected that results from these computations will be competed by Autumn 2009. Initial calculations of Wang and Feingold (2008), see attached, supports the idea that stratus clouds exhibit increased albedo as Nd is increased, but we need to quantify these findings. This work is critical for ensuring that the large scale climate model enhancement effects are replicated in the detailed small scale models and provide more confidence that optimal sizes of seawater aerosol are used.

**VOCALS observational activities.**

In the New Year, a further person will start work on a project to examine the VOCALS data. The main thrust of the work will be to use these data to address the unresolved cloud questions concerning the cloud-reflectivity geoengineering scheme in different regimes of Nd and the effect of possible droplet number enhancement. We will analyse airborne and surface data from VOCALS to examine the relationships, over as wide a range of conditions as possible, between the aerosol, cloud microphysical, and specifically radiative characteristics. This work will involve collaboration with both US and UK scientists, and is in collaboration with Dr Rob Wood from the University of Washington, and Director of the VOCALS REX field campaign.

**Longer term proposed activities.**
We have a long term intention to examine more complex General Circulation Models, which include an integrated Ocean Model, to establish the contribution of the Ocean circulation to the changes in atmospheric circulation and cloud albedo factors. Detailed bin microphysical models could also provide more detailed support for the effects.

**Specific responses to Royal Society questions, as related to our proposed cloud albedo enhancement scheme**

***1. What do you consider to be the current state of knowledge regarding the feasibility, efficacy and predicted impacts of the climate geoengineering schemes?***
Referring specifically to our stratus cloud albedo enhancement scheme (Latham, 2008), our climate simulations and the current, but not yet completed Large Eddy Modelling simulations indicate that it could feasibly produce a global cooling effect. This assumes that suitable spray generation technology (Salter et al. 2008) is successfully developed.

***2 How do you think research into climate geoengineering should be taken forward, and by whom?***
We would very much wish to continue the proposed research activities. We would also like to consider taking part in a field experiment to use aircraft observations from the UK NERC FAAM BAe146 to measure the microphysical and radiative balance. This could be completed with the cooperation of the Universities of Leeds and Manchester - and NERC and EPSRC could easily be a provider of such funds.

***3. What factors need to be considered before deploying any climate geoengineering schemes? Who should be responsible for any deployment?***
It is important that a field test experiment should be be completed as soon as possible. Only when the results are examined should larger scale deployment be considered. Estimations indicate that it would take about 2 years to develop and complete a full experiment. Ultimately, it would require governmental / WMO / United Nations agreement to deploy a significant number of these CCN sources.

***4. What do you consider to be the most important political, social, legal or ethical issues raised by climate geoengineering*?**
Ethically, there are serious questions raised by geoengineering. The global warming problem is man-made, and is best resolved by the reversal of carbon dioxide / methane / pollution etc. Output increases. However, our geoengineering scheme may be capable of providing temporaryamelioration while sensible long-term measures are introduced. The advantage of this approach is that it can be turned off immediately if unfavourable consequences occur and the status quo will return within a few weeks.

***5. What do you see as the main barriers to, and opportunities offered by, climate geoengineering?***
The main barriers are the self-interest of politicians and countries, the fact that geoengineering will not solve the problems in the longer term. The scientific communities are notoriously conservative vis-à-vis new ideas, and the peer review system will take a long time to even assess this approach. The opportunity of this scheme is that it provides the world climate system a chance to take quick action whilst implementing longer term measures.

***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 research, in the UK, largely consists of the use of sophisticated climate models. As an academic, I see that the current climate models are designed to operate simulating the current climate, using parameterisations designed to fit current conditions. It is a leap of faith that they will operate effectively in different climate scenarios. It is critically important that experiments, much greater research in the "weather" processes be conducted. This is are the only way in which we will obtain an ability to predict what the climate will do. It is evident from flying for many hours over the South Eastern Pacific stratus cloud sheet, that the role that marine stratus has on global radiative balance is massive. Much more understanding of atmospheric processes is required in order properly to assess our geoengineering scheme.

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**DR ANDREW GETTELMAN AND DR SIMONE TILMES**

**Answers to Questions on Geoengineering**

Andrew Gettelman and Simone Tilmes
National Center for Atmospheric Research
December 8, 2008

The following answers are personal thoughts and impressions of the researchers and do not represent any official statements or positions by the National Center for Atmospheric Research (NCAR) or the United States National Science Foundation (NSF).

We invite feedback on the following questions. Please respond to any or all of the questions and, if possible, supply references to published material to support your answers. Your answers may be specific to individual climate geoengineering proposals, or more general (covering all albedo modification schemes, for example).

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

First, we want to recognize that we are already conducting a geo-engineering scheme by for example emitting large amounts of greenhouse gases. Paul Crutzen's notion is that we have now entered the 'anthropocene' era. This in itself is an era of geoengineering. Perhaps the discussion should be 'intentional' geoengineering. The feasibility of most schemes to undo what we are doing with greenhouse gases is low to poor. The efficacy of most schemes is also not well known. Projected impacts are highly uncertain. Many schemes such as proposals for modifying clouds by changing CCN for example make assumptions about microphysical processes in clouds that are uncertain, and climate responses that are also uncertain. Even the efficacy of schemes to enhance stratospheric aerosol are reliant on aerosol microphysics and evolution that are not well constrained (e.g.: the median size of injected aerosols).

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

Research on Geo-engineering should proceed within the context of a larger mitigation strategy, and should be perhaps used as an 'emergency brake' to soften the economic impact of rapid transition in fuel and energy systems if adverse impacts occur. Any actual trials that might affect climate or ecosystems should have some intergovernmental approval. Deployment or testing should not be allowed without intergovernmental approval. One way to make sure this happens is to not allow several classes of geoenginering scheme (e.g.: iron fertilization, marine cloud seeding, stratospheric aerosol seeding) to claim permit credits for carbon emissions avoided or radiation reflected. Or to say it another way: a rigorous and limited permit or trading system should not include 'avoided radiative forcing' from Geoengineering.

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

Impacts need to be quantifiable, and adverse impacts avoided. Rapid shut-down is also desireable (an 'escape hatch') should the scheme not performed as planned. A 'perfect' scheme with some uncertainty but no flexibility and long lock in has it's own risks and should be avoided. Reduction of greenhouse gas consumption and maybe CO2 sequestration in whatever way is the only way to solve the problem. Therefore, deployment of any climate geoengineering needs to be proven to reduce CO2 in the atmosphere within the uncertainties of the specific scheme. Small-scale experiments might be necessary. Deployment should be by international consensus, through a UN negotiation process, and probably subject to and part of the UN Framework Convention on Climate Change. This framework should determine who is responsible for deployment.

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

The first issue is that if we are willing to resort to geo-engineering it means we are willing to accept that climate change is real and a problem. It also assumes that we trust climate models and their uncertainties to make economic decisions, and that societies can agree on the distributional tradeoffs inherent in such schemes both over space (who benefits and does not form implementing a scheme) and time (how do we value the future and future generations). Climate change is now generally accepted by society, because of observations that show the anthropogenic impact. Climate models point in a direction that makes us (as scientists and members of society) believe that something has to be done. Therefore, ethically we believe we are responsible to stop greenhouse gas increases in the atmosphere as soon as possible. Aerosol modification schemes produce new problems and are not proven to resolve existing climate problems. Therefore, politically strong action needs to be taken right now to reduce fossil fuel consumptions rather than in Geo-engineering away from impacts. The strategy assumes that we know enough about model predictions to act on them.

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

The main barriers are probably (a) engineering costs and (b) uncertainty in climate projections. The opportunity is to avoid catastrophic impacts. Assuming we believe those impacts and are willing to insure against them. The problem is that any geo-engineering schemes may result in further or different unknown problems instead of focusing on the main goal to reduce greenhouse gases. For example, aerosol emissions in the stratosphere to reduce global warming may increase ozone depletion.

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?

A last resort in the context of a larger mitigation strategy, likely to be used as a temporary fix.

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

Geoengineering schemes generally do imply some climate changes. In the case of adjusting radiative forcing in some way (clouds, mirrors, aerosols), simulations imply that global average mean temperatures could be kept nearly constant, but regional temperature and rainfall patterns may change significantly. Thus climate will still almost certainly change in some spots.

**DR HAROON KHESHGI**

**Comments in response to the Royal Society "Geoengineering climate: call for submissions"**

**Comments submitted by (in his personal capacity):**
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**Summary Comment:**
Below are comments addressing the set of questions raised in the "call for submissions" that are generic to the various geoengineering concepts covered in the scope of the Terms of Reference. Fundamental points of these comments are:
• Geoengineering concepts or schemes are at a very early stage of understanding and not near ready for deployment
• The geoengineering decision facing us today is what is the appropriate research to carry out, and how should this research be managed
• Research to generate concepts, evaluate concepts, and refine concepts is appropriate
• Metrics to measure the performance and readiness of geoengineering concepts would be useful to gauge what research various concepts merit
• Geoengineering will face a host of issues if it is ever deployed, but these will depend on the yet to be developed geoengineering technology – detailed study of such issues is premature

*1. What do you consider to be the current state of knowledge regarding the feasibility, efficacy and predicted impacts of climate geoengineering schemes?*
The current state of knowledge is consistent with the low level of resources dedicated to the study of geoengineering. To better assess geoengineering concepts, it would be helpful to apply metrics to measure both the level of knowledge and the resources that have been applied, in addition to metrics on the feasibility, efficacy and predicted impacts. Ultimately, comparisons might be drawn from assessed schemes and decisions regarding resourcing might be informed by such an assessment. The level of knowledge and resources applied thus far might provide one basis for the level of readiness of a scheme. It may be appropriate for schemes with similar levels of readiness to be compared and compete for resources.

*2. How do you think research into climate geoengineering should be taken forward, and by whom?*
Research into geoengineering technologies should be appropriate for the stage of development of a given geoengineering concept. For R&D generally, governments have a primary role supporting pre-commercial research, and geoengineering schemes are currently pre-commercial. Government support for R&D for this area (as well as for technology generally) would be well served by agency independence in making grants, and use of peer review with clear criteria for selection. Criteria for selection should be aimed at broadening the portfolio of options to address the risks of climate change, and evaluating concepts or technologies in a way appropriate for their stage of development.

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

*4. What do you consider to be the most important political, social, legal or ethical issues raised by climate geoengineering?*
Should a geoengineering technology be deployed, it will raise a host of issues that will be related to the specific characteristics of the technology. Geoengineering concepts to be considered in this report, however, I expect are not at a stage of development close to readiness for deployment and by-and-large

geoengineering technologies do not exist. Since geoengineering concepts are primarily at the concept formation and evaluation stage, primary issues include confounding issues that could be important at the deployment state (for a hypothetical geoengineering technology) with relevant objective factors in deciding if a concept merits further science and technology research.

*5. What do you see as the main barriers to, and opportunities offered by, climate geoengineering?*
The main barrier to geoengineering research at this time is lack of support for the generation, evaluation and refinement of geoengineering concepts. The main opportunity offered by geoengineering research is the broadening of the portfolio of options to address climate change. Geoengineering may provide options that could be implemented more rapidly, could be more effective, could be less costly, and could be implemented more simply; however, we will not know if such potential is real without research.

*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?*
Innovation that may lead to geoengineering options draws from a range of science and engineering disciplines. Innovation is, however, a different objective generally than that of the climate science community and is also a different objective from the deployment of existing technologies for mitigation or adaptation, or the management of climate risk. For this reason, managing and supporting innovation applied to geoengineering might be better modeled by other programs to support innovation than by government-supported programs on climate science or risk management, or technology deployment. To promote innovation, the design of criteria and management of peer-review selection might be informed by criteria and management in areas closer to an innovation objective than is traditionally the case for climate science.

**DR RICHARD LAMPITT**

**Greenhouse gas reduction using ocean biology.**

**Lampitt R.S., Achterberg E., Anderson T.R., Hughes A., Iglesias-Rodriguez M.D., Kelly-Gerreyn B.A., Lucas M. *, Popova E.E., Sanders R., Shepherd J.G., Smythe-Wright D., Yool A.**
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The oceans sequester carbon from the atmosphere partly as a result of biological productivity. Over much of the ocean surface this productivity is limited by essential nutrients but if these can be supplied at appropriate locations, there is the potential for the oceans to sequester more carbon than they currently do. A recent paper that explores the various options (Lampitt et al 2008) concludes that it is very likely that some or all of these schemes could enhance the flux of carbon into the deeper layers of the ocean (sequestration for over a century). Without doubt the effects of fertilisation will extend beyond any sequestration of carbon from the atmosphere and this paper therefore also considers whether there are likely to be unacceptable side-effects of the proposed scheme. It is possible that some of these effects will be significant and may be considered as an unacceptable cost relative to the calculated benefits. It is also possible for instance that even if net carbon sequestration is promoted, radiative forcing will increase as a result of increased production of biogenic gasses which have a large global warming potential.
There is at present a clear and urgent need for tightly focussed research into the consequences of ocean fertilisation. The critical areas of research will involve large scale field experiments (eg 100 x 100Km) tightly coupled to high resolution 3D computational models with embedded biogeochemistry.
Until this research is completed satisfactorily, it is impossible to provide a rational judgement about whether the schemes proposed are (a) likely to be effective and (b) likely to cause unacceptable side effects. Once this research has been carried out, it will be the responsibility of the science community to perform appropriate cost-benefit-risk analyses in order to inform policy. At the same time, discussions between the commercial, regulatory and scientific communities must take place so that the principles and practices of verification can be established.

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

It is likely that carbon sequestration can be enhanced by supplying nutrients to areas and at times when they are limiting. The conclusion from our recent paper (Lampitt et al 2008) is that the various methods suggested have the potential to enhance sequestration although this may not decrease greenhouse warming if a side effect is that other greenhouse gasses are generated. The current level of knowledge from the observations and modelling carried out to date does not provide a sound foundation on which to make clear predictions or recommendations.

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

For ocean fertilisation to become a viable option to sequester $CO_2$ there is an urgent need for more extensive and targeted field work and better computational models of ocean biogeochemical processes (Smetacek and Naqvi 2008). Models are needed both to interpret field observations and to make reliable predictions about the side effects of large scale fertilisation. They would also be an essential tool with which to verify that sequestration has taken place. This research should build on the extensive skills in the scientific and engineering communities whether they be in government, university or commercial organisations. The key factor is that the results of the research must be published in high quality peer reviewed journals before any decisions can be made about commercialising any of the potential methods.

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

None of the proposed schemes will have 100% guarantee of success and none will be free of the risk of unintended consequences. Nevertheless after appropriate field and modelling experiments it will be possible to make decisions about large scale deployment. In order for such deployments to take place the risks of failure (no reduction in greenhouse warming) and of unacceptable side effects must be considered to be low. Methods of independent verification of sequestration must also be agreed prior to large scale deployment.

Financial drivers are strong but if appropriate methods of verification are established, there is no reason why such schemes can not be carried out by the commercial sector or by government organisations.

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

There is no doubt that there is potential to reduce greenhouse warming by encouraging the oceans to sequester additional carbon from the atmosphere. However the main barrier currently preventing such a geoengineering approach is a lack of scientific knowledge about system function. This knowledge is essential if rational decisions are to be made about the efficacy of such schemes and if the risks of unintended and unwelcome side effects are to be adequately estimated. In our view it is not impossible to gain this knowledge using well focussed research.

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

Mitigation includes emission reduction as well as geoengineering and in our view geoengineering must not be considered as an option which removes the need for emissions reduction. Adaptation to climate change will certainly be required and this will be a third component in the quest to reduce the damage of industrial development on the human species and the biosphere. Climate research in its broadest sense is the bedrock on which geoengineering research must be based and without it we will be unable to asses the viability and desirability of carrying out geoengineering.

Reference:

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**JOHN LATHAM, JACK CHEN AND PHIL RASCH**

***Global Temperature Stabilisation via Cloud Albedo Enhancement***
(Geoengineering Climate: Royal Society Call for Submissions)

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**Summary**
*The geo-engineering idea we are investigating is to increase, in a controlled way, the albedos of shallow oceanic clouds, by seeding them with seawater aerosol to increase their droplet number concentration: thereby producing a cooling sufficient to balance global warming. This technique, together with assessments of it from modelling and (to a lesser extent) observational work are summarised below. The provisional conclusion – subject to resolution of specific problems – is that it could hold the Earth's temperature constant as the atmospheric CO2 concentration continues to rise to at least twice the current value. Preliminary results from computations involving a fully-coupled atmosphere/ocean GCM are that maintenance of current values of Arctic ice cover is achievable. The ramifications of possible deployment of this technique are also under examination.*

## 1. The Cloud Albedo Enhancement Geoengineering Scheme

Atmospheric clouds exercise a significant influence on climate. They can inhibit the passage through the atmosphere of both incoming, short-wave, solar radiation, some of which is reflected back into space from cloud-tops, and they intercept long-wave radiation flowing outwards from the Earth's surface: a global cooling, and warming respectively. On balance, clouds produce a cooling effect, which we propose (Latham, 1990, 2000: Bower et al. 2006, Latham et al. 2008) to accentuate by increasing the reflectivity of the marine stratocumulus clouds that cover about a quarter of the oceanic surface. These clouds characteristically reflect between 30% and 70% of the sunlight that falls upon them. They therefore produce significant global cooling. A further 10% increase in reflectivity – which we hope to achieve via cloud seeding - would produce an additional cooling to roughly balance the warming resulting from atmospheric CO2 doubling.
The reflectivity increase could be achieved by seeding these clouds with seawater particles sprayed from unmanned, wind-powered, satellite-guided Flettner-rotor vessels (Salter et al. 2008) sailing underneath the clouds. These particles would be about one micrometer in diameter at creation and would shrink through evaporation as about half of them are carried by turbulence up into the clouds, where they act as centres for new droplet formation, thereby increasing the cloud droplet number concentration and thus the cloud reflectivity (and possibly longevity). In this way the clouds would reflect more sunlight back into space, possibly for a longer time, and so planetary cooling occurs. The global seawater volumetric spray-rate required to produce a cooling sufficient to balance the warming associated with CO2-doubling is estimated to be around 50 cubic metres per second. More information on technological aspects of this idea is provided in the Royal Society submission from Professor Salter.
Ship-tracks can be adduced as evidence showing that the seeding of marine stratocumulus clouds can enhance their reflectivity. More quantitative support is provided by three experimental studies (outlined in Latham et al. (2008)), two involving satellite measurements, the other, flights through and around clouds by instrumented aircraft.
Latham et al. (2008) describe atmosphere-only GCM studies of this global temperature stabilisation scheme conducted using two high-level models, the Meteorological Office HadGAM numerical model, and a version of the NCAR Community Atmosphere Model (CAM). Both models reveal that a technologically feasible imposed increase in cloud droplet number concentration resulting from seeding can cause an overall significant global cooling, sufficient to balance the warming resulting from CO2-doubling. The computations showed strong seasonal variations in the global distribution of cooling, with a maximum in the Southern Hemisphere summer.

## 2. Recent computations using a fully-coupled ocean/atmosphere GCM

The published GCM studies cited above used "atmosphere only" simulations (with ocean temperatures prescribed to climatological values) to assess the possible forcing associated with seeding. The continuing studies outlined in this section have not been published, and results should be viewed as preliminary. We have extended the simulations to a fully coupled climate model, the CCSM3.5 model described in Neale et al (2008). This model is an experimental version of CCSM, similar in many respects to CCSM3 (Collins et al, 2006) except that some components of the ocean and atmosphere have been improved. Of particular importance is the change to the cloud microphysical formulation which now provides an improved formulation for drop activation, condensation and coalescence processes (Morrison and Gettelman 2008, Gettelman and Morrison 2008) and predicts cloud drop number, the quantity that we influence through our geoengineering strategy.

We show two figures indicating the potential of this geoengineering strategy. Each figure compares two simulations averaged over the first 20 years of the simulations started from initial conditions at equilibrium for present day greenhouse gas concentrations. One simulation employed a doubling of CO2 concentration. The other included the doubling of CO2 but also included geoengineering. Our geoengineering strategy was to assume that we could produce perfect cloud condensation nuclei and control them to the point that all cloud between the surface and 850 hPa would attain a cloud drop number of 1000/cm3. This strategy differs substantially from the one employed in a recent UKMO study that used a "slab ocean" framework, and seeded only in small areas of the ocean, so our results will not necessarily be consistent with that study. Our seeding strategy is obviously very artificial, and more exploration of the appropriate choice of area, and amount will be needed to balance a particular warming scenario optimally. Also, the production of CCN and the influence on boundary layer clouds is in itself a formidable task (not dealt with in this study), and our seeding strategy is designed to produce a very strong signal, exceeding that required to compensate for a warming associated with a doubling of CO2. The solutions are not at an equilibrium, but signals in many features are evident. We wish to emphasize that these simulations are not designed to precisely compensate for the CO2 warming, but rather to identify the primary signals seen with geoengineering using this strategy. Figure 1 shows the annually averaged change in sea ice extent in the northern hemisphere. The geoengineering has compensated for the loss in sea ice associated with the greenhouse warming by increasing the sea ice extent by 2% of the surface area of the northern hemisphere during the first 20 years of the simulation compared to the warming scenario.

**Figure 1: Annually averaged sea ice extent. Top left panel shows the simulation for a 2xCO2 enhanced simulation with geoengineering simulation; Top Right the simulation with 2xCO2 but without geoengineering. Bottom Panel shows the difference**

Figure 2 shows the corresponding surface temperature changes over the globe. The model is about 1.8K cooler in the geoengineered run over the first 20 years of the simulation (recall that these are not equilibrium values so these changes just provide hints as to the sign of the changes).

**Figure 2: Annually averaged surface temperature. Top Panel: Simulation with 2xCO2 and geoengineering; Middle Panel: Simulation with 2xCO2. Bottom panel difference.**
The geoengineering has clearly had a strong effect on the simulation, acting to cool the planet by about 1.7K over this 20 year period in the global average with the maximum signal in the northern arctic region compared to the warming scenario.

## 3. Discussion

Much more climate modelling work is required to understand the consequences of geoengineering using this method. Other seeding scenarios and effects on precipitation, ocean circulations, ecosystems, and many other issues remain to be explored. There are also many issues (Latham et al. 2008) associated with the technology needed to produce the CCN and deliver them, to model the real complexities of marine stratocumulus clouds, and to make a detailed assessment of ramifications associated with the possible deployment of our geo-engineering. We should also develop plans for executing a limited-area field experiment in which selected clouds are inoculated with seawater aerosol, and airborne, ship-borne and satellite measurements are made to establish, quantitatively, the concomitant microphysical and radiative differences between seeded and unseeded adjacent clouds: thus, hopefully, to determine whether or not this temperature-stabilization scheme is viable. The scheme has a number of desirable attributes: (1) the amount of cooling might be controlled by measuring cloud reflectivity from satellites and turning disseminators on or off (or up and down) remotely as required: (2) if any unforeseen adverse effect occurred, the entire system could be switched off instantaneously, with cloud properties returning to normal within a few days: (3) the only raw materials are wind and seawater: (4) there exists flexibility to choose where local cooling occurs, since not all suitable clouds need be seeded. This flexibility might help subdue or eliminate adverse ramifications of the deployment of our scheme.

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We thank Andrew Gettelman, Hugh Morrison, Alan Gadian, Alan Blyth, Laura Kettles, Tom Choularton, Keith Bower and Stephen Salter for valuable advice and many discussions.

**Note to Working Group Members**
Our fully-coupled ocean/atmosphere model started to yield acceptable results only 2 or 3 weeks before the Royal Society submission deadline of 11 December 2008, which we felt it important to comply with. There is little doubt that over the next few months a great deal more information will be produced, including assessments of the ramifications associated with the possible deployment of our geo-engineering scheme. If requested at some future time, we would be happy to furnish the Working Group members with such additional material.

**DR DAN LUNT AND PROFESSOR PAUL VALDES**

**Submission to the Royal Society "Geoengineering Climate" call**

Dan Lunt and Paul Valdes, University of Bristol, UK.
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- Current understanding related to the possible efficacy, side-effects, and cost-effectiveness of geoengineering schemes is extremely low.
- Before large sums of money are invested into any of these schemes, they should be thoroughly assessed in a coherant national program of research.

Geoengineering - the ''intentional large-scale manipulation of the environment" (Keith, 2000) - has been considered for the mitigation of dangerous climate change in response to elevated anthropogenic greenhouse gases, at least in conjunction with other mitigation strategies.

However, many of the geoengineering schemes proposed remain un-quantified in their impact, and it is possible that some will not work at all. All may give rise to undesirable climatic side-effects and have hidden 'costs', both economic and environmental. This was highlighted in a recent study (Lunt et al., 2008a) carried out at the University of Bristol, where a state-of-the-art climate model (HadCM3L, developed by the UK Met Office) was used to assess the climatic impact of a space-based sunshade (although much of the analysis was equally applicable to cheaper stratospheric aerosol schemes). Previously, it was widely assumed that these geoengineering schemes could revert climate back to a natural 'pre-industrial' state. However, this study found that, due to the spatial mis-match of the $CO_2$–related warming and solar-related cooling, it was inevitable that there would still be a residual climate change, resulting in the loss of Arctic sea-ice, and changes in ENSO which could not have been predicted without the use of a complex climate model. Nevertheless, the study demonstated that space-based sunshade/stratospheric aerosols *would* mitigate against the majority of anthropogenic warming. Indeed, more recent work we have carried out (Lunt et al, 2008b) shows that these schemes could be successful in preventing dangerous sea-level rise due to melting of the Greenland ice sheet (see below).

Present day Greenland ice sheet | Ice sheet with 4*$CO_2$ | Ice sheet with 4*$CO_2$, plus geoengineering

However, any geoengineering schemes which ultimately aim to modify the albedo of the planet will leave other $CO_2$-related problems, such as ocean acidifcation, completely unaddressed. Furthermore,

geoengineering does nothing to address key issues such as energy security, and pollution associated with burning fossil fuels.

The work we have carried out at Bristol, examining just one particular method of geoengineering, highlights the fact that we currently have insufficient scientific information to adequately support the debate we need to have. An evidence session in front of the Innovation, Universities, Science and Skills Committee of the UK government just last month perfectly illustrates the high-level interest, yet also the critical need for a more reliable quantitative understanding of the benefits, risks, and costs, together with an ethical perspective.

Before any geoengineering scheme is implemented, or substantial funds are invested in geoengineering technologies, we would recommend the funding of a national program designed explicitly to improve current understanding of the efficacy, side-effects, practicality, economics, and ethical implications of geoengineering. This would bring together climate scientists, engineers, economists, and philosophers. Of course, such a program would complement similar investigations into the economics and practicality of other mitigation and adaption strategies, such as improved energy efficiency, reduced energy use, and more energy production from renewable sources.

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