Geoengineering the climate: Science, governance and uncertainty

Responses to call for evidence

Part I

PROFESSOR KEVIN ANDERSON
Tyndall Centre for Climate Change Research

Progressing a research programme on geo-engineering – a personal view

An insurance policy?

Existing Tyndall Centre research demonstrates that maintaining temperatures at or below the UK's and EU's 2°C threshold between acceptable and dangerous climate change is increasingly unlikely. Moreover, emission mitigation currently being discussed, even if fully implemented on a global scale, would probably not keep atmospheric concentrations of greenhouse gases at levels much below 650ppmvCO2e (i.e. ~ a 50% chance of 4°C)[a]. If this position is broadly accepted, it is difficult to construct a cogent argument for not researching the viability or otherwise of geo-engineering options as a potential bridging technology to a low-carbon future (or perhaps even a long-term foil for ongoing carbon emissions). However, given the process of conducting such research will be inevitably controversial, I suggest a position on contentious issues is developed prior to instituting a research programme. Below are some provisional thoughts on several issues for which early consideration may help mitigate later criticism.

Funding integrity

There is a real and perceived risk that the prospect of 'engineering' our collective way out of 'dangerous' climate change may act as a diversionary impetus, both financially and intellectually. This is a serious issue, and any attempt to earmark existing or even future mitigation and adaptation funds for researching geo-engineering options should be scrupulously avoided (there are parallels here with concerns raised about nuclear fission and fusion research and deployment diverting resources away from renewables and energy efficiency). Consequently, funding for geo-engineering must be from new monies made specifically available for such research.

Moral imperative?

Important moral arguments exist as to why *carbon sequestration* (carbon negative as opposed to carbon neutral) from the atmosphere should be researched in preference to *insolation* approaches whereby temperature/heat is controlled. Carbon dioxide is a well mixed gas and hence its removal from the atmosphere has global rather than specifically regional benefits. By contrast, insolation approaches have the potential to 'safeguard' specific regions rather than provide a common global good. Assuming that any successful roll out of geo-engineering options is likely to be on a decadal timeframe, it is probable significant climate change impacts will already be apparent. In such a situation, there is a significant risk that insolation-based options would be used to 'protect' those wealthier nations that had both funded the research and been responsible for significant historical emissions in preference to those more vulnerable and politically marginalised regions. Consequently, issues of equity and the 'common good' (in conjunction with acidification – see below) strongly favour sequestration research over insolation.

Ecosystem impact

Another issue that should inform funding priorities for geo-engineering, is the risk of significant adverse ecosystem impacts arising from the respective options. One upshot of this argument is that ocean sequestration approaches should receive a low priority for funding. Whilst carbon uptake from some ocean approaches *may* be amenable to short-term quantification, our longer-term understanding of ocean circulation and ecosystem dynamics is much less well developed. Insolation approaches also fair poorly under this ecosystem caveat. In theory at least, insolation options facilitate increased CO_2 concentrations without temperature repercussions; however, rising CO_2 levels are already giving rise to serious ocean acidification concerns that would only be exacerbated if insolation approaches were widely deployed.

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[a] Anderson, K. and Bows, A., Reframing the climate change challenge in light of post-2000 emission trends, Philosophical Transactions A, 366, 3863-3882. (http://journals.royalsociety.org/content/a7877169j7163rh2/)

In brief

The high and unchecked level of global emissions is rapidly consuming the greenhouse gas budget associated with temperature rises of up to 4°C. In light of this and global society's failure to tackle even emissions growth, geo-engineering is increasingly becoming an area worthy of serious investigation. However, any subsequent research programme should consider the following caveats:

- *No diversion or weakening of either current or future mitigation and adaptation funding*
- *Prioritise approaches applicable at a global rather than specifically regional level*
- *Focus funding on approaches with lower over higher eco-system impacts*

Tyndall and Geo-engineering

The Tyndall Centre has an established interest in issues of geo-engineering evidenced by close involvement in two important geo-engineering events over the past four years. Firstly, in 2004, Tyndall Centre & Cambridge-MIT Institute hosted jointly a Symposium on Macro Engineering Options for Climate Change Management and Mitigation (http://www.tyndall.ac.uk/events/past_events/cmi.shtml). And, more recently, two senior Tyndall Academics edited a geo-engineering special issue of the Royal Society's Philosophical Transactions A, to which Tyndall authors were amongst the contributors.

Certainly if there were to be a programme of research investigating geo-engineering, the Tyndall Centre would be equipped and pleased to make a significant contribution. Tyndall's expertise could facilitate both discrete and disciplinary evaluations of the science, technology, impacts, economics and siting issues, alongside a more integrated investigation of geo-engineering within a broader climate change context and in relation to emission-reduction pathways.

If in discussing or developing a research programme on geo-engineering Tyndall Centre expertise would be of value, please feel free to contact either me directly or Asher Minns (the Tyndall Centre Manager) who will be able to put you in touch with the relevant academics from within the Centre. Asher's contact details are: email. a.minns@uea.ac.uk; Tel. +44 (0) 1865 275867; Mob. 07880 547843.

ROBERT ANDERSON

Subject: Geoengineering climate: call for submissions

From: Robert Anderson, Lamont-Doherty Earth Observatory of Columbia University
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I am writing in response to the call from the Royal Society for comments related to their study on "Geoengineering climate: call for submissions". Here, I would like to make two points about the potential addition of iron to the ocean to stimulate biological productivity and thereby draw carbon dioxide from the atmosphere and sequester it in the deep ocean. Specifically: (1) In certain parts of the ocean where it would be easiest logistically to add iron and stimulate productivity, such as the equatorial Pacific Ocean, the impact on atmospheric CO2 would be negligible because the macronutrients are completely consumed today, even before iron addition; and (2) It would be impossible to assign carbon credits accurately to iron fertilization schemes, even in regions of the ocean where addition of iron might sequester CO2, due to large uncertainties in the ratio of carbon sequestered to iron added. Each point is addressed in greater detail below.

I. Downstream effects

The earliest experiments in which iron was added purposefully to a mesoscale patch of the ocean (tens to hundreds of square kilometers) were conducted in the eastern equatorial Pacific Ocean, a region where concentrations of macronutrients (e.g., nitrate and phosphate) are persistently high. Scientists observed that addition of iron stimulated the growth of phytoplankton, causing the phytoplankton to consume nutrients and carbon more rapidly than in waters outside of the iron-fertilized region.

One might infer from this that addition of iron to equatorial Pacific waters could induce a net biological sequestration of CO2 from the atmosphere. However, in assessing the impact on atmospheric CO2 of adding iron, one must consider "downstream effects". In the equatorial Pacific, nutrient-rich water upwells near the equator and it is transported laterally at the surface. These nutrients may be transported laterally for hundreds, and even thousands, of kilometers before they are consumed biologically. However, eventually all of the upwelled macronutrients are consumed. Adding iron to sites near upwelling centers will cause phytoplankton to consume nutrients there more rapidly than in the absence of iron addition, but doing so reduces the amount of nutrients transported to regions further away from the upwelling centers; i.e., "downstream". In the case where iron is added to ocean regions near these upweling centers, the total amount of nutrients consumed biologically, and the total amount of organic carbon exported to the deep sea as organic detritus, remains unchanged. Only the location of nutrient utilization and the location of carbon export to the deep sea will have changed. Thus, there is little or no net CO2 sequestration when iron is added to such regions.

Similar conditions exist in coastal upwelling systems. High concentrations of nutrients may persist in surface waters for tens to hundreds of kilometers downstream of upwelling centers. However, these nutrients are eventually all consumed biologically. Thus, adding iron to sites near upwelling centers will have little or no net impact on the drawdown of CO2 from the atmosphere.

The only regions of the ocean in which iron addition can impose a net drawdown of atmospheric CO2 are those regions where macronutrients in surface waters fail to be consumed biologically before the surface waters lose buoyancy and become entrained in newly-formed deep waters. Nutrients that survive at the surface between the time that they are upwelled from depth and subsequently subducted back into the deep ocean are referred to as "preformed nutrients".

Although it has been pointed out in a number of studies that the master variable regulating the biological drawdown of atmospheric CO2, assuming a constant inventory of macronutrients in the ocean, is the efficiency of nutrient utilization, which may be expressed as the ratio of preformed nutrients

to total nutrients in the ocean (e.g., Sigman and Boyle, 2000; Marinov et al., 2006), many people (including oceanographers who should know better) have failed to take this point into account when contemplating iron fertilization as a biogeoengineering strategy. The only places in the ocean where iron fertilization can effectively increase biological sequestration of CO2 are those regions where deep waters form with high levels of preformed macronutrients. By and large, these regions fall within the Southern Ocean, that is, in the ocean around Antarctica (e.g., Marinov et al., 2006 as well as more recent papers by those authors).

II. Assessing carbon credits

Presumably, anyone adding iron to the ocean would want to receive credit for carbon sequestered. Assessing the amount of carbon sequestered per unit iron added is extremely difficult, if not impossible, for several reasons.

First, to be effective as a mitigation strategy, the carbon consumed biologically as a consequence of iron addition must be isolated from the atmosphere for a minimum period, say 100 years. The upper ocean is ventilated, i.e., physically overturns and exchanges its gases with the atmosphere, on time scales of decades. Therefore in order to be effective as a sequestration strategy, the organic remains of plankton must sink to a depth below the level to which water masses overturn on decadal time scales. This reference depth horizon varies from one region of the ocean to another, but it is roughly 1000 m.

The fraction of the particulate organic matter exported from surface waters that sinks to depths greater than 1000 m is small (typically less than 10 %). Furthermore, it varies from one location to another and is very difficult to quantify. Put another way, the vast majority of organic matter that sinks out of surface waters is consumed and respired rapidly by bacteria and zooplankton that inhabit mesopelagic depths (e.g., between 100 m and 1000 m). The rate at which organic carbon is consumed at mesopelagic depths depends on a number of environmental factors, all of which affect mesopelagic ecosystems. Despite their known importance in the ocean carbon cycles, mesopelagic ecosystems remain poorly studied, to the point that it is not possible to estimate from first principles the fraction of organic matter that will be respired as it sinks through the mesopelagic zone to the deep sea, where carbon may be isolated for time periods inexcess of 100 years.

Estimates of the ratio of the amount organic carbon exported to depth per ton of iron added range over a factor of 100 for past ocean experiments (Boyd et al., 2007). This large uncertainty reflects partly the variability in the ratio of nutrients consumed per unit iron added to seawater and partly variability in the fraction of organic tissue produced as the result of iron addition that is exported to depth. Should iron fertilization be employed as a CO2 sequestration strategy, and should those responsible seek credit for the carbon sequestered, then one can easily imagine long battles in the courts where lawyers argue over the size of the credits to be assigned. Ocean iron fertilization does not seem to be a feasible strategy for commercial CO2 sequestration because of the large uncertainty in the ratio of carbon sequestered to iron added.

Second, there are those presently who are calling for additional ocean experiments to better constrain the ratio of carbon sequestered to iron added. Although such experiments would likely reveal important new insights into the biogeochemical cycling of iron and carbon, as well as insights into the interactions between ecosystem structure and biogeochemical cycles, they are unlikely to constrain the ratio of carbon sequestered to iron added well enough to permit carbon credits to be assigned with any reasonable accuracy. This is because horizontal shear in the water column decouples the iron fertilized surface waters from the depth horizon below which the organic carbon must sink in order to be considered effectively sequestered.

To illustrate this point consider an iron fertilization scenario for the Southern Ocean where surface waters are moving eastward at a velocity of approximately 50 cm/sec while water below 1000 m (or whatever reference depth is selected for sequestration) is moving eastward at approximately 10 cm/sec. Iron is added and carbon is consumed in surface waters and then several days to as much as a few weeks are

required before the exported organic material sinks to a depth of 1000 m. In order to quantify the efficacy of iron fertilization, one must accurately measure the net increase in the sinking flux of organic matter at 1000 m that can be attributed to the addition of iron to surface waters. Furthermore, because the consumption of nutrients, the export of organic matter from surface waters, and the sinking of organic matter to the reference depth (1000 m) each involves a spectrum of rates and times scales, one would be obliged to integrate the increased flux of sinking organic carbon through the reference depth horizon along the entire path that the patch of iron-fertilized surface water followed from the point of initial iron injection to the point where the iron had all been consumed by phytoplankton. In energetic regions like the Southern Ocean this could easily amount to distances of thousands of kilometers. Given the huge distances over which the increased sinking flux of organic matter must be quantified, combined with additional uncertainty associated with lateral dispersion of sinking particles due to eddy mixing, it would be logistically impossible to quantify the integrated increase in flux of sinking organic matter through a reference depth of 1000 m that could be attributed to iron addition to surface waters.

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DR PHILIP BOYD

NIWA Centre for Chemical and Physical Oceanography, University of Otago

Submission to the Royal Society on Geo-engineering

This submission supplements an earlier submission of a paper – Boyd (2008) Nature Geoscience, 1, 722-725 that is pertinent to this Royal Society initiative.

General comments

All examples of major climatic events in both the present day (Pinatubo) or in the geological past (changes in atmospheric CO_2 during the LGM) that have been well documented i.e. research and scrutiny – have shown that any major climatic changes are driven by multiple mechanisms, and hence illustrate that Earth system responses to both short-term/regional and long term/global are complex, and often counter-intuitive, suggesting that even disparate aspects of the Earth system are inextricably linked. This provides us a strong precautionary principle regarding geo-engineering, and indicates that we must only consider further geo-engineering schemes that a relatively simple system complexity (Boyd, Nature Geosciences, 2008a).

Specific comments on geoengineering schemes using biological systems

Ecosystems are well known to be complex systems with many examples in the literature of the unexpected changes in ecosystem structure and functioning that occur due to invasive species (seaweeds, ballast water travellers), introduced species (cane toads, possums), perturbation due to resource uses (fishing pressure), regime shifts (climate variability and other unknown effects). Ecosystem effects on terrestrial systems are complex, but those in marine systems (due to the effects of ocean circulation etc) are even greater. The increased cumulative complexity resulting from the interactions between ecosystems and purposeful climate impacts (i.e. geo-engineering) is such that the Royal Society should be urged to term such schemes as "Bio-geoengineering" in the forthcoming to recognise this added level of system complexity.

Specific comments on methods utlising oceanic biological systems

There have been 3 main methods discussed so far - ocean iron fertilisation (OIF) of the offshore High Nutrient Low Chlorophyll (HNLC) waters, nitrogen fertilisation of the coastal ocean, and purposeful upwelling of nutrients in the low latitude oligotrophic ocean. OIF has received a disproportionate amount of media coverage, discussion of the wider issues (moral, ethical, technological, scientific, see MEPS thematic section on OIF, Boyd, 2008b) and research. However, it should be recognised that all of this scientific research has been conducted by researchers who were not considering the efficacy of OIF for geoengineering, but rather for research into several scientific topics. These include the role of OIF on the oceanic C cycle, and knock-on effects that might have explained part of the 80 ppmv decrease in atmospheric CO_2 during the glacial maxima, when it was established that there was sustained OIF of the Southern Ocean for millennia (Martin, Paleoceanography, 1990; Wolff et al., Nature 2007). This is the historical precedent that underpins the discussion on the merits of OIF as a biogeoengineering scheme (Boyd, 2008a).

Hence the research into OIF over the last decades offers valuable lessons and insights into the following aspects of geo-engineering:

a) how a historical precedent can lead to 2 decades of funded research

b) A mismatch of timescales and questions

c) how scientific research can lead to commercial interest in biogeoengineering

d) how the interactions between researchers and commerce can fracture scientific communities

e) How the debate (and means of debate) between researchers and commerce (often in the media) on the merits of OIF has taken place.

f) The development of the wider discussion on OIF as a biogeoengineering method – ethics, morals, verification etc.

g) Science policy and its evolution to deal with these developments in OIF

How a historical precedent can lead to 2 decades of funded research

The iron hypothesis of Martin (1990), and its implications for ocean carbon cycling and global climate, resulted in the development of a new research area in ocean science without precedent in the last 3 decades. This huge suite of research papers is probably without precedent for other geo-engineering and bio-geoengineering schemes.

Several thousand 1000 papers have been published on this topic in the last 2 decades into the links between iron, ocean biota, biogeochemical cycling and climate.

A mismatch of timescales and questions

At present the consensus is that increased iron supply in the geological past can explain for at most 30 ppmv of the 80 ppmv (Sigman & Boyle, Nature, 2000). Of course what has been over looked is that this 80 ppmv change took place over millenia, and while a contribution of up to 30 ppmv to the change in atmospheric CO_2 concentrations means that iron supply is a major driver of global climate, it does so over millennia and not on the decadal timescales that are being reported as required for present day climate mitigation/geoengineering schemes (Boyd, 2008a). Hence the application of historical precedents to support such bio-geoengineering schemes must be done carefully, as in the case of OIF, the scientific questions that were pertinent to research into paleo-climate are markedly different from those needed to address present day mitigation of climate change. There is also clearly a mismatch of the timescales for climate mitigation - OIF is viewed as too slow to have any influence on reducing atmospheric CO_2 via alteration of the ocean carbon cycle in the present day (decades) but did have an influence in the geological past (millennia) (Boyd, 2008b)

How scientific research can lead to commercial interest in biogeoengineering

The high scientific profile achieved by the early studies into iron in both bottle incubations and later in mesoscale iron enrichments (Martin et al., Nature, 1989, 1994) resulted in an unprecedented media coverage in both the popular (front page of the Washington Post etc) and scientific media. A number of speculative articles were written about OIF being a panacea for the effects of climate change, and shortly thereafter a number of commercial companies became interested in pursuing this matter – with submissions for patents etc (Michael Markels) and with the spectacle of OIF trials being conducted (but without any scientific rigour (the Oresman – a feature in Nature about Planktos on board the musician Neil Young's yacht seeding the wake with iron). These trials suggested that OIF was very cheap (2$ a ton of C sequestered, Markels) which was a major attraction to investors, and very potent. Both of these aspects of OIF (panacea/low cost) have since been refuted in the literature (Boyd, 2008b).

How the interactions between researchers and commerce can fracture scientific communities

During the early development of commercial interest in OIF there were efforts to recruit prominent scientists to both offer technical advice and to bolster the credibility of these fledgling companies. Some scientists were recruited as consultants resulting in them being partially ostracised by the scientific community. It is no exaggeration to say that there has been culture clash between these companies and scientists (as witnessed at the ASLO sponsored workshop to bring together policy, commerce and science

in Washington DC (see ASLO website for the 2 page summary that was issues at the end of the workshop in spring 2002). As recently as the WHOI 2007 iron symposium there was still evidence of many fractures across the scientific community with regard to their views on commercial OIF. These fiefdoms range from groups who have consistently and strongly challenged the scientific basis of commercial OIF for the last 20 years, to a middle ground who see working with such companies as the only means to do further research into iron and the oceanic carbon cycle, to those who actively engage and advise such companies and who believe in the efficacy of commercial OIF. Such fractures mean that journalists writing articles on the pros and cons of commercial OIF can get a spectrum of opinions, and can be selective (as required) depending on the slant of their article.

How the debate (and means of debate) between researchers and commerce (often in the media) on the merits of OIF has taken place.

In the absence of any scientific research that has targeted commercial OIF, the companies have used the popular press to push their case for commercial OIF, and have used data from the scientific literature to make their case. Scientists in return have also used the scientific literature to clarify, or refute, or support those articles from companies.

However, this has resulted in an asymmetry in many of these articles – in that commercial companies have tended to be somewhat selective of what they cite from the large body of scientific research, whereas scientists have tended to be more measured in reporting the nuances, contradictions and paradoxes evident from the broad body of literature. Hence the companies have come across as direct and confident, and the scientists less so.

This key issue of presentation and packaging of the pros and cons of commercial OIF has forced scientists 'out of their comfort zone' and made them rethink how they address such asymmetry in the media coverage. A recent approach has been to point out just how inexperienced companies can tackle these logistically difficult OIF trials when experienced scientists cannot do so satisfactorily (see New Scientist article on ocean fertilisation in 2006/7 for some examples of this change in tack).

The development of the wider discussion on OIF as a biogeoengineering method – ethics, morals, verification etc.

Again the field of OIF has explored these avenues most thoroughly and provides insights that might be applicable to the wider debate on other geo-engineering methods (see Hugh Powells 2007 Oceanus special issue, and also the MEPS 2008 Thematic section on this (Boyd 2008b).

Science policy and its evolution to deal with these developments in OIF

sfter many years of a policy vacuum, there have now been relatively rapid progress in the last few years to develop policy (London Convention, UN CBD). As expected such rapidity has resulted in somewhat rushed decisions such as the recent *de facto* moratorium on any OIF activity – whether scientific or commercial. Some advice on this matter has been provided by an *ad hoc* committee of the IOC on OIF.

While it is important to permit scientific research, and to demarcate between it and commercially focussed studies (maybe these can be defined as those which engage in scientific research (ostensibly R&D into aspects of commercial OIF) but with a goal of either paying investors, or in funding further trials by the direct or retrospective sale of C credits), the continued development of links between scientists and companies makes this a particularly murky area. As do recent attempts by some companies to incorporate more scientific rigour into their practices. The latter appears to have taken us back to selective use of the scientific evidence (alarmingly, where the actions of a few scientists begins to discredit the broader scientific community).

Moreover, this ongoing debate about stopping further science into OIF, is diverting attention from more important issues – the lack of promise of commercial OIF to act as a climate stabilisation wedge on

decadal timescales required (Paccala and Solocow, Science 2004; Migone et al., Climate Change, 2008)\; Stern, UK Treasury website, 2008). OIF is a bio-geoengineering scheme that is ranked as having low affordability, low safety, low rate of mitigation, and while being based on a relatively robust historical precedent (up to 30 ppmv decrease in atmospheric CO_2 over millennia) this precedent has no merit with on the now needed decadal timescales for climate mitigation (Boyd, 2008a).

PROFESSOR WALLACE BROECKER FORMEMRS

Lamont-Doherty Earth Observatory, Columbia University

It is my view that no combination of alternate energy and conservation will be able to stem the rise in atmospheric CO2 content. This being the case, we must take out an insurance policy by developing the capability to capture and store CO2. As there is no quick financial return, industry is unlikely to do this. Rather an internationally funded institution should be created and charged with developing all aspects of capture and storage. Not only would this group deal with the technical means, but also its cost, its environmental consequences and its perception by the public. And most important, it would be given a set of firm deadlines.

IAN BRUNT

I'm glad this study is taking off, but I feel it is important to be wary of any scheme from which there is no going back, in case of unforeseen consequences.

If we shall have to paint our roofs white, for example, and then that turns out to be a bad idea, then the previous colour can be restored. But if something is released into the atmosphere and that turns out to be a bad idea, then what?

Sorry, I'm not a scientist. But I'm not a financial expert either and I'm amazed by the mess which the experts have landed the world in while the rest of us said nothing because we assumed that they knew what they were doing.

Regards,

I. Brunt

PROFESSOR HARRY BRYDEN FRS

University of Southampton

Thoughts on GeoEngineering Projects

19 December 2008

Overall, my principal worry is that half-thought out ideas may be started/executed with exaggerated claims for success in carbon drawdown or albedo increase and with no consideration of unintended effects. Individual governments may encourage such projects with various financial incentives, possibly put into place without even knowing the effect of the incentives. How is the amount of effectiveness in a particular geoengineering implementation to be assessed? By an international organisation? By a permanent Royal Society panel? Who is going to assess the potential or real side-effects?

Some geoengineering schemes are appealing. Lovelock and Rapley's ocean pipes for increasing productivity is a case in point: put out an idea emphasising the positive aspects but gloss over possible unintended side-effects. We responded by trying to simulate the pipes globally in an ocean biogeochemical circulation model. Surprisingly for the first decade, the pipes resulted in more CO2 being put into the atmosphere by the ocean because they brought up high CO2 waters into the surface layers. This example illustrates what I think the approach should be:

1. First, try to model the suggested geoengineering project to see if it does what it claims and to judge if there are any unintended effects. This can be a reasonably inexpensive modelling effort using suitable, established models.

2. If the models suggest the project may well work without serious side-effects, then I think the approach would be to design and carry out a reasonable scale field test of the project, with appropriate monitoring of the environment to establish the size of the benefit and the scale of side-effects. Here I think the spatial scale of the project must be beyond a process experiment. A whole basin must be seeded for a limited time period (e.g., with pipes or iron), not merely a 10km**2 area, so that the net effects can be monitored on basin-scale. Or the whole atmosphere must be seeded for a limited time with sulphur particles to decrease radiation and the entire earth climate monitored for effects. While not opposed to smaller field projects to test the physical-biogeochemical understanding of the relevant processes, I think a basin-scale (or earth-scale) project of limited duration is ultimately required to test any geoengineering scheme that could potentially address the size of CO2/radiation reduction needed to make a meaningful impact. A basin-scale project is likely to involve a substantial field deployment and associated monitoring efforts involving many countries.

3. Careful analysis of the effects, positive and negative, is then required with a scientific consensus on the benefits and negative apects. Here is where I imagine an international organisation is required to establish the evaluation procedures and form of final assessment.

My recommendation is that the Royal Society Working Group concentrate on defining the procedures that must be followed before implementation of a meaningful geoengineering project is allowed. I would appreciate the Working Group's views on specific schemes of course and I look forward to reading them. But the key in my mind is to set the ground rules to be followed before any large-scale implementation goes ahead.

Finally I would argue that cost of a geoengineering scheme is clearly an element in deciding which geoengineering schemes are viable. But I do not think cost the financial cost of a scheme enters into the assessment of the positive and negative impacts of any particular scheme.

DR KEN BUESSELER

Woods Hole Oceanographic Institution

Dear Andrew Parker-

Attached is a statement relevant to our request for input on Geoengineering by the Royal Society. I had thought of writing a new version, but this one page piece published in Science, 2008 addresses the information you were seeking, and as a consensus document representing 16 leading international scientists in the field, I think it carries more weight than my personal opinion. We exchanged >350 emails to write these 750 carefully chosen words, so its also much more precise than anything else I could write. Finally, there are further background materials on this topic, written for a broader audience that came out of a workshop at WHOI one year ago, and these can be found (or hard copies requested for no cost) at:

http://www.whoi.edu/oceanus/viewArticle.do?id=34167&sectionid=1000

Sincerely, Ken Buesseler.

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PROFESSOR MARCOS CARVALHO CAMPOS

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Royal Society Geo-engineering scheme proposals

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Proposal 1

An area of mirrors at land distribuited at locations for exemple on Saara or others desertic areas

Proposal 2

Large scale use of energetic forestry

Proposal-1 included at item 2) Albedo modification
Proposal-2 included at item 1) Greenhouse gas (CO_2) reduction

Introdution to the proposals

The global warming phenomenon before being only the greenhouse effect it is a thermal phenomenon, driven by two "forces": the atmosfhere warming driven by greenhouse gases directly speaking (increased atmophere gas carbonic concentration), that without a doubt it is the one of larger force, and that one which was under-estimated by the IPCC report: the atmosphere and hydrophere warming directly caused by human ativities. Or better saying, the machines and processes that you/they use energy that you/they sustain for your time, moves and they represent the human form like her he/she lives nowadays in the Earth. In this introduction it will be treated of the second .

Using the principle of energy conservation, it can be affirmed that all energy used by the human activities it is in flow for the Earth or that was stored previously in the materials: fossil and nuclear fuels and geothermic energy. And, with an energy balance of the terrestrial control volumes, atmosphere and hydrosphere, it can be deduced that an accumulation of energy is the reason of a increased temperature in several points of these control volumes.

This accumulation of energy takes to the thermal unbalance of the same control volumes, whose temperatures tend to increase one time that the only "channel of transfer" of energy of the Earth as a whole is the transfer of heat for the rest of the Universe, or the space out of the Earth. From the principles of radiation heat transfer, this global transfer will be restricted by the finite volume of the atmosphere and by the finite surface of the hydrosphere, considering other parameters of heat transfer little variable along the time.

Human ativities

Using the principles of the energy conservation can be inferred that the human activities generate heat which is transferred mainly to the atmosphere. As examples, it can be mentioned two activities: i) transports with vehicles moved by fossil fuels, ii) electric power generation with fossil fuels used in illumination.

Example i) A vehicle is provisioned with an amount of fuel, gasoline or diesel, for instance, to accomplish a certain trajetory. In the initial time the temperature of this supplied vehicle is same the atmospheric

temperature. This vehicle accomplishes the round trip itinerary to the initial point, and when stopping, the temperature of this vehicle tends to the atmospheric temperature, therefore, all the energy of the fuel was transferred to the atmosphere through the following mechanisms: a) aerodynamic friction heating up the air and the vehicle, in the sequence this amount of energy is transferred to atmosphere, b) attrition with the soil heating up the soil and parts of the vehicle and c) attritions of the movable parts of the vehicles. These two amounts of energy are also transferred to atmosphere in sequence.

Example ii) the electric power generation with fossil fuels promotes the direct heating of the atmosphere through the heat transfer of the condensers in all steam power plant, including all the friction losses and heat transfer losses, in the turbines, boilers, pumps and in the electric generators. The transmitted and distributed electric power possesses a portion that is transformed in heat by Joule effect in the cables, transformers and other parts of the electric system. Finally, good part of the electric power that arrives lamps, of any type, it is transformed in thermal energy and dissipated in the atmosphere. The part of the final luminous energy is later transformed in thermal energy due to degradation of the electromagnetics waves that reach any solid surface and they end transferred to the atmosphere. Therefore, practically all the energy of the fossil fuels used in this application it is transformed in thermal energy and transferred to the atmosphere, except a lowermost part that escapes direct for the space.

Many other examples could be used to show that the energy used in the human activities are degraded for thermal energy and they end up being accumulated in the atmosphere and in the hydrosphere, due to restrictions of heat transfer for the space.

The main argument that settles down here is that the humanity should tend to use mainly energy that would be already in flow on the system Earth, in other words, essentially, the solar energy, in its several available forms: hydropower, biomass, winds, solar heating, photovoltaic panels and several others. During the transition period among an energetic matrix based on fossil and nuclear fuels (stored energy) to a matrix based on the solar energy (in flow through the Earth), it should probably need to increase the heat rejection from the system Earth (isolated materially) for the space.

Proposal -1

Use of mirrors at desertic areas in order to reject heat

In order to correct the thermal unbalance of the Earth caused by the energetic utilization of fossils and nuclears fuels during many decades, it is proposed the use of mirrors of high emissivity distribuited at regions of high solar incidence, for example: Saara desert, Arabian peninsula, Arizona and New Mexico deserts, Brazilian Northern, Atacama desert e Austrialians desertic areas.

For this proposal not to have an exclusive objective of reflection of "excedent" energy intends the use of these mirrors on two types of specific places: on houses and highways in these areas. The secondary beneficial effect would be the decrease of the consumption of energy for climatization in these residences and in the acclimatized vehicles when travel in these highways.

In the future, the support structures of these mirrors could be used to fix photovoltaic panels, when the costs of these solar energy converters become feasible to large scale use.

Proposal -2

Large scale use of energetic forestry

With the large scale use of fossil fuels, mankind is promoting the transfer of the carbon element on oil, coal and natural gas from soil to the atmosphere on the form of carbonic gas. The vegetal reign

promotes the contrary transfer of carbon from atmosphere carbonic gas to complex substances like cellulose making use of the solar energy through photosintesys.

The use every time larger of biomass reforested as renewable source of energy (solar energy in flow on Earth), it will provoke a slow but constant decrease in carbonic gas concentration at atmosphere, once as the combustion of the substances that composes the vegetables is not perfect, it will always remain non reacted carbon in the form of ashes being incorporate to the soil, as it indicates the mass balance, along the time, shown in the illustration below.

This modality of solar energy transformation allows its use so much in the heating of residences as in the electric power generation. Practically all the countries possess degraded areas that can be recovered for handling of forests with the objective of renewable energy generation.

The current indexes of electric power generation for energetic forestries are in the order of 400 kW installed power per km^2 of reforested area. A country as Portugal, that possesses a total area of 92,391 km^2, when using 10% of your area to this objective have an installed power of 3,695 MW, whose annual generation, with a capacity factor of 0,9, can reach 28,700 GWh. With the progress in the application of the termoelectricity, the efficiency of the thermal plants will significantly be able to be gotten better, doing with that the index above used (400 kW / km^2) it can be better.

Questions

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

The current state of the knowledge regarding global engineering schemes seeking to act on the phenomenon of the global warming is relatively incipient due to the short space of time that the humanity is taking conscience of the phenomenon of the global warming. Obviously, that due to this little time of study on such a complex phenomenon, exist divergences among the cientists as the main reasons for this phenomenon to be happening. In terms of scale of necessary time to understand a complex phenomenon sufficiently, he/she can remember how long, for instance, the cientists were long to understand the phenomenon of the light, and until today there is aspects to be studied in this subject, but a lot of applications were developed with the knowledge acquired.

With relationship to the geo-engineering schemes, therefore, consent is not had on any type of performance to be accomplished. This consent to be obtained will have relation to the viability, effectiveness and impacts of the proposed outlines. The more simple it goes an scheme, more easier it will be to foresee your viability, effectiveness and your impacts. Perhaps the most important aspect is the impact. An scheme that can be undone with easiness or that allows your transformation in direction to other future needs it is viable and effective than others one.

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

Perhaps there be not time for many types of researches, except for the theoretical researches, as the mathematical modeling of the atmosphere of the Earth. The current groups of research should unite efforts around the analysis of some proposed schemes and obtain one unique strong proposal to the policymakers.

It is necessary to take urgent attitudes in simple global projects, of easy understanding involving locals investments and with previsible basic consequences.

3. What factors need to be considered before deploying any climate geoengineering schemes?

The subject that accompanies global geo-engineering schemes is plenty complex. It is necessary the use of more simplified concepts and complex numerical methods too, in order to well understand the atmosphere, to understand the thermal tendencies of the atmosphere and of the hydrosphere, that are the principal volumes of control of the body isolated system that it is the Earth.

The proposal 1 considers that the global warming generated by the greenhouse effect can be minimized by the rejection of solar energy in distributed places and that there is an amount of thermal energy stored in the hydrosphere and in the atmosphere besides the amount of medium permanent regime, what provokes the elevation of the temperature. If this affirmative is true it means that the system Earth or it can stabilize in higher temperatures or to continue heating up.

An important factor that should be considered before using any scheme will be to verify other alternatives that will result in the same effect that can be used and if the costs are bearable in the equivalent period of the transition to a world with renewable energy matrix.

Another important factor to be considered in any scheme is the possibility of reversion in compatible costs with the implementação or its evolution. The proposal 1 is perfectly reversible as well as the proposal 2.

3.a Who should be responsible for any deployment?

All the countries, your governments, your companies and your people. The important is the scientific community and institutions of the area of energy, transport and climate to propose some fundamental and basic scheme and to coordinate the actions in medium and long period, monitoring results, implementing corrections.

The oil producers countries and the companies of this area should think about maintaining the production and the trade of this product (of finite reservation) for more possible time, therefore, they should think about investing in the decrease of the negative effects of its use, mainly in what concerns the use in transport and generation of energy, that are the section of larger impact.

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

They are many. First of them it will be the consent on an or more forms of performance. The global warming was created by the way of life of all countries, some more other less. Therefore it will be necessary a performance united, more pledge of some than of other countries.

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

The main barrier it is the knowledge lack and the absent of consent on geo-engineering schemes. Maybe it is happen because that the scheme at the moment proposed or it is very expensive and complex (mirrors in orbit for example) or it has imprevisible consequences.

The geo-engineering scheme to be implemented must swallow benefits to the countries and not only for a type of industry of few countries and that can be implemented at several countries, and also that allows the generation of energy and employments in many countries.

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?

Perhaps it is the only way to solve the problem created by the extraordinary human development in the Earth that occurred with the use of fossil fuels, that without other feasible e cheap energy source, lead to a strong dependence of oil, coal and now natural gas.

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

I think that climate geoengineering could be a good way to offer jobs.

MARK CAPRON

PODenergy

Royal Society: Geoengineering; call for submissions

Executive summary
Geoengineering research should emphasize hybrid processes that address multiple crises. For example, geoengineering with the potential to increase species diversity and produce energy would be less controversial. A process removing carbon dioxide from air would allow fossil fuel users to capture 2 units of carbon for each unit emitted. Natural ocean bacterial anaerobic digestion (NOBAD) is one process addressing multiple crises.

Contained ocean biologic carbon dioxide removal

NOBAD removes carbon dioxide from the atmosphere using oceanic biological systems. NOBAD would harness the biologic, chemical, and physical properties of sunlight and ocean in the following steps:

1. Grow kelp on the ocean surface, absorbing solar energy, CO_2, and nutrients.
2. The kelp is harvested into a large container, deep in the ocean.
3. Naturally occurring bacteria digest the kelp, producing bio-methane (CH_4), CO_2, and nutrients.
4. The CH_4 is a gas, with relatively low solubility at any ocean pressure.
5. The CO_2, with incredibly high solubility, and nutrients remain dissolved in the water within the container.
6. When the contained water is raised (pressure reduced), the CO_2 is captured as it comes out of solution and compressed to liquid CO_2 or converted to "cement" at typical ocean pressures and temperatures. The nutrients are returned to the ocean surface to grow more algae.
7. Once pumped below 3,000 meters, liquid CO_2 is denser than seawater and may be safely stored in repairable containers for many millennia. Or the "cement" may drop to the seafloor.

Generally, the gas produced by anaerobic digestion is 60% CH_4 (or significant H_2[b]) and 40% CO_2.[c] At pressures in excess of a few atmospheres, the differential dissolution of CH_4 and CO_2 allow separation of the two gases with very little energy.[d] At the pressures and temperatures available in the ocean (10 to 400 bar, 3° to 30° C) anaerobic digestion proceeds, but CO_2 dissolves in seawater more than 10x (by moles) than CH_4. When pressures exceed 50-bar (500 meters deep), the CO_2 may be produced as a liquid.

NOBAD's capability for addressing several crises suggests it would be extremely sustainable. For example, consistent goals for a NOBAD operation would include: 100 million tonnes of CO2 removed from air, 400 million MWh of combined biohydrogen and biomethane production, complete nitrogen and most other nutrients recycled locally, increased species diversity, and 200 million tonnes of fish. There is also an opportunity for cleaning ocean dead zones.

Calculations based on current experience with algae growth and anaerobic digestion, suggest 10,000,000 hectares (0.03%) of ocean surface can produce all of the above quantities.[e]

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[b] J. Massanet-Nicolau, R. Dinsdale, A. Guwy. Hydrogen production from sewage sludge using mixed microflora inoculum: Effect of pH and enzymatic pretreatment. Bioresource Technology. 99 (14) 6325-6331. (2008) and Martínez-Pérez N, S J Cherryman, G C Premier, R M Dinsdale, D L Hawkes, F R Hawkes, G Kyazze. The Potential for Hydrogen Enriched Biogas Production from Crops: Scenarios in the UK. Biomass and Bioenergy, 31, 95-104, (2007)
[c] Chynoweth, D.P. and Isaacson, R., *Anaerobic Digestion of Biomass*, New York: Elsevier Applied Science Publishers LTD, 1987
[d] van der Meer, B., "Carbon Dioxide Storage in Natural Gas Reservoirs", *Oil & Gas Science & Technology* - Rev. IFP, Vol. 60 (2005), No. 3 pp. 527-536
[e] Calculated from Sheehan, J., Dunahay, T., Benemann J., Roessler P., *A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae.*, U.S. National Renewable Energy Laboratory, July 1998

Answers to questions

1. Bacterial anaerobic digestion is known to be a robust process, but little is known about allowing dissolved carbon dioxide to accumulate at pressures above 2 atmospheres. Laboratory tests can answer questions: How does high pressure affect biological and chemical processes? Does increasing pressure and dissolved CO_2 concentration (with associated lower pH) affect natural bacterial decomposition rates? What conditions favor the production of H_2? What quantity and quality of H_2 and CH_4 is generated at a certain pressure and temperature and for a particular type of algae? Does an increase in pressure alter the species of bacteria? Are hydrates or clathrates formed and can their production be used to desalt seawater? Might the naturally occurring liquid CO_2 in ocean sediments be the product of biological decomposition? How durable is liquid CO_2 or potential containment vessels in the deep ocean or the seafloor ooze? Can the high dissolved CO_2 concentration form a CO_2 "cement" (proprietary Calera.biz process)?

2. Anyone, with compressed combustible gas safety procedures, can research high-pressure anaerobic digestion in a laboratory. Constraints on field tests should be minimal for scattered 10 – 10,000 ha "test farms." Because large (million ha) procedures can be refined on smaller scales, annual "performance reviews" would be more practical and vastly more time-efficient than constraints.

3. If we identify climate geoengineering schemes that appear to have no side effects, could pay for themselves with simultaneous energy production, hold promise for increasing species diversity, may produce food (also helps pay for the geoengineering), and avoid using fresh water, the only remaining question is economics. Other efforts also have economic issues. For example, in early November, British oil major British Petroleum pulled out of a competition to design the country's first carbon capture and storage project. Instead, BP said it would be concentrating its wind investments in the U.S., effectively exiting the U.K. wind power market. Carbon capture and storage is critical to U.K. energy policy. Coal, which is in plentiful supply in Britain, is a big part of the U.K. energy mix. The U.K. says it will cut carbon emissions by 80% by 2050 -- a target it can achieve only if it can work out a way to sequester and safely store the carbon dioxide emitted by its coal-fired power stations. NOBAD can sequester 2x the coal carbon emissions.

4. No comment.

5. The main barrier is obtaining funding for research on a new concept that does not fit into "traditional" Climate Crisis solution slots. The primary opportunity is for innovation solving multiple crises.

6. No comment.

7. No comment.

Personal submission of:
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Mark Capron filed for a U.S. patent on one potential NOBAD process, November 13, 2007. The NOBAD patent information became unprotected prior art for non-U.S. countries on November 13, 2008.

DR ALAN CARLIN
US Environmental Protection Agency

Dear Mr. Parker:

This is in response to your Society's call for submissions found at http://royalsociety.org/downloaddoc.asp?id=5845 on the subject of Geoengineering Climate. This submission includes a summary followed by a response to each of the questions posed in the order given. The views expressed are personal (non-institutional); nothing in this submission should be inferred to represent the views of the institutions where I am employed.

Summary: This response is based on almost 200 pages of detailed exposition contained in three published professional papers that are available on the Web and referenced below with URLs. These papers should be regarded as part of my response even though they obviously cannot be reproduced here. The very broad conclusion of my submission is that if there should be a need to control global and particularly latitude-based regional temperatures there is currently no realistic alternative to using stratospheric geoengineering (sometimes also referred to as solar radiation management). All of my comments relate to this particular type of climate geoengineering. Although we know this approach could be effective, no field research has been done on unintended consequences and only limited laboratory research. Little has been done to plan for its implementation, to optimize its possible use, nor build a capability to make decisions as to its deployment. This is better done sooner rather than later because it would allow the insurance policy that such a geoengineering capability would provide to take effect earlier than if this is postponed until it might actually be needed. And it would reduce the chances for mistakes resulting from hasty implementation.

Responses to your individual questions:

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

A1. There is little question that stratospheric geoengineering is feasible and practical in terms of its predicted impacts on either reducing or increasing global or latitude-defined regional temperatures given the observed effects of large volcanic eruptions over many years (see Carlin (2007) for discussion and extensive references). What the unintended impacts of its use would be depend on the details of how and where it is employed and have not been adequately explored.

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

A2. It should be given very high priority relative to other climate research and undertaken in its early stages by national governments and later by an international organization such as the United Nations if possible for the reasons discussed in detail in Carlin (2007a).

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

A3. (a) Most important factor: Would the economic benefits be likely to exceed the costs in the largest sense under the circumstances then existing using conservative assumptions?

(b) Next most important factor: Is there reasonable assurance that there will not be significant unintended adverse consequences? If there are such consequences, they need to be taken into account in (a) above.

See Carlin (2007a) for a detailed discussion of who should be responsible for deployment.

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

A4. The most immediate issue is legal liability for any adverse effects. This problem must be resolved before any actual climate geoengineering or even field research is attempted (for a detailed discussion see Carlin (2007), p. 1481). The second most important issue is governance and command and control. Who will exercise control and under what circumstances will action be taken? As in A3 above, see Carlin (2007a) for detailed discussion and references. Most of the other issues are largely irrelevant in the short term if stratospheric geoengineering is regarded as an insurance policy rather than something that would actually be employed anytime soon for purposes other than limited field testing since there would be no intent to do anything other than to develop a potential capability for use only if necessary.

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

A5. The main barriers are the opposition of environmental groups, which in turn has contributed to the lack of adequate research. The main opportunity is that there is really no other practical way to exercise significant control over global or regional temperatures should that prove to be necessary. If such control should be needed (it is not currently needed in my view), the other options, particularly the proposed reductions in greenhouse gas emissions would prove to be ineffective because they would be "technically risky, inflexible, extremely expensive, and politically unrealistic" to quote from Carlin (2008), which explains these strong conclusions at considerable length and with extensive references.

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

A6. It is currently the most urgent and important but neglected area of climate research since it is the only practical way to alter temperatures (as discussed in Carlin (2008)) should that prove to be necessary to avoid serious harm to humans and the environment. At some point, if we should head into a new ice age, for example, it would become overwhelmingly important to avoid widespread and possibly drastic effects on humans and other life on Earth. Since Earth's history over the last few million years has included repeated ice ages, we might as well prepare for the possibility now and have the insurance it offers available sooner rather than later.

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

A7. Climate geoengineering should be viewed as an insurance policy against possible future adverse effects of climate change on global and possibly some regional temperatures. Hopefully it will never need to be used until the next ice age may appear imminent, but we need to be prepared to use it wisely and rapidly at any time that it should be needed. Advance preparation will be more likely to avoid serious errors if it should ever be needed. Since it probably will never actually be needed for quite some time all the arguments about moral and ethical problems are of little importance in the meantime since the most that would occur is limited field experiments. It is the best and only realistic insurance policy against adverse climate change as well as the most efficient and realistic approach to control temperatures. And it is one of the few, if not the only, approach that would permit control of regional climate changes without global control should that be desirable.

Some have been concerned that climate geoengineering has have no effect on possible ocean acidification since they believe that attempts to reduce ambient GHG levels would. Besides the need for greater understanding of ocean acidification before committing huge resources to reducing GHG levels, there is some indication that the reductions in GHG emissions required to avoid some of the most adverse impacts of ocean acidification may be so great as to make any GHG reduction approach totally unrealistic (see Carlin (2007) at pp. 1472-5). If there is no feasible way to avoid these effects there is no real point worrying about them; instead we would do better to concentrate on problems we can do something about, such as taking out an insurance policy against possible future warming or cooling that might actually have significant adverse consequences.

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Sincerely yours,

Alan Carlin, PhD
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