Geoengineering the climate: Science, governance and uncertainty

Responses to call for evidence

Part III

PROFESSOR COLIN R MCINNES FRENG FRSE

ROYAL SOCIETY GEOENGINEERING STUDY
SPACE-BASED GEOENGINEERING

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1. Introduction

Colin McInnes is Professor of Engineering Science and Director of the Advanced Space Concepts Laboratory, a new €2M centre funded by an Advanced Investigator Grant from the European Research Council. The centre will undertake work on a range of visionary concepts including space-based geoengineering. Jason Reese holds the Weir Chair of Thermodyamics and Fluids Mechanics and leads the Multiscale Flows research group.

The key points raised in this submission are:

- Geoengineering is an essential tool to mitigate against both anthropogenic and long-term natural forcing of the climate to deliver a resilient global society.
- Space-based geoengineering may represent the least invasive and most controllable means of manipulating the climate to compensate for anthropogenic and natural forcing.
- Simple occulting disks at the interior Lagrange point may represent a less complex solution than concepts for highly engineered refracting disks proposed recently.
- Emerging capabilities to manipulate the orbits of small near Earth asteroids may provide a route to greatly accelerate the deployment of space-based geoengineering schemes.
- As a long-term venture, the initial large investment costs in space-based geoengineering can be amortised over 100 years representing a small annual fraction of global GDP.

2. General Issues

The recent controversy surrounding rapid human driven climate change has brought into sharp focus the fact that the climate is not static. Even in recent times, regional events such as the transition from the medieval warm period to the little ice age record this fact. The popular view of the climate as being perpetually in equilibrium is only due to the narrow window of human history through which we view the past. Geoengineering is being investigated as a tool to mitigate against anthropogenic climate change, but should also be explored as a means to mitigate against the effects of long-term natural forcing of the climate to deliver a resilient global society.
The greatest barrier to geoengineering is the mainstream view that anthropogenic climate change can only be addressed by a massive reduction in carbon emission and that geoengineering is merely a distraction from this orthodoxy. Geoengineering is an essential tool to (i) provide a means to mitigate against rapid anthropogenic forcing should political agreement on climate change fail (ii) provide a means to reduce the peak costs of conversion to low carbon energy by offsetting some fraction of anthropogenic forcing for a finite period (iii) mitigate against long-term natural forcing of the climate, which may include episodes of rapid cooling through transitions in heat transport in the oceans or stratospheric dust deposition from caldera volcanoes.

3. Space-based Geoengineering

Large-scale geoengineering using orbiting reflectors has been considered by various authors to manipulate total solar insolation [1-8]. These concepts generally centre on fabricating and deploying solar reflectors to reduce total solar insolation. For example, the use of large numbers ($5x10^4$) of 100 km^2, actively controlled reflectors in Earth orbit has been considered, but would likely lead to an apparent flickering of the Sun (2% amplitude) and would pose a significant orbital debris hazard. In addition, various proposals for an artificial ring of dust particles in Earth orbit have been documented with a mass of order $2x10^9$ tons [9]. A recent addition to this class of concepts is the use of clouds of dust particles located at the stable Earth-Moon triangular Lagrange points L_4 and L_5 [10]. In this scheme of order $2x10^{11}$ tons of lunar or cometary dust is deposited in the Earth-Moon system forming a torroidal band at the lunar orbital distance.

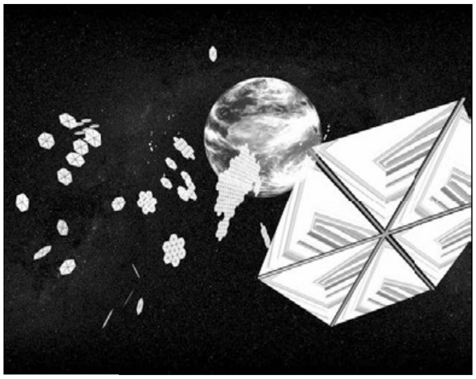

Figure 1. Occulting solar disks stationed along the Sun-Earth line (D Izzo, ESA/ACT)

A more plausible scheme is to station solar reflectors, typically with a total mass of order 10^7 tons, close to the Sun-Earth L_1 equilibrium point sunwards of the Earth [1-7], as shown in Fig. 1. Despite the large-scale of such a venture, solar reflectors near L_1 appear to be the least invasive geoengineering tool, whose effect can be more easily controlled than other schemes. A scenario can be envisaged whereby the total effective reflector area grows over a period of 50-100 years to match the required reduction in solar insolation to maintain a fixed global mean temperature. An optimised scheme has been proposed by McInnes which uses absorbing occulting disks (rather than reflectors) to minimize the total mass of the system. A swarm of occulting disks with a minimum total mass of $5.2\text{x}10^7$ tons at a sub-L_1 point is proposed [5-7].

The use of L_1 for geoengineering has been revisited by Angel who proposes a swarm of engineered thin film refractive (rather than reflective) disks with a total mass of order $2\text{x}10^7$ tons [8]. Rather than directly reflect solar radiation, the refractors divert sunlight to avoid the Earth's disk, but are highly engineered thin film devices which require terrestrial fabrication. However, the simpler occulting disk concept could be fabricated in-situ from near Earth asteroid resources at significantly lower cost, although the total deployed mass is somewhat larger [5-7].

A key advantage of using large solar reflectors for geoengineering is the vast energy leverage obtained in a relatively short time. The total accumulated solar energy intercepted by the reflector quickly grows beyond the energy required for its fabrication, leading to a highly efficient tool for climate engineering. While solar reflectors offer many advantages, there are clearly challenges associated with the fabrication of such large structures. It is almost certain that in-orbit fabrication would be required, either using lunar material or material processed from a suitable near Earth asteroid. A prerequisite for space-based geoengineering is the capability to economically exploit the resources of near Earth asteroids. This capability is currently being developed through technology development for near Earth asteroid deflection missions, as discussed in Section 5.

4. System Level Trade-off

The use of space-based geoengineering has been reviewed above and a concept for occulting disks presented with a total deployed mass of $5.2\text{x}10^7$ tons [5-7]. As can be seen from Table 1, this is somewhat more than the scheme proposed by Angel ($2\text{x}10^7$ tons) using terrestrially manufactured refracting disks [8], but significantly less than the dust cloud schemes proposed by Pearson ($2\text{x}10^9$ ton) [9] and Struck ($2\text{x}10^{11}$ ton) [10]. For comparison, the mass of a range of terrestrial engineering ventures are listed in Table 2. It can be seen that the Three Gorges Dam requires approximately $6\text{x}10^7$ ton of concrete, and so forms a structure of comparable mass to the occulting disks. While the challenges posed by space-based geoengineering are clearly significant, it interesting to note that measured in terms of mass, such large-scale geoengineering represents a venture of comparable scale to current terrestrial engineering.

Geoengineering concept	Mass (ton)	Area (km^2)	Comment
Struck (Lunar $L_{4/5}$ dust cloud)	$2.1\text{x}10^{11}$	-	Unprocessed dust
Pearson (Earth dust ring)	$2.3\text{x}10^9$	$1.10\text{x}10^8$	Unprocessed dust
McInnes (L_1 occulting disks)	$5.2\text{x}10^7$	$6.57\text{x}10^6$	Thin film metallic disks
Angel (L_1 refracting disks)	$2.0\text{x}10^7$	$4.70\text{x}10^6$	Engineered refractive disks

Table 1. System level trade-off for space-based geoengineering

Scale	Mass (ton)	Engineering venture
10^5	$6.5x10^5$	'Knock Nevis' oil tanker (fully laden)
10^6	$6x10^6$	Great pyramid of Giza
10^7	$6x10^7$	Concrete used for Three Gorges dam
10^8	$2x10^8$	Water stored in London's reservoirs
10^9	$7x10^9$	World annual CO_2 emissions

Table 2. Mass comparison with terrestrial engineering ventures

While Angel proposes a swarm of engineered refractive (rather than reflective) disks with a total mass of order $2x10^7$ tons [8], the refracting disks are highly engineered thin film devices which require terrestrial fabrication and launch at extremely high cost. McInnes proposes simple occulting disks [5-7] with a total mass of order $5x10^7$ tons which could be fabricated in-situ from near Earth asteroid resources. Pearson and Struck propose clouds of coarse dust grains with a mass of $2x10^9$-10^{11} tons which do not require any form of processing [9,10]. It is clear that there is a trade-off between the total mass of a geoengineering scheme and the engineering challenge and cost of fabrication and deployment. Such systems level issues must be addressed in future evaluation of competing geoengineering concepts.

5. Space-based Fabrication

The fabrication of a swarm of occulting disks with a mass of order 10^7 ton would require the capability to exploit in-situ resources such as near Earth asteroids, unless launch costs are significantly reduced (Angel envisages terrestrial fabrication of refracting disks and launch to L_1). For example, the mass requirements for the minimum mass occulting disk scheme can be satisfied by small M-type asteroids, which are abundant in Nickel-Iron materials [11]. A range of novel technologies are currently under investigation to deflect small near Earth asteroids for hazard mitigation purposes [12,13]. However, the same technologies can, in principle, be used to capture a small near Earth asteroid in the vicinity of the L_1 point for subsequent resource extraction, particularly for a small near Earth asteroid in a low energy orbit.
It can be assumed that the swarm of occulting disks are fabricated from thin metallic film processed from such a near Earth asteroid, and that the asteroid has a bulk density half that of Iron (7860 kg m^{-3}) to account for the non-metal content. It is then found that a small M-type asteroid with a radius of only 145 m will provide the required mass for fabrication of the occulting disks [5-7]. The asteroid would require to be processed in-situ, probably using solar heating, and the metallic products extruded into thin film for fabrication of the disks. If it is assumed that a modest sized terrestrially fabricated solar reflector is initially deployed, then the time required to process the asteroid can be estimated. For example, a 500 m radius disk reflector will intercept a solar flux equivalent to approximately 1 GW of power at 1 astronomical unit. If the disk has an areal density of order 1 g m^{-2}, its total mass is of order 800 kg, well within the Earth escape capacity of a large commercial launch vehicle. Assuming the asteroid material is liberated by focusing this energy to raise the local surface temperature above the melting point of the metallic component (heat of fusion of Iron $2.8x10^5$ J kg^{-1}), the maximum rate of production of mass is potentially of order $3.6x10^3$ kg s^{-1} resulting in complete processing of the asteroid on a timescale of order 150 days. The liberated material can then be extruded into thin film using a vacuum vapour deposition process by directly cooling onto a rotating cylindrical substrate for example.

6. Future Prospects

In order to advance geoengineering in a measured way a number of steps are now required:

- Government, through the research councils (principally EPSRC and NERC), should invest in basic research to evaluate geoengineering concepts and solicit new ideas.

- Small-scale experimental programmes are required to validate numerical models and reduce the risk of any future large-scale deployment of geoengineering technologies.

- A well executed public outreach activity is required. A repeat of the often hysterical media reaction to contemporary issues such as nanotechnology and GMOs must be avoided.

While the scale of space-based geoengineering may appear daunting, the availability of vast quantities of freely available material and solar energy in space, and the active control of such energy using orbiting thin film reflectors can enable large scale space-based geoengineering ventures. With emerging capabilities to manipulate the orbits of near Earth asteroids along with advances in space robotics, space-based geoengineering can be considered as a strategy which can mitigate against both anthropogenic and long-term natural forcing of the climate.

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MALCOLM NEWELL

Andrew,

Further to your request for proposals for Greenhouse Gas reduction schemes.

I am a retired Oil Industry Marine Design Engineer who specialised in the design and operation of shipping for energy transportation projects including the transportation of Liquefied Gases. For the last few years, between various periods where I have been acting as a Consultant Engineer I have been researching the causes and effects of Global Warming and compiling notes with a view to understanding and possibly writing a book on the subject aimed at Mariners.

I believe that, despite the many uncertainties and disapproval from the scientific community we shall very soon be forced to take up some form of large scale Greenhouse Gas Reduction scheme(s) involving chemically treating the Oceans. My background leads me to believe that large ocean going vessels will be needed for any such scheme and I believe that if the selected chemicals are added to their ballast water, when taken on in port, it will be possible to very quickly perform any initial trials or indeed to ramp up to a full blown world wide operation

The possible adverse effects on Oceanic life forms are largely unknown and are being actively investigated at this moment by very many people and in view of the probability of causing adverse and unforeseen effects it is definitely necessary to proceed with extreme caution. However the time for action is right now. The present economic down turn is in many ways a godsend as CO2 emissions are reducing all over the World in a manner that no other form of Political inducement could have achieve. Also the prices of Commodities, Ship hire and Fuel are all dropping in a manner which makes my proposal more and more viable.

My initial intent would be to have a number of parallel studies performed as quickly and thoroughly as possible prior to (hopefully) putting in hand my main proposal which involves the use of commercial shipping utilising Ballast water exchange while on passage at sea:-

Suggested Initial studies:-
- Identification of most desirable initial study/application areas.
- The optimisation of choice of treatment chemicals for these areas.
- Establish likely benefits and negative effects of selected treatments.
- Anticipated type and scale of side effects.
- Methods of procuring, producing, storing, handling and delivering the chemicals.
- Identification and involvement of likely project partners and ships.
- Confirm shipping rout suitability and discharge areas.
- Design of initial application studies.
- Monitoring requirements and Data collection/analysis
- Full scale implementation planning

etc

I have attached two word documents, the smaller is the Submission (unfortunately more than your requested 4 pages) and the second is a rough draft of an explanatory paper which gives more background and justification for my proposal.

Best regards

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A Possible Roll for Shipping in Global CO2 Sequestration.

Executive Summary:-

- The removal of excess CO2 (above historic levels of about 280ppm) from the atmosphere is vital and must commence on a huge scale as soon as possible
- Biological absorption by Land and Marine organisms are both possible options.
- However, biological and chemical management of the world's oceans appears to be more likely to succeed than any land based bio management (or currently possible industrial based processes).
- Recent scientific trials appear to have demonstrated the feasibility of drawing CO2 out of the atmosphere using biological processes by seeding certain ocean areas with iron or other chemical mixes.
- The results from these trials appear to provide pointers to the achievable scale of drawdown which may be possible as well as highlighting some of the many previously unknown/unconsidered side effects.
- However, trials performed so far have not adequately proved or disproved rising scientific concerns about these unwanted side effects nor have they proven the true scale of the drawdown that can be hoped for.
- Additional, much larger scale trials are urgently required. They must be scientifically targeted and closely monitored and must be performed on a much longer time basis than past trials and in very specific parts of the deep oceans.
- Inadvertently, the recently introduced (mandatory) International Ballast Water Management requirements for trading ships could provide a possible treatment delivery mechanism, which is already available world wide.
- The new regulations affect all ships trading internationally and require the replenishment (or sterilisation) of all ballast water carried as well as the mandatory compilation of comprehensive associated records.
- The regulations therefore also provide a mechanism which also includes the compilation of many necessary data records which will allow close monitoring of such enriched ballast deliveries.
- At the same time, the Scientific Community have many of the essential systems in place, or planned, to allow the identification and monitoring of the most desirable oceanic sequestration areas as well as to follow up on the developing results being obtained from any ongoing trials.
- The shipping and industrial world is keen to participate in potential green, environment projects provided that this involves minimal commercial exposure to risk (i.e. lots of kudos for as little expense/commercial loss, as possible).
- An example quoted shows that a single large vessel may have the potential to draw down up to **25,000,000 tonnes of CO2** per existing commercial voyage.
- A single large shipping project appears to have the capability to draw down in the region of up to about **9.4 Gigatonnes of CO2 per year.**
- Participation in a world wide CO2 sequestration project, by even a very small proportion of the currently available world fleet of suitable ships, **may** have the potential to sequester well in excess of 100 Gigatonnes of CO2 per year.
- Initial large scale trials must be strictly limited to involve only a few carefully chosen vessels passing through suitable sea areas which are at present low in iron. Very few existing trade routes will be suitable, nevertheless it should be possible to complete a thorough set of initial trials which should be able to provide "proof in principle" of the proposed process.
- If such initial trials are successful, the commercialisation of the sequestration project (by applying a realistic universally accepted value to the sequestered CO2 and hence to the delivered soluble iron e.t.c) offers the possibility of sustaining and even greatly enlarging the initial level of support and participation.
- If the safety and viability of the process is proven, new Commercial opportunities can be identified which arise from the adoption of new Carbon Tax regimes and from the precise value applied to the sequestered carbon or delivered soluble iron.
- These opportunities may encourage the further expansion of the enriched ballast water process to involve ships (possibly specially designed and built for the job) which will specifically target the more remote and most prolific sequestration targets.

- Whilst careful consideration must be given to any future proposal, in order to identify and avoid any harmful consequences of such an approach to CO_2 sequestration, undue delay must be avoided when making decisions to apply the process, **or not**.
- A similar approach may be used for other forms of Ocean Geo-engineering such as combating rising acidification with lime dosage.

The use of Iron to stimulate Plankton growth.

Current scientific thinking, which is based on the results from small scale field tests performed over about the last 10 years, seems to indicate that seeding certain biologically depleted open areas of ocean with dissolved iron and possibly also with other chemicals such as urea and phosphorous) could result in the massive but controlled stimulation of additional phytoplankton growth leading to the initial draw down of massive amounts of atmospheric CO_2.

At the moment **only** Deep Ocean Sequestration of CO_2 by some form of biological stimulation appears to hold out any promise in having either the capacity or capability of being applied in anything like the necessary time frame or on the required scale.

It has to be added that many parts of the scientific community are both fearful and sceptical about our ability to manage such a program without incurring huge and lasting damage to the ocean biology. They also say that the draw down results so far observed show that long term sequestration resulting from such a program may be negligible or possible even counter productive.

The link between Draw-down of Atmospheric CO_2 and Ships.

Existing commercial shipping offers a possible delivery mechanism by which can be provided a form of carbon sequestration which appears to be controllable. Using the lowest estimate from the previously quoted figures, it is possible that each tonne of iron added to the water ballast (loaded into certain vessels and subsequently discharged into specific pre-designated areas of the sea) could result in the long term sequestration of perhaps (up to about) 2,500 tonnes of CO_2.

There are at present more than 60,000 ocean going vessels in the world shipping industry which are involved in international trade. As can be seen from the table below, most ships must handle ballast water in order to safely perform their various operations and some of the quantities of water which must be exchanged in mid voyage are very large.

There have been several ocean fertilisation proposals already previously put forward including one based on the addition of Iron (as Ferrous Sulphate) to iron depleted (and therefore biologically depleted) offshore areas. Others are based on the addition of nitrogen based fertilizer such as Urea, which again is dissolved in sea water but in this case acts as a general growth stimulant in areas where sufficient iron is already in place.

If the science stands up following further large scale trials, the new ballast water management regulations which are currently being applied to ships world wide, could inadvertently provide a ready available method of actually delivering the required minerals to the right places as well as providing a mechanism for recording and controlling the application and thus allowing the very rapid implementation of an atmospheric CO_2 extraction scheme based on the controlled enrichment of the impoverished surface layers of (still to be specifically defined) areas of the World's open Oceans.
Although carbon sequestration by biological action is also possible in land based schemes such as tree planting, it is useful to keep in perspective the relative size of the terrestrial vs. oceanic carbon sinks.
Carbon; Forests and soils worldwide are together believed to hold just under 2,000 gigatonnes of carbon (and man's activities are rapidly reducing this figure).
The oceans at present hold between 50 - 60,000 gigatonnes and there is the possibility of increasing these figures substantially by enriching several existing large depleted areas.
In practice both land based and oceanic carbon sequestration should take place in parallel.

CO_2 Sequestration using Ballast Water discharges.

In many areas of the World, the means are already in place (in the form of existing trading ships and routes) to allow the immediate start up of **large scale controlled trials** whereby the ballast water loaded before leaving a cargo discharge port, is enriched with precise quantities of dissolved minerals. These are specifically selected for the task (dependent on conditions within the targeted area) and are then pumped from the commercially trading vessels while passing through scientifically defined sea area(s) during the mandatory ballast water exchange process.

The quantities, times and positions of the discharges are subsequently readily available (from a standard record system which is already defined, in place and in use on board these same vessels).

Implementation.

The remaining immediate task, in addition to actually funding the trials and determining the most suitable sea area and vessels for such trials, is to identify the cheapest/safest/best methods of introducing the (correct selection and quantities of) **pure** minerals into the ballast tanks of any selected trial vessels. The results of such trial discharges can easily be independently monitored and controlled by the scientific community via ships record books, local based survey ships, drifting instrumentation, satellites e.t.c. and the trials can be extended, moved or stopped as found necessary.

The greatest benefits will be derived if it is possible to utilise specific groups of ships which are already operating continuously on regular and fixed round voyage routes which transit through suitable, depleted deep ocean areas, or which can be deviated at low cost to do so.

It will probably be better, at least initially, to concentrate only on the addition of iron to areas that are deficient, rather than to additionally stimulate areas by adding urea or other chemical fertilisers to biologically depleted sea areas. Over stimulation of growth is unlikely to occur when only pure soluble iron is added, any excess should quickly sink out of the surface system and any excessive phyto-plankton or other growth should stop almost completely once the iron is used up.

In the case of adding e.g. nitrate based fertilisers, any excess may stay dormant in solution until it is later absorbed and plant growth triggered by changing sea conditions at which time an uncontrolled bloom may occur in an un-intended position, possibly leading to local anoxic poisoning or worse.

However, it is unlikely that just pure iron alone will provide the long term optimum solution and part of the trial intent must be to identify an optimum, safe mixture and dosage rate for each depleted zone.

Identification of suitable Trade routes for Ocean Fertilisation.

Ocean fertilisation trials have so far only been attempted intermittently, on a small scale and in a very few select localities; examples are in the Southern Ocean adjacent to the Antarctic Continent as well as in the Pacific Ocean near the Galapagos Islands. These are highly sensitive areas and each may or may not in practice be the most suitable choice for trials of the type and scale being proposed here. The Southern Ocean in particular is very remote, far from any suitable shipping lanes and is subject to a very short summer period during which growth rates could be expected to be high enough to be depended upon for CO_2 sequestration. Wild life in the area is also highly sensitive to the sort of changes that could result from our trials.

In each of the major oceans, Atlantic, Pacific and Indian, there are major gyres which are displaced north and south of the equator. These gyres are permanent features which are all far from land and in areas which receive high levels of summer sunshine. Each has at its heart a huge area of plankton depleted water which remains away from most coastal influence.

It would appear that provided that these gyres do indeed have suitable biological characteristics, then one or more (in particular the North Atlantic Gyre which is the best known and most studied) could be utilised as a large scale trial site.

It should also be noted that the size and position of the areas (both depleted and high growth) vary according to the season of the year and the position of various ocean weather systems as well as strength and temperature of the currents (and winds). The areas change size and to a lesser extent change locality throughout the year but are always in roughly the same Global position. Many are also on or near major shipping routes (see Fig 2) and are easily accessible for statutory and scientific monitoring purposes.

An example of what may be possible if Ships are used for CO2 Sequestration.

I was recently involved, over several years, in the specification of a series of new, very large, Liquid Natural Gas carriers fitted with very efficient and novel propulsion systems. They are all going to trade from a common loading port in the Arabian Gulf, with the first batch delivering Liquefied Natural Gas to Europe and most of the rest delivering their similar cargoes to dedicated reception ports in the US Gulf of Mexico, the Far East or Japan. They will be making regular deliveries along dedicated shipping routes.

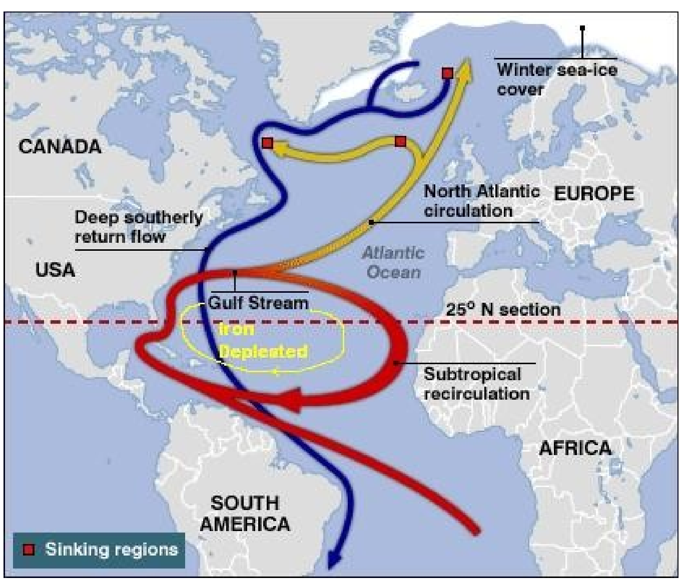
When in operation, after discharging their LNG cargoes the ships will each be loading between 50,000 m^3 and 70,000 m^3 of sea water ballast in the Cargo discharge port before setting off back to the loading port. The ships departing from the USA Gulf of Mexico will be transiting the northern mid Atlantic depleted zone (between the Caribbean and the Straits of Gibraltar). Others will be unloading cargo in Japan or Korea and transiting part of the North Pacific Gyre and Indian Ocean while returning to the Middle East.

All of these ships have been designed specifically to comply with all current and anticipated emission and ballast water standards and will have the capability to operate with the lowest currently attainable CO2 emissions of any LNG delivery system. The increased size of the ships (compared with currently available steam powered LNG vessels) plus the use of very high efficiency direct drive slow speed diesel engines, means that about 40% less CO2 will be emitted from them than if the same volume of cargo was to be delivered by using existing standard sized steam turbine propelled vessels.

Never the less, each of the ships operating to the USA will emit roughly 22,000 tonnes of CO2 per round trip and perform about 8.3 delivery voyages each per year, while those delivering cargo to Europe will emit about 14,800 tonnes of CO2 per round trip and perform about 12 deliveries per year.

With a very small addition [in the order of approximately 9 tonne Fe per ballast trip] of iron to the initial load of Ballast water taken on board in the US port which will be exchanged for fresh clean ballast while transiting the oceanic depleted zones, it appears to be possible for at least some of these ships to operate in a permanently Carbon Neutral mode i.e. achieve net zero overall exhaust emissions.

Fig 3



If the Ballast exchange is arranged to take place within the Northern portion of the North Atlantic Gyre as the ships Trading to North American Gulf of Mexico ports return to the Arabian Gulf via Gibraltar and the

Mediterranean it should be possible to initiate a strong Planktonic growth within the Gyre and hopefully induce a strong Carbon drawdown effect .

Taking this possibility one step further, if utilised as part of a Global CO2 sequestration project these vessels could in addition deliver very much larger quantities of iron based nutrients during each trip and thereby contribute in a very major way to CO2 extraction from the atmosphere. Just how much dissolved iron can be carried in ballast water is difficult to estimate and whether other problems such as sediment accumulation in the ship ballast tanks can be avoided is also unknown. These are some of the questions to be answered by the results from early seeding trials. It is probable that in the order of 10,000 tonnes of dissolved iron could be delivered in a single 50,000 to 70,000 tonne ballast exchange from one ship.

If this is so, then each ship could hope to sequester up to something like 25,000,000 tonnes of CO2 per round trip. Again, if this should prove to be actually possible, then each participating vessel in this project alone would have the capability of sequestering about 208,250,000 (American operation) tonnes per year.

(If all 45 ships could be operated in such a manner as to achieve this result it would add up to the possibility of sequestering a staggering 9.4 Giga tonnes or 9,371,250,000 tonnes of CO2, per year).

In reality these figures, despite being based on the lowest available estimates, are still likely to be highly optimistic. Nevertheless, they do indicate that potentially, a well controlled and properly targeted series of ballast water exchanges may have very beneficial results in the removal of Atmospheric CO2.

Also, it should be noted that the LNG cargoes are produced from slightly sour gas extracted from a gas field in the Middle-East and a major bye product of this production is sulphur, an important element in the production of the sulphuric acid required to produce the soluble ferrous sulphate for the ballast water treatment.

In addition it can be stated that one of the Operating Partners in the new ships is also the largest operator of Iron Ore vessels in the world.

These LNG vessels (and many others like them) will be both loading and discharging their LNG cargoes in very close proximity to major existing chemical plant where soluble Ferrous Sulphate, Urea and other more specialised dosing chemicals could be readily made available in bulk.

In practice, it is likely that a convenient method of operation would be to load a concentrated solution of iron sulphate dissolved in a clean fresh or sea water base into a small barge or tank vessel and to then pump this solution in metered quantities directly into the larger vessels ballast tanks as the LNG cargo is being discharged and the usual (sea) water ballast is being loaded.

MN

JOHN NISSEN

Geoengineering to save the Arctic sea ice

Submission to the Royal Society for their geoengineering study

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The given questions

1. What do you consider to be the current state of knowledge regarding the feasibility, efficacy and predicted impacts of climate geoengineering schemes?
2. How do you think research into climate geoengineering should be taken forward, and by whom?
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?
5. What do you see as the main barriers to, and opportunities offered by, climate geoengineering?
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?
7. Are there any other issues related to climate geoengineering that you consider to be important?

The Magnitude of the Problem

The earth's climate system shows signs of tipping into a new super-hot state, with barren lands, sterile seas, mass extinctions, a huge rise in sea level and almost inevitably the collapse of human civilisation. Over the past century, the earth's energy balance has been disturbed by a growing pulse of anthropogenic greenhouse gases (GHGs) in the atmosphere, now more than sufficient to tip the system, judging by previous tipping events in the earth's history [20].

One dramatic sign of this tipping is the decrease in the remaining Arctic sea ice at the end of summer, which causes positive feedback through the albedo effect. Other signs include the doubling of ice loss from the Greenland ice sheet over a decade, the reduction in the oceans' capacity to absorb CO_2, and the increasing stress on tropical forests, with photosynthesis slowing as temperatures rise. The stress on ecosystems is threatening a mass extinction event [21].

This tipping has to be stopped, with a return towards the original state of the climate system, in which mankind can prosper. This is an extremely tough challenge.

Introduction

The world community, as exemplified in the Kyoto process, appears to believe that global emissions reduction, if sufficient by 2050, can alone prevent a global temperature rise of over 2° C. However this belief is wishful thinking. There is already a net anthropogenic forcing of around 1.6 Watts per metre^2, largely from the 105 ppm of anthropogenic CO_2 in the atmosphere (current 385 ppm less pre-industrial 280 ppm). Even if we could halt emissions overnight, this forcing would largely continue for many decades. And to reduce this direct forcing to zero, we would have to reduce the atmospheric concentration to somewhere around its pre-industrial level. Meanwhile there is significant positive feedback in the climate system, particular from the Arctic sea ice albedo effect (as ice gives way to water, more solar radiation is absorbed). It is difficult to see how the Arctic sea ice can be saved except through geoengineering, especially geoengineering using Solar Radiation Management (SRM) to cool the Arctic region. (BTW, I am referring to saving the sea ice from near disappearance at the end of summer. From the first such disappearance it could take decades before the Arctic Ocean is ice-free throughout the year. On the other hand, there is a risk that this could happen in only a few years.)

I expressed my concerns in an email to Professor Martin Rees, 6th November (copied to Ken Caldeira on your panel) as follows.

I am extremely concerned that we will act too late to save the Arctic sea ice, which some experts now believe could be disappear in summer 2013 or earlier [1]. Such a retreat might then trigger an unstoppable chain of events (permafrost methane release [2], Greenland ice sheet disintegration [3], etc.) leading to catastrophe for civilisation and extinction for most species of animals and plants. I believe the risk is very significant.

However I also believe that two of the geoengineering options are capable of reducing the Earth's albedo, one using enhancement of marine clouds and the other using stratospheric sulphate aerosols. Both have withstood a great deal of criticism to emerge as benign but effective weapons in the fight against global warming. They are discussed in the Philosophical Transactions of the Royal Society special edition on Geoengineering, September 2008 [4], with two papers concerning each option: albedo enhancement of marine clouds [5] [6], and stratospheric sulphate aerosols [7] [8]. Could they be used to save the sea ice?

I have discussed this with authors of the papers, and they each claim that their technology could be used. As regards marine cloud enhancement, Stephen Salter and John Latham argue that the technique could be used to cool the Gulf Stream in the North Atlantic before it enters the Arctic ocean, thus reducing sea ice summer melting (and increasing winter freezing) sufficient to prevent its disappearance. As regards sulphate aerosols, Ken Caldeira claims that they could be deployed in the stratosphere over the Arctic in sufficient density to offset the regional warming from the "albedo effect" (as sea ice is replaced by open water), thus halting the summer retreat of sea ice.

It appears that each of these albedo engineering techniques could, in theory, be used by itself to save the sea ice. What we lack is practical experimentation and engineering experience. To have the best chance of saving the sea ice, we need to be able to ramp up the deployment of both of these technologies (belts and braces), to full scale over two years. This warrants a programme implemented with the determination, resources and urgency of the Manhattan project.

The argument for urgent deployment of SRM techniques

This argument has been developed on the geoengineering blog [9]:

Considering:

1. Emissions cuts cannot save the Arctic sea ice.

Even if we were to stop all CO2 emissions overnight, the CO2 level in the atmosphere would remain at around 385 ppm, and the net positive climate forcing (i.e. heating) around 1.6 Watts per square metre, for decades, other things being equal. (The CO2 forcing is greater than 1.6, but net forcing allows for a negative forcing from tropospheric aerosols, which is actually on the decrease.) The global warming would therefore continue for decades [10]. Therefore there is no way that emissions reductions can produce a cooling effect on a timescale of a few years.

Actually the point can be made even stronger. To produce a cooling effect, one would need to have a net **negative** forcing. To produce this you would need to bring the CO2 down below the pre-industrial equilibrium point, generally taken as 280 ppm. And to do this in the Arctic, and counter the local albedo forcing, you'd need to take CO2 well below 280 ppm within a few years. This is clearly **absolutely impossible**.

2. The Arctic warming is probably at least double the speed of average global warming [11].

Note that this Arctic warming has continued during the last decade, whereas global warming has not been significant during this period. This suggests local positive feedback and/or more local transport effects, such as warming of the Gulf Stream or strengthening of the Northerlies, are at work. (It is not because greenhouse gases are more effective at the poles – they produce much the same forcing wherever they are, assuming a uniform distribution. However methane release could produce a local effect perhaps.)

3. If the sea ice goes, the Arctic warming accelerates and is liable to trigger huge releases of methane from permafrost, long before the global warming reaches 2 degrees, this methane causing runaway global warming [12]. It is also liable to trigger disastrous sea level rise from Greenland ice sheet melting, eventually reaching 6 or 7 metres [13].

I think it extremely doubtful that civilisation could survive such a combination of catastrophes.

4. According the latest research, documented in the Climate Safety report [14], the sea ice could disappear in 3-7 years (at the end of summer).

5. Geoengineering now appears to be the only possible means to save the Arctic sea ice, and prevent a "tipping point" becoming a "point of no return".

6. The local climate forcing (heating) from the albedo effect, as Arctic sea ice retreats in summer, could more than double between now and complete sea ice disappearance.

7. Geoengineering needs to be up to full scale as quickly as possible, to maximise the chance of saving the Arctic sea ice.

Therefore:

We need immediately to initiate a top-priority, super-urgent project for geoengineering to save the Arctic sea ice - a project with the focus, determination and urgency of the Manhattan project.

This is not to say that we should not continue urgently on emissions reduction – a combined strategy is needed [15] [16] [17]. Without such a strategy, there are the dangers of continuing ocean acidification, and with SRM withdrawal – such as the temperature rebound effect [18]. Such dangers are often unfairly levelled against particular SRM techniques, as if they would be used without emissions reduction. But no responsible scientist would suggest SRM without emissions reduction. SRM buys time for the necessary reductions to be implemented.

Discussion of questions

I will discuss these in relation to cloud-related SRM only – cloud brightening [5] [6] and stratospheric aerosols [7] [8].

1. Current state of knowledge

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 is severely limited because the knowledge is concentrated in simulations, and there is the almost complete lack of any engineering experience, especially from experimental field trials.

Much research seems to have been to find fault with geoengineering (particularly stratospheric sulphate aerosols), rather than finding how it can be made to work. At least that is the impression from media reporting, which concentrates almost entirely on the negative aspects, tending to exaggerate possible side-effects. This has given a very bad name to geoengineering. The possibility that geoengineering could be key, to preventing disastrous global warming and disastrous sea level rise, has been totally disregarded by leading scientists, environmentalists and the media. One continues to hear that the dangers of deployment, or even considering deployment, outweigh the benefits.

Yet I have yet to find anybody who can provide a convincing counter to my train of argument above.

2. How and by whom research should be taken forward

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

Considering its multi-disciplinary nature, and the urgency, we need top scientists and engineers, to move quickly from research onto development and deployment with all necessary resources at their disposal. It could be advantageous to involve the military for stratospheric aerosol precursor dispersal. Speed is of the essence. Considering that the albedo effect is tending to grow rapidly from year to year, the objective should be to be able to ramp up to full scale deployment within two or three years, and maximise the chances of success in saving the Arctic sea ice.

3. Considerations and responsibility

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

The main factor, with SRM schemes, should be the urgency. How fast can the scheme be deployed without risking counter-productive or catastrophic side-effects? For example, is catastrophic ozone depletion a significant risk with stratospheric aerosols? If so, could the risk be reduced to an acceptable level by better control of CFCs and other ozone depleting chemicals? What would happen if there were a volcanic eruption on the scale of Mount Pinatubo, during SRM?

The responsibility should be government, because of the international nature of deployment and, in the case of SRM, the lack of financial incentive for industry (unlike mitigation or carbon capture, where carbon trading can provide an incentive). However industry and private funding could have a role.

4. Political, social, legal and ethical issues

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

I think these issues are overwhelmingly positive towards geoengineering, both for almost immediate deployment in the Arctic and for halting global warming.

- Saving the Arctic sea ice could be saving us from ultimate disaster.
- SRM in the Arctic can help to save an entire ecosystem for animals and sea creatures, with their food chain having repercussions elsewhere;
- SRM in the Arctic could restore a way of life for Inuit people.
- Marine cloud brightening can be used regionally or for particular ecosystems, such as corals.
- SRM for halting global warming would much reduce the need for extremely expensive adaptation measures.
- SRM for halting global warming could save millions of lives otherwise lost through the affects of climate change or inability to adapt, regardless of the Arctic sea ice.
- SRM for halting global warming could prevent a mass extinction event [19].
- SRM might be applied in the Antarctic to halt the decline of the WAIS, detachment of ice shelves and ecosystem stress (for penguins, etc.).
- SRM applied to both Arctic and Arctic might prevent a significant sea level rise this century, and hence avoid mass emigration from low-lying regions, cost of flood defences, etc.
- SRM for halting global warming would protect oceanic and terrestrial carbon sinks, whose efficacy reduces with temperature.
- SRM for halting global warming, or perhaps just for mountainous regions, could maintain glaciers and associated water supplies for millions of people, their crops and livestock.
- SRM and cloud seeding techniques could be combined regionally for reducing droughts or countering desertification.
- Note that the use of both stratospheric and tropospheric techniques together offer advantages in terms of balancing cost, the targeting of specific regions, reduction of side-effects, etc.

The main ethical issue is the moral hazard of **not** applying geoengineering, when you know of its capabilities.

The main political problem could be avoidance of panic, if people were told how serious the situation really was. Thus the government might have to appear casual, whilst at the same time putting the required focus, determination, and urgency into a project for rapid geoengineering deployment.

5. Barriers and opportunities

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

The main barrier seems to be psychological – that nobody with knowledge, authority and leadership is prepared to face up to the disaster that could happen, so they seem to deny the possible remedy. This denial is well described in Jared Diamond's book – where the bigger the problem, the more worrying, up to a point when denial sets in. He illustrates this effect with an experiment with people living below a dam [17].

For opportunities, see above.

6. Relation to climate change: research, mitigation and adaptation

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

It has been generally accepted that significant climate change is inevitable, and therefore we must prepare for adaptation – even adaptation for 4 degrees whilst targeting 2 degrees [18]. However this inevitability is challenged by geoengineering, if it proves capable to halt global warming.

However mitigation should be spurred on by confronting the enormous danger of the Earth system continuing to tip into a super-hot state (see "The Magnitude of the Problem" above). Often, in criticising geoengineering, it is assumed to be applied maximally, e.g. to counter a doubling of anthropogenic CO_2 in the atmosphere. The best use of geoengineering should be preventative rather than remediative.

Note that by halting global warming, SRM techniques would protect the carbon sinks, terrestrial and oceanic, vital for absorbing about 50% of CO_2 emissions. Thus the carbon cycle has to be a consideration in research. Similarly the hydrological cycle and other cycles, relevant to the Earth system, need consideration.

7. Other important issues

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

The cost of geoengineering is sometimes thought to be prohibitive, but it is actually ridiculously cheap in comparison with the financial savings that could be achieved, let alone the savings in lives.

If geoengineering can halt global warming, and reduce stress on environments worldwide, there should be a significant reduction in conflicts and human misery. Nearly all regions of conflict have environmental stress. Therefore it is right to treat global warming as a planetary emergency [19]. Perhaps the most alarming danger from significant global warming is the provocation of nuclear conflict.

Global warming has increased as the result of the removal of sulphur-based aerosols from the troposphere. We must be careful that future legislation is not in the same direction of increasing global warming as a side effect, or that it is balanced by SRM.

More mundane measures to help reduce the Earth's albedo, such as painting roofs with reflective paint, should not be ignored.

Conclusion

Geoengineering gives us an opportunity to leave future generations a world that is as hospitable as we have enjoyed for the past 8000 years or more. We should seize the opportunity, and go with it as fast as possible, before this opportunity slips away.

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Argument for urgent need of SRM

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Appendix

Calculations concerning the use of marine cloud brightening to save the Arctic sea ice, by Stephen Salter.

Saving Arctic Ice

The site http://www.crrel.usace.army.mil/sid/IMB/pdfs/2008GL034007_for_IMB_web_page.pdf reports that the 2007 Arctic ice reached a minimum area $Amin := 4.2 \cdot 10^{6} \cdot km^{2}$ which was $\Delta A := 1.6 \cdot 10^{6} \cdot km^{2}$ less than the previous low in 2005. There is also a mention of thickness changes of 0.26 and 0.64 m.

We wish to increase the area of ice by $Ainc := 2 \cdot 10^{6} \cdot km^{2}$ and its thickness by $Tice := 0.5 \cdot m$

If water density is $\rho w := 1020 \cdot \frac{kg}{m^{3}}$ this a mass of $Mice := Ainc \cdot Tice \cdot \rho w = 1.02 \times 10^{15} kg$

Latent heat of ice is $LHTice := 334000 \cdot \frac{J}{kg}$ so the energy is $En := Mice \cdot LHTice = 3.407 \times 10^{20} J$

If we want to do this in $Time := 0.5 \cdot yr$ the power is $POW := \frac{En}{Time} = 2.159 \times 10^{13} W$

The Phil. Trans. hardware paper suggests that allowing for the 0.18 Charlson and Lovelock fraction of low cloud but not high cloud cover the cooling power per vessel is $powvess := 420 \cdot 10^{9} \cdot watt$

so the number of vessels is $Nvess := \frac{POW}{powvess} = 51$

If we can predict where the good cloud can be we may be able to reduce this. Vessels can operate anywhere where water is flowing towards the Arctic but should avoid polluted air in shipping lanes.

DR TIM PALMER FRS

Royal Society Report on Geoengineering Climate

A submission by T N Palmer FRS: ECMWF and Co-Chair World Climate Research Programme International Scientific Steering Group, Climate Variability and Predictability Project

In this brief submission, I wish to establish a fundamental principle in the geoengineering climate debate, in order to answer the following question: do we currently have the means to simulate reliably the regional impact of any particular climate geoengineering proposal? Below I state a necessary condition for answering this question in the affirmative. We are currently far from meeting this condition.

Any forced perturbation to climate, whether natural (eg due to orbital variations) or manmade (eg due to anthropogenic emissions of greenhouse gases, or due to one of the proposals to geoengineer climate) has both global and local impacts. In a nonlinear system such as climate, one way to view these local impacts is in terms of changes in the frequency of occurrence of internal modes of climate variability (Palmer 1999). For example, an increase in the frequency of occurrence of El Niño will have a substantial impact on precipitation climate across much of the tropics; an increase in the frequency of Euro-Atlantic blocking anticyclones will have an impact on precipitation and storminess across much of Europe. Hence it is essential that we are able to simulate reliably the impact of any putative proposal to geoengineer climate on these internal modes of climate variability.

However, it is well know that the current generation of climate models do not simulate internal modes of climate variability well. I quote from the IPCC Fourth Assessment Report (2007): "Models still show significant errors. Although these are generally greater at smaller scales, important large-scale problems also remain. For example, deficiencies remain in the simulation of tropical precipitation, the El Niño-Southern Oscillation and the Madden-Julian Oscillation…The ultimate source of most such errors is that many important small-scale processes cannot be represented explicitly in models and so must be included in approximate form... This is partly due to limitations in computer power."

As a result of these problems, climate models suffer significant biases in temperature and precipitation around the globe. Typically these biases are as large as the likely anthropogenic climate change signal. In a nonlinear system such as climate, the existence of such biases is a recipe for regional forecast unreliability.

In the case of anthropogenic climate change, these models, based on the laws of physics, are the best we have available and it is absolutely right that they have been used extensively (eg by IPCC) to warn society of the risks of unmitigated climate change. However, whilst such models must similarly be used to determine the regional weather and climate impacts of geoengineering climate, the existence of these significant biases must lead to considerable caution. Whilst such models may well be capable of giving a sense of changes to global mean temperature of a geoengineering proposal, they are currently untrustworthy in giving predictions of changes to regional weather patterns. It would be a disaster if one of the unforeseen consequences of geoengineering climate was to make parts of the world uninhabitable (consider, for example, a general drying of the African Sahel) due to changes in precipitation or storminess.

Given the need to be able to simulate reliably the regions impacts of geoengineering climate, I propose here that a fundamental principle should be established once and for all: proposals to geoengineer climate should never be endorsed by learned societies such as the Royal Societies whilst biases in contemporary climate models are not small, compared with the potential impacts of these proposals.

The Royal Society report on geoengineering climate should be used as an opportunity to stress that our scientific understanding of climate, particularly of regional climate, and the way in which internal modes of climate variability interact with external anthropogenic or natural forcings, is poor. This is something not well appreciated by politicians and other decision makers (many of whom view the science of climate as done and dusted).

As noted in the IPCC quote above, improving our understanding, and ultimately our capability to predict climate reliably on regional scales, is hindered by insufficient high-performance computing infrastructure, and it would be helpful if the geoengineering climate report highlighted this as a significant roadblock to progress.

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DR GREG RAU

In response to TRS request for input on geoengineering concepts:
Geoengineering via Chemical Enhancement of Ocean CO2 Uptake and Storage

Scheme type: Non-biological greenhouse gas reduction systems
Author: Greg H,. Rau, Ph.D. Senior Researcher, Inst. Marine Sciences, Univ, California, Santa Cruz, CA USA (off campus - Carbon Management Program, Lawrence Livermore National Laboratory, L-645, 7000 East Ave., Livermore, CA, USA; rau4@llnl.gov, 925 423 7990)

Summary:
Given that the ocean is the largest CO2 absorber on the planet (gross absorption = about 92 GT C/yr), and plays the central role in the natural mitigation of excess atmospheric CO2, ways of safely enhancing this uptake and storage via ocean chemistry modification deserve to be seriously considered. The advantages of using the ocean in such CO2 mitigation efforts include:
1) the ocean presents the largest planetary CO2 exchange surface,
2) the ocean is earth's largest potential carbon storage reservoir,
3) use of the ocean reduces the dependence on uncertain and more space-limited, landbased CO2 capture/storage schemes, and
4) the excess carbon would be stored in stable bicarbonate and carbonate forms, not as less stable and less permanent molecular CO2 or organic carbon.
Furthermore, ocean alkalinity modification as reviewed here can also directly moderate ocean pH (currently being lowered by the invasion of excess air CO2) and directly help preserve or enhance ocean biogeochemistry (e.g., bio calcification), unlike geoengineering schemes employing albedo manipulation, and unlike land-based CO2 mitigation such as CCS with geologic CO2 storage. The uncertainties in capacity, efficacy, impacts, and/or cost inherent in these latter approaches demands that the vast mitigation potential of the ocean be considered in our attempts to preserve earth habitability. Further work is clearly needed, however, to accurately determine the costbenefit, impacts, and possible role of marine chemical approaches in stabilizing or possibly even reducing atmospheric CO2 concentration.

Background
The ocean currently absorbs about 92 GT of C as CO2 per year and emits about 90 GT C/yr, for a net gain of about 2 GT C/yr, the largest CO2 sink on earth. This net absorption is driven by an average difference in CO2 concentration between the atmosphere and the ocean, currently maintained by anthropogenic CO2 emissions into the atmosphere. However, once in the ocean, little of the absorbed CO2 remains in molecular form; rather it reacts with the OH- and CO3 2- ions naturally present in seawater to form primarily dissolved bicarbonates:

$$CO_2 + OH^- \rightarrow HCO_3^-$$
$$CO_2 + CO_3^{2-} + H_2O \rightarrow 2HCO_3^-$$

It is therefore understood that any increase in concentration of OH- and $CO_3$2- in the ocean (loosely - "alkalinity") increases the ability of seawater to absorb and store CO_2.
Thus, Kheshgi (1995) proposed to exploit this feature by purposely adding OH- to the ocean in the form of highly soluble $Ca(OH)_2$ in order to chemically enhance absorption of atmospheric CO_2. Even considering the carbon intensive nature of $Ca(OH)_2$ production via limestone calcination, Kheshgi showed that the net effect would still be to produce an ocean CO2 sink.
More recently House et al, (2007) proposed using the electrochemical chlor-alkali process to produce NaOH which when added to the ocean would enhance ocean CO2 absorption, The Cl2 and H2 co-generated by the process would be reacted in a fuel cell to produce electricity and the strong acid, HCl. They proposed that this HCl be consumed and neutralized by reacting it with globally abundant silicate minerals to form more environmentally benign chlorides. Also employing electrochemistry, Rau (2008) demonstrated that seawater pH and OH- could be significantly increased when the anode of a seawater electrolysis cell was encased in porous calcium carbonate. The excess OH resulting from the dissolution of the carbonate at the acidic anode with the excess calcium ions combing with the hydroxyl ions from the cathode to form Ca(OH)2. It was proposed that various known methods be employed to promote oxygen over chlorine evolution, thus allowing the hydrogen produced to further mitigate CO2 by substituting for fossil transportation fuels or for chemical feed stock. Use of electricity from renewable rather than from

fossil energy sources ensures that the process would be very significantly carbon-negative (CO_2 consumed per H_2 produced = 22/1 by mass; CO_2 avoided/H_2 produced = 31/1 by mass; Rau, 2008)
The input of additional CO_3^{2-} to the ocean is more problematic since the most abundant, naturally occurring carbonate forms are virtually insoluble in surface seawater ($CaCO_3$, $MgCO_3$). Nevertheless, such carbonates will dissolve and absorb CO_2 when exposed to water acidified with excess carbon dioxide:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-.$$

This reaction was proposed as a means of absorbing and mitigating terrestrial point CO_2 sources, using the ocean both as a source of water and as a reservoir for the resulting $Ca(HCO_3)_2$ produced (Rau and Caldeira, 1999; Rau et al., 2007). Recently, Harvey (2008) suggested that calcium carbonate particles be "rained" into the mildly acidic, elevated CO_2 environment of the subsurface ocean to generate excess alkalinity for CO_2 absorption. Both methods essentially are a way of accelerating natural marine or continental carbonate weathering that will otherwise absorb most excess atmospheric CO_2 but over geologic time scales (Archer et al. 1997).

Ocean Chemistry Modification as Large-Scale Geoengineering
With an objective of absorbing 1 GT C (3.7 GT CO_2) per year, what are the prospects for any of the preceding methods? The following is a preliminary outline of the issues:

Reactants - With seawater, carbonate or silicate minerals, and/or NaCl as starting compounds, the global abundance of these are orders of magnitude greater that needed to mitigate all fossil-derived CO_2, i.e., the capacity of the schemes is not limited by global availability of reactants. Rather, the local availability of these commodities to mitigation process sites can be limiting, but unlike point source CO_2 mitigation, ocean-based air capture schemes have the luxury of being sited anywhere that seawater and reactant availability, energy supplies, and infrastructure are optimized (Keith et al., 2006; House et al. 2007). In the case of water demand, it was estimated that 6000 m3 of seawater per sec would need to be pumped to mitigate 1 GT C/yr via electrolytic NaOH formation, a volume equivalent to that pumped by about 100 sewage treatment plants (House et al 2007). Rau suggested seawater pumping could be avoided by conducting the electrolysis directly in seawater from stationary or mobile platforms. Assuming >2 tonnes of mineral is required per tonne CO_2 mitigated (House et al., 2007; Harvey, 2008; Rau, 2008), then >7GT/yr of mineral would be needed to consume 1 GT C/yr as CO_2. This is >5X the annual crushed stone production of the US (global statistics not available), indicating a significant increase in global mineral extraction would be needed by such CO_2 mitigation approaches.

Energy - For electrochemical schemes, House et al. (2007) and Rau (2008) reported required energy expenditures ranging from 0.8 to 2.3 MWh of renewable electricity required per tonne of CO_2 mitigated, meaning a global expenditure of 3 - 9 $x10^3$ TWhe per 1 GT C mitigated/yr. For comparison, global annual electricity production is about $19x10^3$ TWhe, but the use of grid electricity for these electrochemistry schemes is not suggested. Rather, stranded renewable energy could be exploited, with the potential ocean energy alone (wind, wave, thermal, solar etc.) amounting to >2 106TWh/yr (Rogner, 2000). Considerably less energy would be required for limestone mining, crushing, transport, and application (Harvey, 2008).

Environmental impacts/benefits - Based on the widespread practice of adding mineral hydroxide or bicarbonate to seawater aquaria to perverse or enhance pet marine biota
(e.g., Holmes-Farley, 2002), adding such compounds to the ocean should in principle be similarly safe and beneficial. However, the concentration of these additives would needed to be kept below impactful levels, and there could be soluble contaminants in the minerals used that could have negative downstream effects. Also, increased environmental impacts will accompany increased mineral extraction, crushing, transport, etc. Disposal of residual solids could also pose a problem. Increased exploitation of renewable energy for such systems would also likely have environmental consequences. An accurate estimate of impacts versus benefits is obviously needed before any ocean chemical schemes or other alternatives are employed at large scales.

Economics - Most ocean chemistry modification schemes decline to mention economics, no doubt due to the preliminary, conceptual state of this technology. Using a host of assumptions, Rau (2008) calculated a net mitigation cost of $74/net tonne CO_2 mitigated using the electrochemical limestone splitting approach. Costs in excess of $100/tonne CO_2 have been calculated for various land-based chemical air CO_2 capture approaches (Keith et al, 2006; Zeman, 2007). Passive addition of limestone to the subsurface ocean (Harvey, 2008) should be much less expensive, but also less immediately effective in influencing atmospheric CO2 due the time lag in subsurface ocean chemistry influencing atmospheric CO2. If a mean cost of $50/tonne CO2 mitigated is assumed for all ocean chemistry approaches, then mitigation of 3.7 GT of CO2 per year would require an expenditure of about $190B or about 0.3% of global annual GDP.

Needs and next steps - Lab to pilot scale testing is needed to fully evaluate effectiveness, capacity, costs, environmental impact, and safety. At this early stage, ocean chemistry modification needs to be part of a larger geoengineering roadmap, and its potential cost, impacts, and benefits need to be fairly evaluated and weighed with those of other approaches in the process of allocating available R&D resources.

Response to specific questions posed by TRS
In the context of ocean chemistry geoengineering approaches:

Current state of knowledge - Primarily conceptual regarding feasibility, efficacy, cost,and impacts; Some proof of concept experimentation has been done - see preceding.

How and who to take forward - Proposals from any team or entity should be evaluated by an independent body (national/international) providing priority and ranking for further R&D and policy roadmapping and investment.

Factors to consider before deploying and who should deploy - The usual factors include safety, efficacy, environmental impact, capacity, and cost. Competency should be the primary criteria as to who tests/deploys, but what and where deployed must have strong national/international oversight.

Most important political, social, legal ethical issues - Fear of the unknown and the assumption/hope that other approaches will be sufficient so as to not require study and implementation of alternatives like geoengineering.

Main barriers to geoengineering - Ignorance and apathy; the assumption that the nongeoengineering approaches will be sufficient.

Where geoengineering fits into greater scheme of climate research and action – Serious consideration of geoengineering is required given the magnitude and urgency of the CO2 problem, and the uncertainties in the effectiveness and timeliness of other CO2 mitigation strategies, i.e., increased efficiency, use of renewables, and decarbonizing fossil energy.

Other issues -I am very surprised and disappointed that TRS is requesting input on planetary geoengineering exclusively in the context of climate mitigation, failing to even mention ocean acidification, the other serious concern re anthropogenic CO2 as previously reported on by the same TRS (2005).

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DR PETER READ

Geo-engineering the Earth's Climate
Submission responding to the Royal Society's call of October 2008, from
Peter Read, Hon Research Fellow, Massey University Centre for Energy Research, New Zealand.
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This submission is provided in my personal capacity. It is based in part on my paper "***Global Gardening with a Leaky Bucket: Addressing the threat of climatic catastrophe through Article 3.3 of the UNFCCC***", enclosed herewith.

Summary

- Mankind has been engaged in geo-engineering since the dawn of settled agriculture
- It is an illusion that fossil carbon emitted into the atmosphere stays there a very long time.
- With biotic exchanges with the atmosphere ~10 times the rate of fossil fuel emissions logical policy should focus on biosphere carbon stock management (BCSM),
- Reversibility is an important criteria, along with socio-economic and developmental benefits

The take home message of ***Global Gardening with a Leaky Bucket*** is

- Article 3.3 of the Convention, calling for cost-effective action without delay on account of scientific uncertainty, can be the basis for addressing threats of climatic catastrophe.
- Such threats are real, possibly imminent, and have been wrongly ignored by policy analysts.
- The metric for danger may be cumulative meltwater formation on Greenland, broadly proportional to the integral of CO_2 levels since melting accelerated (post WW2 ?)
- This metric cannot be contained by emissions reductions which, even with implausible success in reducing to zero within 25 years, see it trebling by 2060, and no end in sight.
- Negative emissions systems are needed, especially negative emissions energy systems, which engage energy industry muscle in large scale irrigation and land improvement projects.
- Easily reversible cloud albedo modification may also be needed and should be trialed.
- 'Global gardening', storing carbon in the soil could, with large scale commercial forestry and bioenergy linked CCS can limit the metric to doubling by 2060, with no further increase..
- Biotic processes are difficult to measure and variable in performance and are a poor fit with continuing cap and trade.
- The Leaky Bucket architecture enables policies and measures that drive global gardening, and other benign geoengineering, to receive *ex ante* buy-out of emissions reductions commitments (rather than high transactions cost *post hoc* offsets, as under the CDM).
- Generating gains from North-South trade, and facilitating numerous UN environmental and sustainable developments benefits, the Leaky Bucket is more geo-politically feasible than the conflictual burden sharing of emissions reductions.
- Moreover, by yielding large quantities of sustainable bioenergy, global gardening enables more ambitious emissions reductions commitments, making the leaky bucket architecture complementary to, and supportive of, cap and trade.

Two definitions

"**Global Gardening**" means treating all managed lands worldwide – farmlands, managed forests, grazed savannahs, etc., in the way that good gardeners treat their soil, raising soil organic matter and fertility by returning organic wastes to the soil – e.g. traditional mulching, etc., but now, specially, biochar, the recently emerged technology for adding pyrolyzed organic material to the soil, yielding multiple benefits in improved soil fertility, very long term storage of carbon in soil and energy services from the hydrogen-rich volatile fractions released in pyrolysis.
"**Leaky bucket**" is a policy approach that rewards good behaviour, whether 'additional' or not, *per contra* the project based mechanisms of the Kyoto Protocol, which, through the incentives to cheat that result from 'additionality', create the need for onerous monitoring and reporting arrangements and generate large transactions costs – a 'silver teaspoon', costly and watertight, but not much use for baling CO_2 out of the atmosphere. The 'Leaky bucket' aims to shift carbon out of the atmosphere fast and put it somewhere safer (in the terrestrial biosphere or deeper in the lithosphere) through policies and measures that are negotiated as an *ex ante* buy-out from emissions reductions commitments rather than Kyoto mechanism's *post hoc* offset against an already negotiated cap on emissions. 'Additionality' carries

over theoretical economists' concepts into policy making, where it makes no sense to practical businessmen, farmers or foresters.

My Submission

Mankind has been engaged in a benign geo-engineering project since the dawn of settled agriculture, with forest clearance by fire shifting carbon stocks into atmosphere. This likely prevented descent into a (by now well overdue) cooling phase towards global glaciation [1]. This was supplemented by the shifting of fossil carbon into atmosphere since ~1750, a process that intensified post WW2 and has led to the threat of climatic catastrophe [2]. It is an illusion that geo-engineering is anything new and there should be no shyness about countering the current malign geo-engineering process with further geo-engineering designed to prevent catastrophe.
It is also an illusion that fossil carbon emitted into the atmosphere stays there a very long time. To my astonishment I heard this repeated by a Hadley Centre scientist at a joint Hadley-DEC sideshow at COP14. This myth is extremely damaging to sensible policy making since it supports the false notion that CO_2 is a pollutant which, in line with economic theory, can only be addressed by emissions reductions that are most efficiently achieved by a price signal. Ironically CFC's, which are a pollutant, have been effectively addressed under the Montreal Convention without any price signaling. In reality any carbon emitted into the atmosphere (whether fossil sourced or bio-sourced, with the latter greater by a factor of ~10) stays in the atmosphere for about 14 years, i.e. the ~800Gt in the atmosphere divided by the annual biotic flux of ~60Gt. In response to my questions the Hadley scientist finally accepted the reality that fossil carbon, once released as CO_2 , stays not in the atmosphere for a very long time, but in the linked atmosphere-ocean-terrestrial biosphere system (due to the slowness of transfer from ocean into benthic slimes and from soil into lithosphere), thus providing ample opportunities for capture into terrestrial safe storage as carbon is cycled into and out of the biosphere.
Logical policy therefore should focus on managing carbon stocks, with bio-geo-engineering both to slow malign fossil emissions and to drive benign processes that stock carbon safely : –

- in deep strata (BECCS – Bio-Energy with Carbon Capture and Storage [3]) which is climatically benign but costly
- in the soil as biochar yielding multiple benefits previously mentioned
- above ground in new commercial forest plantations, managed for rotational felling and regrowth, which stocks ~half the carbon possible if the whole area is grown to maturity, but yields a continuing supply of timber and biofuel, in lieu of exploiting ancient forest.

The bioenergy supplied through global gardening substitutes for fossil fuel based energy and enables the malign process to be slowed (emissions reductions) and, on a large enough scale, eventually halted, while enabling the continued use of convenient carbon based energy carriers and minimizing the volume of 'stranded assets' in the existing carbon based infrastructure, thus minimizing the extended transition time that can otherwise be expected [4].

Such biosphere carbon stock management (BCSM) [5] may not be sufficient and other geo-engineering options should be demonstrated and deployed if needed. ***Reversibility is important*** :- stratospheric cloud albedo modification [6] involves sulphur quantities that are small compared with low level sulphur emissions from power stations or occasional high level volcanic injections and which can be terminated quickly, with sulphur aerosol dispersion in a matter of weeks;
tropical cumulus cloud albedo modification [7] involves injections of seawater droplets that can be stopped at short notice with droplet dispersion in a matter of hours;
BECCS [3] and fossil fuel related CCS, yielding CO_2 compressed and injected into deep saline strata, may be reversible, at least partially, over a timescale of years;
commercial forest plantations can be fired, quickly raising atmospheric CO_2 again, if needed;
deep ocean sequestration of CO2, like 'star wars' solar reflectors, cannot be easily reversed, may have harmful side effects, and should not be deployed;

The take-home message of "Global Gardening with a Leaky Bucket" is:

1. UNFCCC Art 3.3 requires action by the Parties individually, if there is a **threat** of serious or irreversible damage, without delay on account of scientific uncertainty and without reference to the Conference of Parties or need for consensus.
2. The **threat** of climatic catastrophe is real [2], albeit not with full scientific certainty, and has been wrongly ignored by all mainstream policy analysts [8]. The threat is evident from statistical analysis of the outcomes of climate scenario models and from reported current climatic events in

the context of studies of the paleo-climatic record. Treating climate scenarios as a sample from the true probability distribution of possible outcomes Weitzman shows that the damage weighted probability of catastrophe – generally treated as *de minimis* in policy analysis – is highly significant,. Hansen *et al* show that precursors of triggers for the rapid (decade scale) collapse of land based ice masses, are currently detectable and collapse (hopefully partial) may be imminent. Uncertainty besets these results but Article 3.3 of the Climate Convention calls for action without delay on account of uncertainty.

3. The metric of danger [9] must be included amongst the uncertainties but a cumulative metric of year-on-year greenhouse gas generated thermal input is plausible, maybe likely [10]. This is in relation to Hansen's concern for a trigger point in ice-sheet surface melt-water formation, with transport via crevasses to basal regions of ice sheets and lubrication of movement under gravity towards the oceans. Increasing frequency of ice-quakes may be symptomatic of eventual runaway collapse of, possibly, large areas of Greenland's ice cover into the oceans.
4. That metric CANNOT be contained by emissions reductions alone. Even a reduction of global emissions to zero over 25 years, beginning in 2010, implausible though that may seem, and zero emissions thereafter, sees a trebling of this cumulative metric 50 years hence, with no end in sight to its continued growth for the rest of the century.
5. Negative emissions systems are needed, actively removing carbon from the atmosphere. For practical purposes, this means increased biotic fixation, leading to enhanced supplies of biomass that can form the basis for bioenergy production. This aspect of addressing threatened climatic catastrophe means that bioenergy has a special role amongst technology 'wedges'[11], maybe even crowding out non-fuel zero emissions technologies if the catastrophic threat becomes acute.
6. Biotic Carbon Stock Management (BCSM) [5] is needed, enhancing natural ~60Gt of photo-synthetic fixation and slowing natural oxidation and return to atmosphere
    - i.e. '**Global Gardening**' - treating farmland and forest land soils with the care that gardeners treat their gardens, building up soil carbon
    - biochar technology is inspiring and important but
    - the immediate big bang for bucks is a vast 25 year programme to extend commercial plantation forestry, likely with huge irrigation schemes (gardeners do do watering) managed with the big project capability of major energy industry players
7. Global gardening could limit the cumulative metric to a doubling by 2050 and ending then, with CO_2 back to pre-industrial, and no further cumulative heating
    - this may not be enough, or may not be capable of sufficiently rapid deployment, and benign reversible geo-engineering (e.g. cloud albedo modification) should be demonstrated and deployed if need be
8. Paid for by energy firms obligated to invest in developing their future biomass raw material supplies (e.g. a rising programme of BCSM portfolio standards)
9. This cannot fit into the cap and trade framework since biotic removals are inherently uncertain and substantially incommensurate with emissions reductions..
10. Thus the need is for '**Leaky Bucket**' that bales CO_2 out of the atmosphere fast, rewarding certified best practice good behaviour (whether additional or not) and driven by policies and measures outside the cap and trade framework
11. A complementary framework provides for policies and measures to be taken into account when allocated amounts are negotiated resulting in *ex ante* <u>buy out</u> of emissions reductions commitments rather than the *post hoc* <u>offsets</u> available under the CDM and JI
    - Global gardening generates large supplies of sustainably produced biofuels making ambitious commitments easier (i.e. leaky bucket is complementary to cap and trade).
    - Policy success can be monitored and policy re-negotiated if need be in the spirit of Schelling's [12] model based on experience of Marshall Plan negotiations, noting that commitments to outcomes that are dependant on circumstances (e.g. finance market turmoil and economic downturn or rebound) involve insincerity whereas policy commitments can be honest.

Issues with biofuels and bioenergy

Global gardening enables a large and crucial role for 'good' bioenergy. This 'good' and 'bad' usage comes from the Sustainable Biofuels Consensus [13] and distinguishes biofuel produced sustainably from biofuel produced without regard to climatic impacts, e.g. for reasons of farm support or of oil supply security. Recent studies focusing on aspects of 'bad' biofuels [14, 15] have prejudiced perceptions of

'good' biofuels, and/or of bioenergy generally. The position taken here is that there is need for the rapid expansion of good bioenergy and for early closure or modification of bad biofuel production facilities.
Biofuel expansion is happening and is inevitable given dwindling supplies of conventional oil and the demands of newly industrializing developing countries. This is because biofuels are near-perfect substitutes for fossil transportation fuels, also bioenergy for fossil fuels generally, thus shortening the transition time needed for adoption of these not very new technologies [4]. Without appropriate policy, low cost bad biofuels will do immense environmental damage.
The financial strength and managerial experience of energy sector firms can be enlisted more easily to secure the needed expansion of sustainable negative emissions systems, if these involve bioenergy. Conditioned to accepting climate change related costs and experienced in handling large scale projects, such as future water management schemes induced by policies negotiated as an *ex ante* buy-out, these energy sector inputs are needed for a rapid transition from fossil fuels.
Geopolitical practicability for a post-2012 architecture based on BCSM, and with it a large role for bioenergy, arises because it offers prospect of gains from trade rather than conflictual burden sharing between Parties that have widely different views of responsibility. This is because many developing country Parties have comparative advantage in biotic fixation due to greater land availability, better climate, year-round growing season, etc., while the demand for carbon credits and sustainable biofuels lies with industrialized country Parties.
Sustainability conditionality generates extra costs that imply additional income for the producing countries and (relative to unfettered 'bad' biofuels) impose a burden on fuel consumers. These are initially mainly in the industrialized countries, held largely responsible for current CO_2 levels, but the burden transfers to fast developing countries as their imports grow. There is a need to guard against sustainability criteria being undermined by competition between producers.
Multiple developmental and environmental benefits – countering desertification, conserving biodiversity and protecting wetlands, etc.; and sustainable rural development through soil and crop yield improvement, rural electrification, etc. – can be targeted through conditionality that offers higher incentives for BCSM activities yielding such co-benefits, thus providing linkage between commercial activity and UN sustainability objectives. Such conditionality can be upgraded in the light of experience embodied in improving codes of best practice. Learning from mistakes (such as, most obviously, first generation 'bad' biofuels) and taking advantage of research and development both with social systems and technological innovations, such linkage and upgrading can provide the mechanism for the emergence of a sustainable global society.

Summary on geo-engineering through worldwide Global Gardening.
The vision of the Sustainable Biofuel Consensus [13] is of "a landscape that provides food, fodder, fiber and energy, that displays sustainable rural development; that restores ecosystems, protects biodiversity, and sequesters carbon; and that contributes to global peace by diversifying the energy supply". The aim of Biosphere Carbon Stock Management (BCSM), on a scale that constitutes geo-engineering, is to deliver that vision whilst addressing the growing threat of climatic catastrophe. Fortunately, although addressing climatic catastrophe may seem to policy makers to be infeasible (given the difficulty of implementing Kyoto, developed in response to perceptions of CO_2 as a pollutant and global warming as a gradual and very long term process) this is not the case. That is because BCSM involves a range of low cost and land use improving technologies that are largely sidelined by the Kyoto architecture, and because their deployment realizes gains from trade rather than imposing the burden sharing that is inherent in 'converge and contract'. Moreover, effective implementation of BCSM, yielding an increasing supply of bio-energy, will enable the Parties to the Protocol more easily to commit to increasingly ambitious emissions reductions within the context of the post-2012 emissions cap regime..

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Appendix: Questions asked in the call for submissions

1. Current state of knowledge

Bioenergy: Sugar cane ethanol is sustainable and capable of rapid expansion; 2nd generation biofuels verge on commerciality; bio-digesters in use worldwide and sustainable; co-firing with coal or stand alone furnaces in use worldwide and sustainable; gasification for advanced generation not quite market ready due to problems with tar formation.
Biochar : Pyrolysis a well established technology for fuel supply objectives but research is continuing on best designs for biochar production. Behaviour in soils and fertility benefits are active research fields (which does not put in question the efficacy of biochar for carbon sequestration).
Tropical cumulus clouds Theory worked out, no practical experience
Arctic high latitude clouds Theory worked out, no practical experience

2. Research needs

Bioenergy Current development stage needs to be hurried through to deployment of sustainable 2nd generation biofuels. Industry will do research and development if driven by, e.g, rising sustainable biofuel mandates that do not support unsustainable 1st generation technologies. There is great need for socioeconomic and developmental research and capacity building driven by government and international agencies (e.g. the GEF) related to deployment of bioenergy in prospective low latitude trading partner countries, (applies to biochar also).
Biochar Research, development and deployment of pyrolysis for biochar supply can be left to industry financing, driven by appropriate mandates which may need to be banded to ensure progress in a range of desirable technological technologies that are at different stages of commercialization. Understanding of soil improvement potential is at the fundamental research stage and funding to universities and research institutions is needed.
Tropical and Arctic cloud albedo modification both need to be trialed, a low cost move for any Party that recognizes the risk of climate catastrophe and the need for action under Article 3.3.

3. Deployment criteria

Reversibility → Trial cloud albedo modification
Socioeconomic and developmental benefits and carbon management effectiveness → recognize catastrophe threat, negotiate 'leaky bucket' architecture, and drive biosphere carbon stock management (BCSM) through bi-lateral or group lateral (e.g. G8 GBEP) partnerships with (initially) selected developing countries.

4. Political etc., issues

The key political issue is to challenge the conventional wisdom that climatic risks can be met by emissions reductions. Successfully achieved, and recognizing that geo-engineering is nothing new, no social legal or ethical issues should arise to deployments that meet the above criteria

5 Barriers

The conventional wisdom just mentioned, and the notion that putting a price on carbon can fix the problem, springing from the false view of atmospheric carbon as pollution problem rather than as an excess stock problem to be handled through management of all flows into and out of the atmosphere.

6 The geoengineering fit

Treating BCSM as geoengineering, in the 6000 year tradition of geoengineering, first benign, recently malign, but now with simple and straightforward opportunities to again become benign, then the relevant research (along with cloud albedo modification as a low cost supplement if needed) into BCSM should receive high priority consistent with the rising threat of catastrophe.

7 Other issues

Maybe an investigation of the social and cultural forces, and the related media coverage, that underpin the current irrational and unscientific policy process which suffers from the delusion that removing a cause will remove its effects and manifests irrational scapegoating of energy supply industries and/or guilt-tripping by the consumers of their products.

DR DAVID REAY

Geoengineering the Earth's climate

Response by Dr David S. Reay relating to managed Nr inputs to the biosphere (personal position statement).

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Summary:

- Managed increases in reactive nitrogen (Nr) inputs to most ecosystems would be a poor and potentially damaging strategy (e.g. oceans and non-forest terrestrial ecosystems).
- Such managed increases in some tropical, temperate and boreal forests do have significant potential in terms of enhanced C sequestration and storage.
- Precedent for this approach exists in commercial forestry – extension to much wider areas of forest has significant practical barriers and would require careful targeting of applications, but forest sink strength enhancement of the order of 3 billion tonnes CO_2 per year is possible.

Relevant areas:

1) Greenhouse gas reduction schemes

a) Removal of CO2 (and other greenhouse gases (GHGs)) from the atmosphere or oceans
i) Methods utilising terrestrial biological systems
ii) Methods utilising oceanic biological systems

Specifically, managing reactive N inputs to the biosphere.

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

Reactive nitrogen (Nr) fertilisation is already a common practice in commercial forestry and recent research (e.g. Magnani et al. 2007) has suggested that the enhancement of net C sequestration by elevated reactive N (Nr) inputs could be as much as 200g C per g Nr in northern forests.

As yet, proposals to increase C storage by increased Nr inputs have centred on N-deficient oceanic surface waters, either by direct addition (analogous to iron fertilisation) or by artificial mixing of N-rich deep waters with N-depleted surface waters.

Unintentional increases in Nr inputs to many terrestrial and oceanic ecosystems are predicted during the 21st century, mainly due to an expansion in global livestock production and continued fossil fuel burning. However, such increases in Nr inputs to the biosphere are unlikely to result in large increases in net C sequestration unless they deliberately targeted at areas with the potential for a substantial response in net primary productivity aligned to lasting storage of the additional C sequesters.

In the oceans, as with iron fertilisation, large algal blooms may be induced by elevated Nr inputs in many areas, but the C sequestration benefits are likely to very short term in most cases with only a very small fraction (1-10%) of this new production ending up in deep sediments (e.g. Krishnamurthy et al. 2007). For coastal and ecosystems, increased Nr inputs also have the potential to induce harmful algal blooms.

For unforested terrestrial ecosystems, there is insufficient data available to predict the impacts of changing Nr inputs, though those soils studies available indicate no net increase in soil C content, with many such areas already receiving substantial anthropogenic Nr (e.g. agricultural lands).

For forests, both secondary tropical, temperate, and boreal, there exists the greatest potential for enhanced C uptake and storage in response to engineered increases in Nr inputs. A doubling of Nr input to these systems (relative to year 2000) could result in the additional sequestration of 3 billion tonnes of CO_2 per year (Reay et al., 2008). For unmanaged increases in inputs (i.e. via atmospheric deposition) the magnitude of this response and its benefits are likely to be limited in many areas by N-saturation, enhanced N_2O emissions, drainage losses and down-stream eutrophication and water quality problems (e.g. Galloway et al. 2008). However, where applications were properly targeted to maximise the response in plant and soil C storage and minimise the negative consequences of Nr saturation there would appear to be significant potential for this strategy.

In summary, an extension of current commercial forestry practice in terms of Nr fertilisation to a much greater area of forest based upon enhanced C sequestration and storage should be examined.

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

For the above, research on such global engineering of Nr inputs to forests should be undertaken by existing carbon and nitrogen consortia, such as CarboEurope, NitroEurope and FluxNet.

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

Key factors to be considered relating to the above would include suitability of application methods, N status of forest and soil, leakage risks, monitoring and verification infrastructure/techniques. Deployment should involve public and private sector forest managers (e.g. Forestry Commission) in tandem with expert academic advice.

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

In this context, there will be issues of pollution swapping to consider, with the negative impacts, however small, having to weighed against any net increase in C sequestration and storage.

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

Cost and uncertainty are the major barriers. Main opportunity is to upscale robust and effective practice to the global scale.

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?

Currently it is niche. Too many uncertainties, big potential negative side-effects, poor publicity and often seen as pipe dreams that distract from reducing emissions/enhancing sinks immediately.

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

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PROFESSOR ALAN ROBOCK

Geoengineering Climate: Submission to Royal Society Working Group
December 10, 2008
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Summary
This submission deals only with the idea of using stratospheric aerosols for "solar radiation management." Based on my expertise on the effects of volcanic eruptions on climate and my recent studies of geoengineering, as requested I present the key points:

- We need a well-funded research effort to examine the efficacy and dangers of different proposed geoengineering schemes, and to do engineering studies of the means of doing geoengineering.
- As of now, there are at least 18 reasons why geoengineering may be a bad idea. But there still may be pressures to attempt it to address planetary emergencies, as a stop-gap measure while we implement mitigation and carbon sequestration.
- Perceptions that geoengineering would work or will be implemented will lessen the incentive to mitigate greenhouse gas emissions.
- Small-scale field tests of stratospheric geoengineering (that is, actually injecting aerosols or aerosol precursors into the stratosphere) cannot be done; you would have to put in so much, to get a detectable response, that you would actually have to do geoengineering in the real world to test it. However, it is possible to test the means of geoengineering, such as aerosol nucleation and airplane systems.
- Contrary to claims of geoengineering proponents, volcanic eruptions serve as examples of why stratospheric aerosols do NOT just produce cooling with no side effects. In particular, they produce ozone depletion and precipitation reductions.
- Using H2S or SO2 gas to produce sulfate aerosol particles in the stratosphere, as volcanic eruptions do, is the most investigated proposal and the only one that I know of that could be implemented quickly and relatively safely, as far as the direct effects of the material. The amount of sulfur needed would not produce dangerous acid rain.
- It would be relatively cheap to inject the sulfur, as H2S gas, by modification of existing U.S. military aircraft, the F-15C Eagle and the KC-135 Stratotanker.
- If there were a way to continuously inject SO2 into the lower stratosphere, it would produce global cooling.
- Tropical SO2 injection would produce sustained cooling over most of the world, with more cooling over continents.
- Arctic SO2 injection would not just cool the Arctic, since atmospheric circulation would spread the aerosols at least down to 30°N.
- Solar radiation reduction produces larger precipitation response than temperature, as compared to greenhouse gases.
- Both tropical and Arctic SO2 injection would disrupt the Asian and African summer monsoons, reducing precipitation to the food supply for billions of people.

To answer your specific questions:
1. What do you consider to be the current state of knowledge regarding the feasibility, efficacy and predicted impacts of climate geoengineering schemes?
Based on my recent work, to be presented at the Fall 2008 American Geophysical Union Meeting next week and soon to be submitted to a journal, it would be relatively cheap to inject the sulfur by modification of existing U.S. military aircraft, the F-15C Eagle and the KC-135 Stratotanker. As shown by Rasch et al. (2008) and Robock et al. (2008), if enough sulfate aerosols could be produced in the stratosphere, the global average surface temperature could be set to whatever value one wanted – keep it constant at the current level, or bring it down to the 1950 or 1900 level, in spite of continuing anthropogenic emissions. This would stop the decline of Arctic sea ice and reduce or reverse the melting of land-based ice sheets. However, Robock et al. (2008) show, based on observations from past volcanic eruptions and from climate model simulations, that either tropical or Arctic SO2 injection would disrupt the Asian and African summer monsoons, reducing precipitation to the food supply for billions of people.

The amount of this precipitation effect needs to be evaluated by other models and with differing injection schemes. Kravitz et al. (2008) show that the additional acid deposition would be so small that it would not have negative consequences for natural ecosystems.

Geoengineering with stratospheric aerosols would also deplete ozone (Robock, 2008a; Rasch et al., 2008), make skies less blue, but give us red sunsets (Robock, 2008b, 2008c), and provide less solar radiation for solar power, especially for systems using direct solar radiation (Robock, 2008c). There would also be rapid warming if it were to stop abruptly, if society lost the will or means to continue geoengineering (Robock, 2008c; Robock et al., 2008). And there would be environmental impacts of the aerosol injection, including producing and delivering the aerosol precursors (Robock, 2008c).

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

An international, well-funded research program is needed to evaluate the efficacy of proposed schemes and their potential negative effects. This can be done as climate research is now done, through national funding organizations. But the Intergovernmental Panel on Climate Change should be involved, too. As part of the standard scenarios for the Fifth Assessment Report, geoengineering proposals, of continuous stratospheric aerosol injections for a period to counteract the worse effects of global warming, should be created and provided to all the climate modeling groups, and run along with mitigation and business-as-usual anthropogenic emissions. Such a coordinated set of climate model experiments will allow evaluation of the climate response. The few experiments that have been done so far have all been with different injection scenarios, making them harder to compare.

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

The consequences of doing geoengineering and of not doing geoengineering need to be thoroughly evaluated. This includes effects on all the standard variable we look at with global warming, including temperature, precipitation, sea level rise, disease vectors, and political instability. The United Nations, advised by the Intergovernmental Panel on Climate Change, should make any final decision. In my opinion, if there were negative consequences to any party, geoengineering would violate the UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques. Thus, this treaty would have to be changed first. Only with such an international consensus, should geoengineering proceed.

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

As discussed by Robock (2008a, 2008b), and in more detail by Robock (2008c), perceptions that geoengineering would work, or will be implemented, will lessen the incentive to mitigate greenhouse gas emissions. In addition, it may be perceived that geoengineering technology, especially if deployed by the military, could be used for military purposes, to attack an enemy. And this may be a real concern, since there are examples of such use (weather modification) in the past. I am also concerned about commercial control of the technology. As is clear now, fossil fuel companies and American automobile companies operate for their own selfish interests and not those of society. As mentioned above, geoengineering violates the UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques

Another important concern is that even if geoengineering works, whose hand will be on the thermostat? How could the world agree on the optimal climate? What if Russia wants it a couple degrees warmer and India wants it a couple degrees cooler?

Do we have the moral right to advertently modify the global climate? How do we weigh the rights of all beings on the planet, including plants and animals, who have no say in the matter?

We would always have a concern about human error, and on a planetary scale. And there may be unexpected consequences.

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

The main barrier is that it is potentially very dangerous, and should not ever be done without much more analysis. The main opportunity is that once society realizes how impractical and potentially dangerous geoengineering is, that it is not a cheap solution to our global warming problems, then this will increase the drive for mitigation, for reductions of anthropogenic emissions.

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?

I think geoengineering research is necessary to evaluate the efficacy and potential problems with different proposed schemes. Such research will teach us about the climate system and produce tools (improved climate models and observing systems) that can advance climate research in general. (This was the experience with nuclear winter research.) But geoengineering research should not be done if it drains resources from the important work on mitigation and adaptation. Funds for geoengineering research need to be added to the current climate research budgets, which themselves need to be increased.

7. Are there any other issues related to climate geoengineering that you consider to be important?
The UN Framework Convention on Climate Change thought of “dangerous anthropogenic interference” as due to inadvertent effects on climate. We now must include geoengineering in our pledge to “prevent dangerous anthropogenic interference with the climate system.”

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JIM ROLAND

Dear sirs,

This is advance three simple geoengineering suggestions.

(I) re. Q1 re. preventing GHG entry **1)** b) i).

Re. methane clathrates in permafrost. I wonder if there is any simple chemical/biochemical way of reducing methane emissions as these progressively thaw, e.g. by scattering minerals for nutrients and/or to alter pH, so as to optimise conditions for microorganic oxidation to carbon dioxide.

(II) re. Q1 re. Albedo modification **2)** a), b), also re. preventing GHG entry **1)** b) i).

I wonder if there is any whitish-coloured, frost-tolerant plant species that could in any way be encouraged to colonise large areas of Boreal permafrost containing methane clathrates, so increasing surface albedo and so reducing soil warming and the rate of thawing and methane emissions?
Or whitish strains of existing local plant species developed and sown?

(III) re. Q1 re. Albedo modification **2)** a), b), also re. preventing GHG entry **1)** b).

Use of fresh water mist-making devices in summer in polar regions

Latham (2000), Salter etc. propose wind-driven mist-making devices deployed at sea so as to generate saline clouds with high albedo.

I suggest that this kind of technology be deployed to generate 'Scotch mist'/low cloud in polar regions during summer months from freshwater:

(i) Stationed in rivers and meltwater streams in Boreal permafrost areas in order to deflect sunlight, so as to abate the release of methane from permafrost clathrates, and to a lesser degree the warming of arctic waters and offshore methane clathrates (if the wind blows the mist/cloud offshore). Hydro-turbine powering is also an option if a rig is stationed in fast-flowing water or by falls.

(ii) Stationed over moulins (water sinkholes) on large icecaps (Greenland; Antarctica?) as a water source, again to deflect sunlight, this time to slow summer melt and water supply to under the icecaps.

This is a personal contribution.

Yours faithfully,

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PROFESSOR STEPHEN SALTER

Royal Society Call for Submissions on Geoengineering Climate October 2008

Submission on wave-powered sinks for hurricane-suppression, carbon removal and enhanced phytoplankton growth.

Stephen Salter, Institute for Energy Systems, School of Engineering, University of Edinburgh. S.Salter@ed.ac.uk

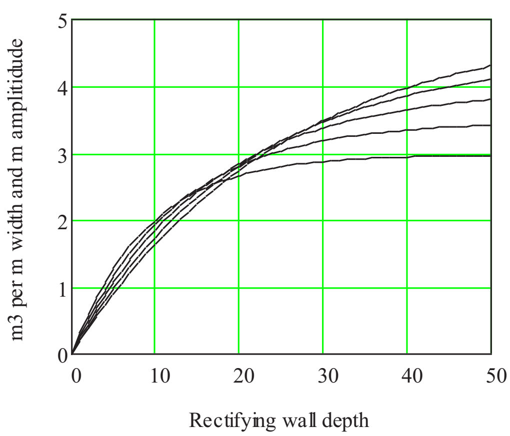
Background

This project followed an invitation to study ways to suppress hurricanes. The probability and severity of hurricanes rises sharply if the sea surface temperature exceeds 26.5C. Perhaps we can make a 'sink' using the energy of sea waves to move large volumes of warm surface water to below the thermocline where it will mix with nutrient-rich cold water and rise to some intermediate level.

Wave pumps

There have been several proposals for using waves to pump sea water for energy generation. Some involve water moving over the top of a ramp or wall into a lagoon above sea level with height optimised to maximise the product of head and flow volume. For the hurricane-suppressing project we need a head only just large enough to overcome the density difference between the upper and lower thermal layers. For a salt concentration of 35,000 ppm and temperature range from 25 C down to 10C this is only 3.024 kg/m^3 so that the head of water needed to start flow is very small compared with ocean wave heights. This means that we can use a low freeboard enclosure with a wall of non-return valves with water entering horizontally as well as over-topping. A vertical non-permeable tube below the valve wall will carry the water down to the thermocline. The lower part will be subject to a gentle steady hoop tension.

In a deep water wave the particles move in circular orbits with diameters which decay with depth, but the rate of decay is less for longer wave periods. If we integrate the displacements from the surface down to the bottom of the valve wall, multiply by the wave frequency and ignore any effect of standing waves generated by the non-permeable tube below the valve wall, we can calculate water transfer as a function of wall depth for any period. The figure below plots flow in cubic metres per second, per metre width of valve wall, per metre amplitude of the incident wave for periods of 6 to 10 seconds as a function of the wall depth.



This shows that the effect of rapid orbital decay of short waves balances the slower occurrence of long waves at wall depths of about 17 metres, giving a flow of about 2.6 cubic metres a second per metre width and metre amplitude for most of the useful wave periods.

If we take the annual wave climate scatter-diagram for Lanzarote, typical of many trade-wind sites, reduce wave amplitudes by 0.14 metres for the thermal head and 0.03 metres for loss through a non-return valve, we find that a 100 metre diameter valve wall will transfer a mean annual flow of about 150 m^3/second. If we multiply this flow rate by the specific heat of sea water and a temperature difference of 15K we get a mean annual transfer rate of thermal energy of 9.6 GW for each unit.

However we can argue that this analysis is conservative because water that enters the enclosure will form the crest of a wave that travels across its diameter until it reaches a closed valve-wall at the opposite side. It will then be reflected and the trough of the resulting anti-node will draw more water into the enclosure. The process will be repeated after another diameter of travel. To estimate the possible gain from multiple internal reflections we need to understand wave energy devices.

If there are no spilling or plunging breakers the transfer of energy by deep water waves is extremely efficient. One certain way of making a very good wave energy device is to let the water move in same way as it does when driving the next bit of sea with the correct pressures and displacements at each point through the depth. For this to happen the water should be driving a purely resistive load with a force in proportion to velocity and with no reactive components. Practical wave converters must have the inevitable mechanical inertia of the material of their displacing elements and also some added hydrodynamic inertia if the displacement of the water around them differs from that of an undisturbed wave. The skill of the wave energy designer should be aimed at minimising total inertia, cancelling the remaining inertia at the most useful frequency with a spring term and then providing the correct resistive damping for small and moderate wave heights and periods.

The wall of rectifying valves will present the perfect loading and displacement for half the time but will act as a reflector for the other half of the cycle. It will behave like an electrical transmission cable with the correct matching resistor in series with an ideal diode. This suggests that the conversion of wave energy to pumping energy ought to be 100% for half the time and zero for the other half, an average of 50% less any flow losses caused by pressure drop through valves or leakage from imperfect closure. When we calculate power from flow and pressure for the valve-wall system described above it is only 10%, leaving considerable room for improvement and a question about where the rest of the energy has gone.

A second approach is to suppose that, because for half the time we have the ideal mechanism and half the time a bad one, the incoming energy will split equally between transmitted and reflected waves. As energy depends on the square of amplitude, the amplitudes of successive reflections and transmissions should be $1/\sqrt{2}$ of the previous incoming wave. This series converges on the value 3.414. The project needs numerical modelling and tank tests but perhaps we may hope for a flow increase of 2 to 2.5, giving flow rates of 300 to 375 m^3/sec from a 100m unit in a gentle wave climate and a thermal transfer of more than 20 GW per 100m diameter valve-wall.

Moving warm water down provides a large but only temporary thermal store of heat. This may be useful for saving New York from the next Katrina but there is a second benefit. Water at the surface will be in carbon dioxide equilibrium with the present-day atmosphere but mixing with water below the thermocline is normally very slow. The deep water has pre-industrial CO_2 level. The solubility of CO_2 rises with falling temperature and higher pressure so the second effect of the system will be the transfer of some CO_2 from the atmosphere to deeper parts of the ocean.

We can influence the amount of mixing by choosing the shape of the bottom tube. A nicely shaped return curve and an outer sleeve will allow warm water to stay close to the down-tube and perhaps rise back to the surface. However vertical slits will give thin planar jets with a large area to mix with the outside water. By filling or emptying water tubes in the slit edges we can change the exit slit geometry and so adjust the mixing ratio. Numerical models support a conjecture, due to Myhrvold (2008), that warm surface water mixed with cold but nutrient-rich thermocline water will rise to the level at which it finds water of its own density and then spread sideways as a ‘density stratum’. Caldeira (2008) points out that if the mix is controlled so that the equilibrium point is 100 metres below the surface there will be enough light for the growth of phytoplankton. The biological food chain is a powerful way to move carbon dioxide from the atmosphere to the sea bed without increasing acidity, Behrenfeld et al (2006).

Marine productivity is measured in grams of carbon per square metre per year with many mid ocean regions having low rates of 50 gC/m^2yr. However in regions with natural upwelling caused by winds moving surface water during a la Niña event the productivity can reach 1000 $g\ C/m^2yr$. Half the world’s fish are caught in only 1% of the sea area and much of the rest is a desert. A wave-driven sink would make a private local la Niña in any hitherto unproductive region, even in warm seas. A steady input of all the natural nutrients all the year round at the right level might be better than intermittent short surges such as those that occur when fertilizers brought down the Mississippi to the Gulf of Mexico produce excessive growth leading to an oxygen shortage. Provisional estimates for carbon removal are between 10^4 and 10^5 tonnes per year from each sink, with a corresponding increase in world fish protein, Caldeira and Wood (2008).

Many wave inventors leave moorings and mooring installations to the end of the design process and find that the problem is expensive and the installation slow. The sinks will be subject to the drag forces of any local current and also to momentum forces proportional to the squares of incident and reflected waves. Furthermore the structure has no strong points to which mooring cables can be connected and we may need to operate in very deep water.

Many ocean currents take the form of very large vortices known as gyres. One solution to the mooring problem is not to moor at all. We let the units drift freely but we bias the exit flow to one side so that there is a force tending to move them towards the centre of whichever gyre is to be cooled or enriched. By adjusting the proportion of side flows we can keep them moving round the gyre at any chosen radius from its centre. This looks quite easy in the many gyres of the Caribbean and the two alternating currents along the hurricane-breeding track from West Africa. The Coriolis effect means that there will be a change in the direction of a current with changing depth so the trail of nutrients will diverge from the path of the sink and give good dispersion of nutrients.

The figure shows a sketch of the design. The top of the structure is a buoyant ring formed by lashing used tyres in a hexagonal array with buoyancy provide by foamed concrete. Tensile members in the form of spokes made from polypropylene rope can give it strength in the horizontal plane. This gives a structure which can conform to the deflections of long waves and which has low or, because of the tyres, even a negative material cost. Hanging at a depth of 17 metres below this is a second ring of tyres containing normal density concrete for negative buoyancy. The rings are joined by vertical strands of a high tensile glass/Kevlar composite around which are Vee-shaped chlorinated rubber extrusions which can move together to form a low drag foil section or open to make contact with the adjacent extrusion to form a closed valve. Outside the vertical strands are horizontal hoop strands of the full wall diameter which lie in notches in the noses of the foils and pull the vertical strands inwards to give a double curvature. These horizontal hoops will resist the pressure inside the walls. The downward water velocity is very low and so the down tube can be tapered. It can also be tilted to direct the flow to one side. If it carries a series of inflatable tubes it can be raised to adjust its length or for movement in shallow water. It will not be easy to handle a 100 metre diameter 200 metre long tube of thin plastic in air but it will be possible to edge-weld material being unwound from six rolls with axes slightly tilted from the vertical mounted on six rafts joined in a ring. The tube can be lowered into the water as welding progresses.

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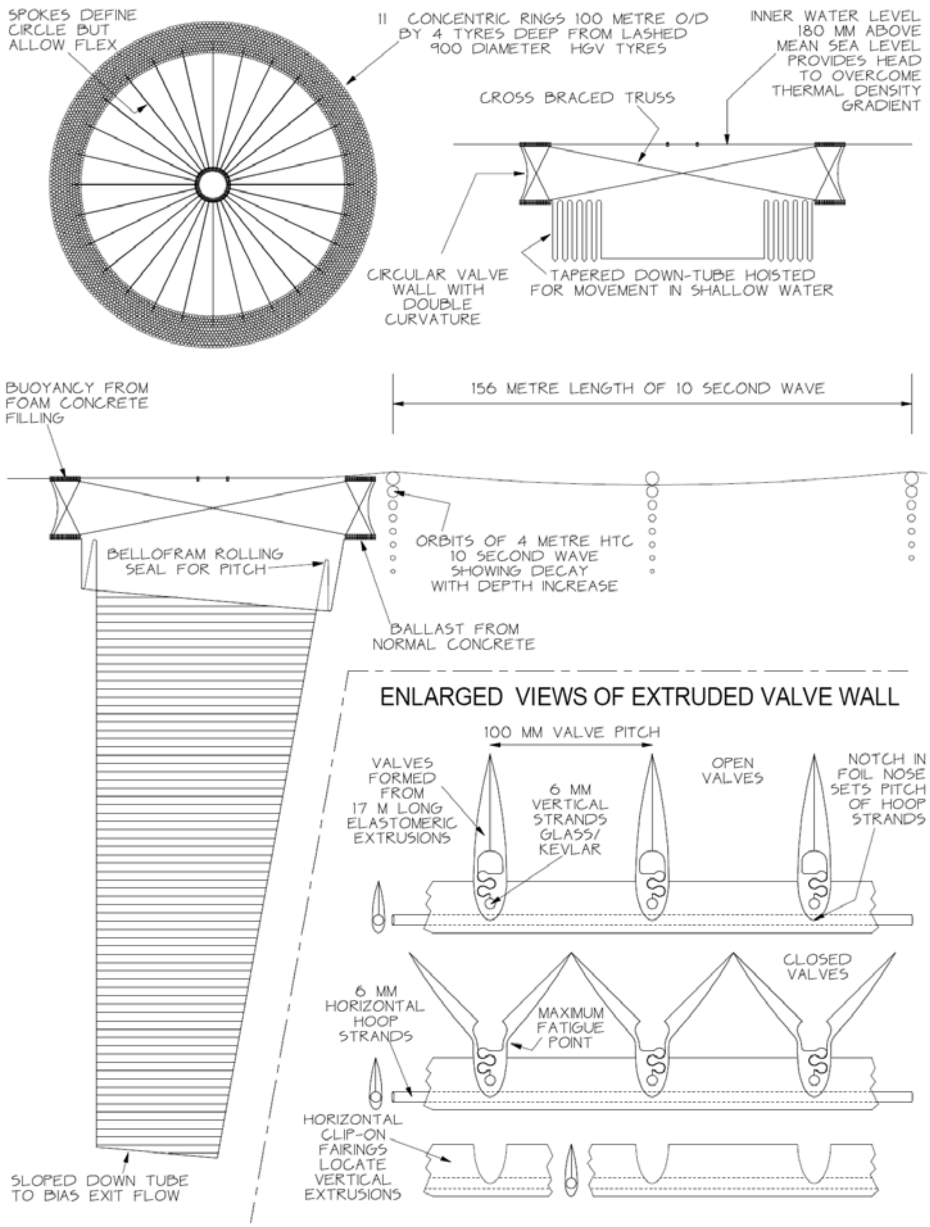

SPOKES DEFINE CIRCLE BUT ALLOW FLEX
11 CONCENTRIC RINGS 100 METRE O/D BY 4 TYRES DEEP FROM LASHED 900 DIAMETER HGV TYRES
INNER WATER LEVEL 180 MM ABOVE MEAN SEA LEVEL PROVIDES HEAD TO OVERCOME THERMAL DENSITY GRADIENT
CROSS BRACED TRUSS
CIRCULAR VALVE WALL WITH DOUBLE CURVATURE
TAPERED DOWN-TUBE HOISTED FOR MOVEMENT IN SHALLOW WATER
BUOYANCY FROM FOAM CONCRETE FILLING
156 METRE LENGTH OF 10 SECOND WAVE
BELLOFRAM ROLLING SEAL FOR PITCH
ORBITS OF 4 METRE HTC 10 SECOND WAVE SHOWING DECAY WITH DEPTH INCREASE
BALLAST FROM NORMAL CONCRETE
ENLARGED VIEWS OF EXTRUDED VALVE WALL
100 MM VALVE PITCH
VALVES FORMED FROM 17 M LONG ELASTOMERIC EXTRUSIONS
6 MM VERTICAL STRANDS GLASS/ KEVLAR
OPEN VALVES
NOTCH IN FOIL NOSE SETS PITCH OF HOOP STRANDS
CLOSED VALVES
6 MM HORIZONTAL HOOP STRANDS
MAXIMUM FATIGUE POINT
HORIZONTAL CLIP-ON FAIRINGS LOCATE VERTICAL EXTRUSIONS
SLOPED DOWN TUBE TO BIAS EXIT FLOW

Royal Society Call for Submissions on Geoengineering December 2008

Submission on hardware to implement Latham's proposal for the modification of the reflectivity of marine stratocumulus clouds to reverse global warming.

Stephen Salter, Institute for Energy Systems, School of Engineering , University of Edinburgh.
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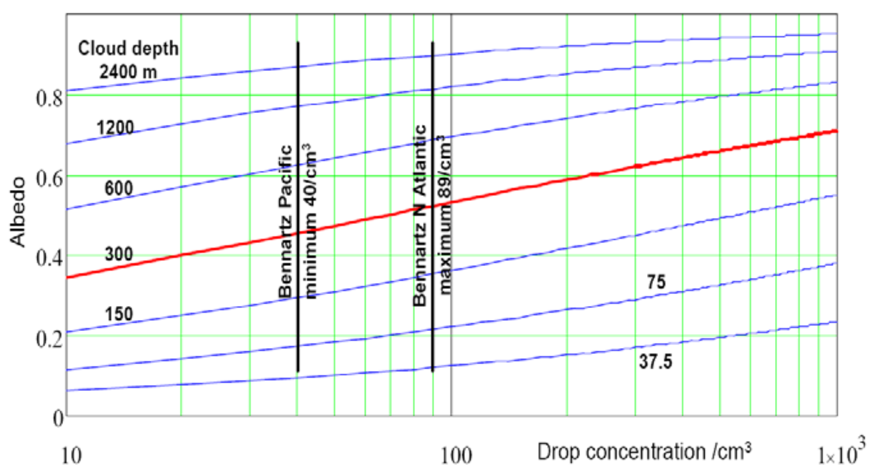
Cloud albedo physics

John Latham (1990, 2008) has proposed that the Twomey effect (1977) could be used to increase the amount of solar energy reflected back to space. His idea is to spray submicron drops of sea water in regions of the mid-oceans where marine stratocumulus clouds are likely to be found. Salt residues from evaporated spray are ideal cloud condensation nuclei so the liquid water in a cloud will be shared between a large number of smaller drops, thus giving a higher reflective area.

The 24-hour solar input to the equator is about 440 watts per square metre and falls to about 240 at the latitude of Patagonia. For engineering purposes we can use a figure of 340. The Royal Society Call for submissions mentions changing this by only one watt per square metre or 1 part in 340. About one fifth of the world's surface is covered by clouds suitable for Latham's suggestion so, if all of them were used, the reflectivity would have to increase by only 5 parts in 340 or 0.0147. From Schwarz and Slingo (1996) the change in reflectivity as a function of cloud drop concentration is shown in the figure below for various cloud depths and a liquid water content of 0.3 gm/m3. The vertical black lines show the present range of drop concentrations suggested by Bennartz (2007).



The number of new condensation nuclei required for a given amount of cooling depends on the initial drop concentration, the depth of the marine boundary layer, the cloud depth, the liquid water content, the fraction of drops which get to cloud altitude, the fraction of cloud coverage and the drop lifetime. For reasonable assumptions for these parameters Twomey predicts that one watt per square meter of cooling would be achieved with global spray rates between 4 and 8 cubic metres a second of 0.8 diameter micron drops. The effect has diminishing returns for higher spray rates but a cooling of 3.7 watts per square metre (an amount predicted for double pre-industrial CO_2) could be achieved with spray rates between 30 and 70 cubic metres per second. This is because of the enormous ratio between the surface tension energy needed to create a 0.8 micron diameter drop and the solar energy which will be reflected from the 20 micron drop that grows on it.

I have been designing wind-driven spray vessels that could release 30 litres a second. Ideas and drawings were given in the November 2008 edition of a special geoscale engineering issue of Phil. Trans. Roy. Soc., Salter (2008). The vessel displacement will be 300 tonnes, the water line length 45 metres and the power of the plant about 150 kW. They will sail across the direction of the prevailing wind, dragging turbines through the water to generate energy for spray. Design work has been taken far enough for general arrangement drawings to be shown to industrial groups. There must be tests of components and sub-assemblies to ensure reliable operation at sea. However we are getting close to a feasible spray vessel. At present I am working on a spray generation system in a package that could be used on a conventional ship as well as on the purpose-designed spray-vessel. Its spray rate would be 10 litres per second.

The project needs a great deal of work on the prediction of global side effects. This is being done by several groups. A distilled consensus is that the local effects are as expected but can be accompanied by opposite results in other parts of the world. These effects will be less if large areas are given a small dose rather than small areas given intense treatment. However the technique does allow the option of local treatment for the rescue of Arctic ice or coral reefs. Judicious operations on either side of the Pacific could moderate the amplitude of el Niño and la Niña events. A cool high-carbon world is less unpleasant than a warm high-carbon one.

The better the climate modeller the more caveats will be attached to results. There is a need for field experiments that will allow modellers to improve the accuracy of various coefficients. This could be done with a large number of MODIS satellite images of the clouds downwind of a single research vessel carrying three spray modules on a zig-zag cruise across the Pacific and along the Norwegian coast in water flowing to the Arctic.

Replies to your questions

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

I cannot comment on other schemes except to say that a combination of several might be desirable. The basic physics of the cloud albedo proposal is well enough known to allow reasonable estimates (say to a factor of two) of the required areas, weights, energy and even approximate costs of equipment. However we still need to learn, from large eddy studies of the region downwind of spray release, what fraction of nuclei will reach the clouds, how long they will take to reach them and how long they will last. We also need global climate models to predict local and global effects on temperatures, changes in the speed and direction of winds and currents, the formation of ice and, in particular, any effects on precipitation. Phil Rasch is making rapid progress on a global model with fully-coupled air-ocean effects. I hope that he will be submitting evidence to your enquiry when his model time has reached 50 years. Much of the hardware needed for the project looks quite feasible and not even very expensive. The main area of uncertainty concerns the spray generation system and especially the filtration.

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

We need to understand every detail of all the proposed geoengineering solutions. We need to design equipment for each of the feasible proposals and build enough for limited field measurements. We may need new methods to detect very small changes to variables with large natural variability. Most of the progress so far has been made by academics. Despite the very large amount of money that can be made from damaging the environment there is at present no commercial return on preventing climate change and so progress depends on unpaid workers and charitable donations.

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

Everyone working in geoengineering does so with reluctance and several people started from the point of hostility. None of us would want deployment without a great deal of careful work on side effects. Any decision about deployment must be made without commercial pressures. But several people believe that we may have very little time left before irreversible positive feedbacks come into play. It would be better to have the technology ready before it is needed than to be too late. Deciding to deploy a system will be a daunting responsibility and humanity much prefers to be blamed for sins of omission than for positive action that goes wrong. But delaying research for the wrong reasons will be seen by future generations as treason to the planet.

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

The most important but also most difficult political decision will be the choice of what the best pattern of temperature and precipitation should be. Something that opened a seaway through ice and increased the area of farmland in Siberia might also dry out a tropical rain forest and spread malaria. Until we have very wise world leadership perhaps the best solution for the albedo method might be to agree on a year that had a generally good pattern of climate and try to achieve the same pattern of sea surface temperatures and ice cover.

What do you see as the main barriers to climate geoengineering?

The present barriers are:

- Political concerns about the use of geoengineering as an excuse to accelerate the use of fossil fuels.
- The uncertainties surrounding the predictions of computer climate models.
- The assumption that carbon dioxide increase is, and always will be, the only cause of climate change.
- The hope that enough countries, even those with many millions of dreadfully poor people who might be lifted out of poverty by burning fossil fuels, can be persuaded to reduce carbon emissions by amounts up to 80% and that doing it by 2050 will be soon enough.
- An official disregard of the possibility of positive feedbacks leading to irreversible change.
- The almost complete absence of funding.

In fact water vapour contributes a larger effect than CO_2. Methane now accounts for about one third of the greenhouse effect but releases from permafrost could soon quite easily equal or exceed the effects of carbon dioxide. While it is often said that methane is 23 times worse as a greenhouse gas than carbon dioxide, this is true only if effects are integrated over a 100 year period. Methane half-life in the troposphere is less than ten years so the short term effects are about 70 times higher.

The assumption that humanity can actually make any reduction in CO2 emissions is not supported by the slope of the Keeling curve.

The official complacency about the time we may have available ignores the recent rapid decrease of Arctic ice. Nobody has a satisfactory explanation of the many cases where ice records showed an abrupt temperature increase when there were no anthropogenic emissions.

What do you see as the main opportunities given by climate geoengineering?

The near-term opportunity is the prevention a great deal of misery and environmental damage. Climate engineering may buy the time to develop cleaner sources of energy. In the longer term it would be valuable to have a group of technologies ready for use if there were to be a sudden rise in temperatures caused by some event other than anthropogenic CO_2 such as is shown repeatedly in ice core samples before humans were making their own contribution. I believe that anthropogenic CO_2 is probably the cause of much of the present problem and also that there are many good reasons other than climate change to reduce consumption of fossil fuels. But I also believe that a correlation, however strong, is not sufficient evidence of causation or of the direction of causation.

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

Meteorology is an observational science and many meteorologists have been taught that any intrusion by meddling engineers must be wicked. The subject requires them to piece together the working of a complex mechanism without being able to build sub-assemblies or doing the sort of controlled experiments which have been needed since the early days of physics, chemistry, biology and engineering. However aerosol concentrations are known to have very strong influence on the atmosphere: the introduction of a small perturbation with a known modulation pattern coupled with measurements of the magnitude and phase of the response of other parameters could lead to better understanding of the atmosphere. Disruptions often throw up new ideas and I believe that the work on global climate models will benefit from a geoengineering input especially with regard to climate oscillations and stability.

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

There may be very good reasons why geoengineering technology should not be used especially if there are uncertainties about side effects. But there is no reason to impede research on the atmospheric physics and the development of hardware to the point where it could be deployed rapidly. Geoengineering is the equivalent of providing brakes and steering to a vehicle which at present has only an accelerator. The driver must be given time to learn how to use the new controls but we may not have much time left.

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