Geoengineering the climate: Science, governance and uncertainty

Responses to call for evidence

Part IV

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Urban Heat Harvesting as Geo-engineering: Moderating Urban Climate for Global Climate Control

The Objective:

- Intervention in the global warming potential (GWP) of the Earth's climate
    - via modification and manipulation of the urban climate in cities

The Methodology:

- draw waste heat accumulating in the urban atmosphere
    - through city buildings
        - by utilization of their air-conditioners
- and capture and remove it at rooftop outlets

The Outcome:

- by removing thermal pollution from the urban air
    - moderate urban climate extremes
        - thus diminishing costs of damage and losses from injury
    - by extrapolation, cool the global atmosphere, by whatever degree
        - thus moderating climate-change, to that degree

AND

    - cool city buildings - which require less energy for air conditioning
    - recycle the captured waste heat as energy equivalent to pre-heat 'domestic' water
        - thus saving energy resources, and emitting less GHGs

The Future Goal:

- conduct research into the development of thermal electric cells
    - to efficiently convert this low grade toxic waste heat into clean renewable energy
        - where each building's small contribution of Watts into the electricity grid
            - accumulates into Megawatt proportions nationally.

Urban Heat Harvesting - for Sustainable and Habitable City Climates

Heat is the potent agent that transforms otherwise innocuous but infra-red sensitive greenhouse gases into climate-changing toxins. Given that the central focus of concern and research is currently on reducing greenhouse gas (GHG) emissions via energy efficiency, renewable energy adoption, cap-and-trade and carbon capture at power stations - and a nuclear energy renaissance, the objective of this paper is to suggest a fundamental paradigm shift: towards simultaneously and directly mitigating thermal emissions from urban environments. This is considered here as a vital sustainability precondition since, irrespective of any actions instigated now or in the near future, the greenhouse gases already present in the atmosphere have extensive longevities which inevitably will warm cities and the earth and induce increasingly virulent climate change negativities during the 21st century. Acting directly, forcefully and immediately on reducing and preventing heat accumulations in urban environments seems an opportunistic but overlooked method to act upon the climate-changing catalyst itself – by reducing the global warming potential (GWP) of *all* greenhouse gases ie not only CO_2 but $CO_{2\text{-}e}$ including water vapor as humidity. Urban thermal pollution, moreover, has no vested interests associated with it, nor any economic value but is a noxious waste product which could be controlled and harvested to reduce thermal stresses on cities -

and by logical extension, given the impact of cities in the climate-change scenario - on global climatic excesses.

Heat accumulates in all cities due to the inherent thermal mass of their material structure and infrastructure, sourced primarily from solar radiation, then from human activities including driving hot internal-combustion vehicles on hot roads, heating and lighting of buildings, running of electrical equipment, industrial and chemical activities and, ironically but crucially, cooling of buildings. In the long-term (which we do not have), some degree of thermal mitigation can emerge from the urban form itself. Compaction and densification combined with street grids that are naturally cooler and discourage traffic (narrow, humane-scaled organic rather than broad orthogonal canyon morphologies) can encourage pedestrianization, offer sky-ventilation opportunities, and accommodate subterranean mass transit systems which contain heat underground. In addition, measures to assist buildings to reject urban thermal pressures include roof greening and low emissivity surfaces and colours, which help cool individual buildings and reduce their energy cooling consumption but do not neutralize the heat - which is likely to be transmitted to adjacent buildings that are not heat resistant, or blown downwind above the canopy layer. Trees are effective natural air-coolers but urban planting issues are complex, involving governance and territorial issues, infrastructural adaptations and maintenance and watering requirements exacerbated in warming drought-prone conditions.

At question, then, is whether any remedial urban cooling measure is likely to be efficacious? This paper will hypothesize that buildings themselves might contain an unexpected resolution. Buildings that are air-conditioned emit waste heat - extracted from interiors and the metabolic emissions of occupants, and from solar-urban radiation absorbed by façades and roofs - back into the urban heat island. The author has measured the excessive radiant temperature emitted at air conditioner outlets (in NYC) on a 32^0C/90F summer day as 58^0C/136F – considerably more than ambient. If air-conditioners are adapted to contain this heat at rooftop outlets, to that extent at least it could removed from the urban air – and absorbed by adjacent (insulated) water tanks, where the recycled heat substitutes (as energy equivalent) for a proportion of energy expended to preheat water for each building, reducing demand on energy resources and GHG emissions. Should heat harnessing help cool the urban heat island it will militate against excessive urban climate disruptions and, by logical extension, where sufficient cities participate, have a positive affect on the warming global atmosphere. Potential benefits for citizens include a reduced incidence and severity of heat stress episodes, lowered potency of thermo-chemical air pollution, and increased thermal comfort in the public realm and with this enhanced habitability a rise in natural community-security.

The laws of thermodynamics insist that waste heat emitted from energy use is lost as entropy to the environment; but in theory at least advanced technology might be able to overcome this by transforming the harvested waste heat into zero emission renewable energy – and returning it to the electricity grid from each building, much like PV arrays today. Where thousands of buildings participate each small contribution could accumulate into megawatts. Thermal-electric cells can convert heat to electricity, but are inefficient at low temperature differentials (between the ambient air and the heat ejected); possibly empirical research could overcome this limitation with sufficient experimental funding. Should this be the case, this power would be produced when it is most needed (and brown-outs most likely): when the load on the grid is greatest due to hot conditions.

Obviously the heat harvesting notion can only work where buildings are air-conditioned, and applies particularly to hot climate cities and seasons, but currently there are millions of centralized systems in buildings ranging from commercial and high-rise residential to libraries and airports and hospitals etc. installed across the globe which could come on line with sufficient local governance incentives and policy modifications. State- and government-owned buildings could lead the way, and then inter-agency collaborations with private-sector building owners/occupiers could be instigated and coordinated, while green building codes are mandated to include heat harvesting as well as energy efficiency and carbon neutrality. Retro-fitting costs and complexities should be minimal in comparison to the vast social, economic and ecological costs of disasters and potential GDP losses identified by research from the IPCC and the Stern Report, etc. Moreover, credits for thermal sequestration could become a tradable system as per carbon footprints.

Poor nations and poor people suffer most from excessive heat conditions, and the usual argument that air-conditioning is too expensive and/or inappropriate given the status quo - and environmentally irresponsible presuming the energy is even available - could be re-conceived in the light of the benefits

from the harvesting of waste heat and the associated resilience factors alluded to above. This is a form of low-tech social-capital enhancement program which could be supported by global facilities such as the IMF and World Bank.

PROFESSOR JEFF SEVERINGHAUS

Dear Dr. Parker,

I would like to make one very brief comment regarding geoengineering via removal of CO2 from the atmosphere by growing biofuel crops. As Paul Crutzen has pointed out, the fertilizer that must be applied to field crops leads to approximately 5% of the nitrogen ultimately becoming N2O, that is released to the atmosphere. A rough calculation shows that such CO2 removal could be self-defeating from a climate mitigation perspective:

If 200 atoms of carbon are removed from the atmosphere as part of a climate protection scheme; and if 40 atoms of nitrogen must be applied in the form of fertilizer to facilitate this removal; and if 5% of this nitrogen (2 atoms) becomes nitrous oxide released to the atmosphere; then one molecule of N2O will be created. Each molecule of N2O has a heat-trapping effect 200 times that of CO2. Hence, the climate protection is nullified.

Furthermore, N2O has an atmospheric lifetime of 130 years, making the committed warming from emissions a long term issue that brings in the issue of intergenerational equity.

Sincerely,
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N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels

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Abstract. The relationship, on a global basis, between the amount of N fixed by chemical, biological or atmospheric processes entering the terrestrial biosphere, and the total emission of nitrous oxide (N2O), has been re-examined, using known global atmospheric removal rates and concentration growth of N2O as a proxy for overall emissions. For both the pre-industrial period and in recent times, after taking into account the large-scale changes in synthetic N fertiliser production, we find an overall conversion factor of 3–5% from newly fixed N to N2O-N. We assume the same factor to be valid for biofuel production systems. It is covered only in part by the default conversion factor for "direct" emissions from agricultural crop lands (1%) estimated by IPCC (2006), and the default factors for the "indirect" emissions (following volatilization/deposition and leaching/runoff of N: 0.35– 0.45%) cited therein. However, as we show in the paper, when additional emissions included in the IPCC methodology, e.g. those from livestock production, are included, the total may not be inconsistent with that given by our "topdown" method. When the extra N2O emission from biofuel production is calculated in "CO2-equivalent" global warming terms, and compared with the quasi-cooling effect of "saving" emissions of fossil fuel derived CO2, the outcome is that the production of commonly used biofuels, such as biodiesel from rapeseed and bioethanol from corn (maize), depending on N fertilizer uptake efficiency by the plants, can contribute as much or more to global warming by N2O emissions than cooling by fossil fuel savings. Crops with less N demand, such as grasses and woody coppice species, have more favourable climate impacts. This analysis

only considers the conversion of biomass to biofuel. It does not take into account the use of fossil fuel on the farms and for fertilizer and pesticide production, but it also neglects the production of useful co-products. Both factors partially compensate each other. This needs to be analyzed in a full life cycle assessment.

1 Introduction

N2O, a by-product of fixed nitrogen application in agriculture, is a "greenhouse gas" with a 100-yr average global warming potential (GWP) 296 times larger than an equal mass of CO2 (Prather et al., 2001). As a source for NOx , i.e. NO plus NO2, N2O also plays a major role in stratospheric ozone chemistry (Crutzen, 1970). The increasing use of biofuels to reduce dependence on imported fossil fuels and to achieve "carbon neutrality" will further cause atmospheric N2O concentrations to increase, because of N2O emissions associated with N-fertilization. Here we propose a global average criterion for the ratio of N to dry matter in the plant material, which indicates to what degree the reduced global warming ("saved CO2") achieved by using biofuels instead of fossil fuel as energy sources is counteracted by release of N2O. This study shows that those agricultural crops most commonly used at present for biofuel production and climate protection can readily lead to enhanced greenhouse warming by N2O emissions.

2 A global factor to describe N2O yield from N fertilization

We start this study by deriving the yield of N2O from fresh N input, based on data compiled by Prather et al. (2001) and Galloway et al. (2004) with some analysis of our own. Fresh fixed N input includes N, which is produced by chemical, biological and atmospheric processes. The pre-industrial, natural N2O sink and source at an atmospheric mixing ratio of 270 nmol/mol is calculated to be equal to 10.2 TgN2ON/yr (Prather et al., 2001), which includes marine emissions. By the start of the present century, at an atmospheric volume mixing ratio of 315 nmol/mol, the stratospheric photochemical sink of N2O was about 11.9 TgN2O-N/yr. The total N2O source at that time was equal to the photochemical sink (11.9 TgN2O-N/yr) plus the atmospheric growth rate (3.9 TgN2O-N/yr), together totalling 15.8 TgN2O-N/yr (Prather et al., 2001). The anthropogenic N2O source is the difference between the total source strength, 15.8 TgN2ON/yr, and the current natural source, which is equal to the preindustrial source of 10.2 TgN2O-N/yr minus an uncertain 0–
0.9 TgN2O-N, with the latter number taking into account a decreased natural N2O source due to 30% global deforestation (Klein Goldewijk, 2001). Thus we derive an anthropogenic N2O source of 5.6–6.5 TgN2O-N/yr. To obtain the agricultural contribution, we subtract the estimated industrial source of 0.7–1.3 TgN2O-N/yr (Prather et al., 2001), giving a range of 4.3–5.8 TgN2O-N/yr. This is 3.8–5.1% of the anthropogenic "new" fixed nitrogen input of 114 Tg N/yr for the early 1990s; the input value is derived from the 100 Tg of
N fixed by the Haber-Bosch process, plus 24.2 Tg of N fixed due to fossil fuel combustion and 3.5 Tg difference from biological N fixation, BNF, between current and pre-industrial times (Galloway et al., 2004), reduced by the 14 Tg of Haber- Bosch N not used as fertilizer (Smeets et al, 2007). (This total of 114 TgN is very similar to the sum of the different values for N from fertilizer and BNF given by Smeets et al.: 81+38=119 Tg.) In an earlier study (Mosier et al.,1998) the source of N2O from agriculture was estimated to be even larger, 6.3 TgN2O-N, giving an N2O yield of 5.5%. In comparison, the N2O-N emission estimated by Prather et al. (2001) is 2.9–6.3 TgN2O-N/yr, or 3.4–6.8 TgN2O-N/yr if we also include biomass and biofuel burning (which we consider an agricultural source), leading to N2O-N yields of 2.6–5.5% or 3.0–6.0%, respectively.Because of good knowledge of the chemical processing of N2O in the atmosphere and its tropospheric concentrations, obtained from air enclosure in ice cores, its natural sources and sinks are well known and can be calculated with models. Thus, pre-industrial, natural conditions provide additional information on the yield of N2O from fixed N input. For that period, the global source and sink of N2O was 10.2 TgN2ON/yr with 6.2–7.2 TgN2O-N/yr coming from the land and coastal zones (Prather et al., 2001), derived from a fresh fixed N input of 141 Tg N/yr (Galloway et al., 2004), giving an N2O-N yield of 4.4–5.1%. Both for the pre-Haber-Bosch natural terrestrial emissions and the agricultural emissions in the Haber-Bosch era, we find that the ratio y=N2O output/fresh fixed N input is 3–5%. This is a parametric relationship, based on the global budgets of N2O and fixed N input, and atmospheric concentrations and known lifetime of N2O, and thus is not dependent on detailed knowledge of the terrestrial N cycle. We assume that this global ratio will be the same in agro/biofuel production systems. This is a reasonable assumption, as similar agricultural plants are currently used as feedstocks for biofuel production as those grown in regular agriculture. Some correction is needed for the use of animal manure in biofuel crop production, but this is quite small: Cassman et al. (2002) noted that approximately 11% of total N input to world's cropland came from animal manures. A comparison of our "top-down" estimates of N2O emissions from inputs of newly fixed N with the "bottom-up" estimates

that are made with the IPCC inventory methodology (Mosier et al., 1998; IPCC, 2006) is presented in Appendix A. A key feature of our methodology is that the 114 Tg of newly fixed N entering agricultural systems (synthetic fertilizer N and N from biological nitrogen fixation (BNF)) is regarded as the source of all agriculture related N2O emissions.

3 N2O release versus CO2 saved in biofuels

As a quick indicator to describe the consequence of this "background" N2O production we compare its global warming with the cooling due to replacement of fossil fuels by biofuels. Here we will only consider the climatic effects of conversion of biomass to biofuel and not a full life cycle, leaving out for instance the input of fossil fuels for biomass production, on the one hand, and the use of co-products on the other hand.

We assume that the fixed nitrogen which is used to grow the biofuels is used with an average efficiency of 40% (see below) and that this factor determines how much newly fixed N must be supplied to replenish the fields over time. We also obtain the fossil CO2 emissions avoided from the carbon processed in the harvested biomass to yield the biofuel. With these assumptions, we can compare the climatic gain of fossil fuel-derived CO2 "savings", or net avoided fossil CO2 emissions, with the counteracting effect of enhanced N2O release resulting from fixed N input. Our assumptions lead to expressions per unit mass of dry matter harvested in biofuel production to avoid fossil CO2 emissions, "saved CO2",(M), and for "equivalent CO2", (Meq), the latter term accounting for the global warming potential (GWP) of the N2O emissions. We derive M from carbon contained in biomass as the lower heat value per carbon, and consequently the CO2 emissions per energy unit, are almost identical for the fossil fuels and biofuels discussed here (JRC, 2007):

$M = rC * \mu CO2/\mu C * cv$ (1)
$Meq = rN * y * \mu N2O/\mu N2 * GWP/e$ (2)

Table 1. Relative warming derived from N2O production against cooling by "saved fossil CO2" by crops as a function of the actual nitrogen content rN(actual). Uncertainty ranges presented derive from the uncertainty of the yield factor y (see text).

Crop	rN(actual) (g N/kg dry matter)	Relative warming (Meq/M) (N-efficiency e=0.4)	Type of fuel produced
Rapeseed	39	1.0–1.7	Bio-diesel
Maize	15	0.9–1.5	Bio-ethanol
Sugar cane	7.3	0.5–0.9	Bio-ethanol

In these formulae rC is in g carbon per g dry matter in the feedstock; rN is the mass ratio of N to dry matter in g N/kg; cv is the mass of carbon in the biofuel per mass of carbon in feedstock biomass (maize, rapeseed, sugar cane); e is a surrogate for the uptake efficiency of the fertilizer by the plants; y=0.03–0.05, the range of yields of N2O-N from fixed N application; GWP=296; $\mu CO2/\mu C=44/12$, $\mu N2O/\mu N2=44/28$, where the μ terms are the molar weights of N2O, N2, CO2, and C.
Inserting these values in Eqs. (1) and (2) we thus obtain, with expressions in parentheses representing ranges,

$M=3.667.cv.rC$ (3)
$Meq=(14 – 23.2)rN/e$ (4)
$Meq/M=(3.8 – 6.3)rN/(e.cv.rC)$ (5)

The latter term is the ratio between the climate warming effect of N2O emissions and the cooling effect due to the displacement of fossil fuels by biofuels. These equations are valid for all above-ground harvested plant material, and separately also for the products and residues which are removed from the agricultural fields. If
Meq>M, there will be net climate warming, the greenhouse warming by increased N2O release to the atmosphere then being larger than the quasi-cooling effect from "saved fossil CO2". There will neither be net climate warming nor cooling by biofuel production when Meq=M, which occurs for

$rN=(0.158 – 0.263).(e.cv.rC)$ (6)

Under current agricultural practices, worldwide, the average value for e _0.4 (or 40%) (Cassman et al., 2002; Galloway et al., 2003; Balasubramanian et al., 2004). This value reflects the considerable amounts of N lost to the atmosphere via ammonia volatilization and denitrification (N2) and by leaching and runoff to aquatic systems. Fertilizer N use efficiency much higher than this (e.g. Rauh and Berenz, 2007) is certainly possible when fertilizer N is made available according to plant uptake requirements, but this does not reflect the agricultural practice in many countries of the world. Nonetheless, we recognise the possibility of better efficiencies in future, as has been possible in special circumstances on a research basis. Below we derive values for rN based on both e=0.4 and e=0.6.

The data (and their sources) used to calculate the carbon contents, rC, and the conversion efficiency factors, cv, and the calculations themselves, are given in Appendix B. As rC we use 0.61, 0.44 and 0.43 for rapeseed, maize, and sugar cane, respectively. We derive values of cv=0.58 for rapeseed bio-diesel, cv=0.37 for maize bio-ethanol, and cv=0.30 for sugar cane ethanol production.

Consequently, for e=0.4,

rN=22.3–37.2 g N/kg dry matter for rapeseed bio-diesel,
rN=10.3–17.1 g N/kg dry matter for maize bio-ethanol
rN=8.1–13.6 g N/kg dry matter for sugar cane bio-ethanol.

Similarly, for e=0.6,
rN=33.5–55.8 g N/kg dry matter for rapeseed bio-diesel,
rN=15.4–25.7 g N/kg dry matter for maize bio-ethanol
rN=12.2–20.4 g N/kg dry matter for sugar cane bioethanol.

For each of these biofuels, a larger value of rN in the plant matter than this range implies that use of the fuel causes a net positive climate forcing.

Note that our analysis only considers the conversion of biomass to biofuels, emphasizing the role of N2O emissions. It does not take into account the supply of fossil fuel for fertilizer production, farm machinery and biofuel process facility, which require a considerable fraction of the energy gained (Hill et al., 2006). Furthermore, we assume that biofuel production is based on mineral fertilizer only (substitution of manure for synthetic fertilizer would offset our result by the percentage of synthetic fertilizer that is not used). The energy content gained from by-products will largely be offset from additional energy needed to produce it (Hill et al., 2006), here we also neglect its potential to replace other animal feed crops (and the associated N2O emissions). We are aware that integrated processes exist which better connect biofuel production with animal husbandry, but we believe this cannot be taken for granted on a global scale.

4 Results and discussion

4.1 Nitrogen content in biofuels

Data on rN for several agricultural products, in g (N)/kg dry matter (Velthof and Kuikman, 2004; Biewinga and van derBijl, 1996), are presented in Table 1, together with results on"relative warming".They show net climate warming, or considerably reduced climate cooling, by fossil fuel "CO2 savings", due to N2O emissions. The rN value for maize is equal to 15 g N/kg dry matter, leading to a relative climate warming of 0.9–1.5 compared to fossil fuel CO2 savings. The effect of the high nitrogen content of rapeseed is particularly striking; it offsets the advantages of a high carbon content and energy density for biodiesel production. World-wide, rapeseed is the source of >80% of bio-diesel for transportation, and has been particularly promoted for this purpose in Europe. For bio-diesel derived from rapeseed, this analysis indicates that the global warming by N2O is on average about 1.0–1.7 times larger than the quasi-cooling effect due to "saved fossil CO2" emissions. For sugar cane / ethanol the relative warming is 0.5–0.9, based on a rN value of 7.3 g N/kg dry matter (Isa et al., 2005), causing climate cooling with respect to N2O (not necessarily for the whole process, as fossil energy input is not considered).
Although there are possibilities for improvements by increasing the efficiency, e.g. for the uptake of N fertilizer by plants (Cassman et al., 2002) – which is much needed in regular agriculture as well – on a globally averaged basis the use of agricultural crops for energy production, with the current nitrogen use efficiencies, can readily be detrimental for climate due to the accompanying N2O emissions, as indicated here for the common biofuels: rapeseed / bio-diesel, and maize / ethanol. However, if nitrogen use efficiency can be increased to e=0.6, then as the calculations above and in Table 2 show, maize / ethanol

and rapeseed / biodiesel may be climate-neutral or beneficial. Also the effect of other assumptions on our result (substitute manure; replace other crops) is tested in Table 2.

Table 2. Sensitivity analysis, showing the impact on relative warming (Meq/M) resulting from changes to parameters used for Table 1. The calculations depend on assumptions made about the global agricultural practice of biofuel production. In each column, values differ from those presented in Table 1 by one parameter only as indicated in the relevant column heading.

Crop	Increased N-efficiency harvested (e=0.6)	High share of manure (20%) in fertilizer for biofuels	Efficient use of by-products: Considerable fraction (50%) of N for biofuel production replaces crops that would need N fertilizer
Rapeseed	0.7–1.2	0.8–1.4	0.5–0.9
Maize	0.6–1.0	0.7–1.2	0.4–0.7
Sugar cane	0.4–0.6	0.4–0.7	0.3–0.4

More favourable conditions for bio-energy production, with much lower nitrogen to dry matter ratios (Tillman et al., 2006), resulting in smaller N2O emissions, exist for special "energy plants", for instance perennial grasses (Christian et al., 2006) such as switch grass (*Panicum virgatum*) and elephant grass (*Miscanthus* × *giganteus* hybrid), with a rN of 7.3 g N/kg dry matter. The production of biofuel from palm oil, with a rN of 6.4 g N/kg dry matter (Wahid et al., 2005), may also have moderately positive effects on climate, viewed solely from the perspective of N2O emissions. Other favourable examples are ligno-cellulosic plants, e.g. eucalyptus, poplar and willow.

The importance of N2O emissions for climate also follows from the fact that the agricultural contribution of 4.3–5.8 TgN2O-N/yr gives the same climate radiative forcing as that provided by 0.55–0.74 Pg C/yr, that is 8–11% of the greenhouse warming by fossil fuel derived CO2. Increased emissions of N2O will also lead to enhanced NOx concentrations and ozone loss in the stratosphere (Crutzen, 1970). Further, NO is also produced directly in the agricultural N cycle. Adopting the relative yield of NO to N2O of 0.8 (Mosier et al., 1998), and the agricultural contribution to the N2O growth rate of 4.3–5.8 TgN2O-N/yr, the global NO production from agriculture is equal to 3.4–4.6 Tg N/yr, about 20% of that caused by fossil fuel burning (Prather et al., 2001), affecting tropospheric chemistry in significant ways.

4.2 Potential impact on life cycle analysis

An abridged analysis as presented above, yielding N/C ratios to indicate whether biofuels are GHG-positive or GHGnegative, can not replace a full life cycle assessment. In recent years, a number of such assessments have become available (Adler et al., 2007; Kaltschmitt et al., 2000; von Blottnitz et al., 2006; Farrell et al., 2006; Hill et al., 2006). At this stage, we can not discuss the differences between these respective approaches, which also affect conclusions. But we may look into the release rate of N2O-N used, presented as a function of applied fertilizer N. In these life cycle studies, release rates typically are based on the default values estimated by IPCC (2006) for "direct" emissions which were derived from plot-scale measurements (1% of the fertilizer N applied, or, in a previous version, 1.25%). Only a few studies (Adler et al., 2007) also incorporate the corresponding default values for "indirect" emissions also specified by IPCC (totalling less than 0.5% and which, together with the direct emissions, add up to c. 1.5% of fertilizer N), whereas our global analysis indicates a value of 3–5%. Past studies seem to have underestimated the release rates of N2O to the atmosphere, with great potential impact on climate warming. The effect of applying higher N2O yields can be assessed using the openly accessible EBAMM model (Farrell et al., 2006).

5 Conclusions

As release of N2O affects climate and stratospheric ozone chemistry by the production of biofuels, much more research on the sources of N2O and the nitrogen cycle is needed. Here we have shown that the yield of N2O-N from fixed nitrogen application in agro-biofuel production can be in the range of 3–5%, 3–5 times larger than assumed in current life cycle analyses, with great importance for climate. We have also shown that the replacement of fossil fuels by biofuels may not bring the intended climate cooling due to the accompanying emissions of N2O. There are also other factors to consider in connection with the introduction of biofuels. Here we concentrated on the climate effects due only to required N fertilization

in biofuel production and we have shown that, depending on N content, the current use of several agricultural crops for energy production, at current total nitrogen use efficiencies, can lead to N2O emissions large enough to cause climate warming instead of cooling by "saved fossil CO2". What we have discussed is one important step in a life cycle analysis, i.e. the emissions of N2O, which must be considered in addition to the fossil fuel input and co-production of useful chemicals in biofuel production. We have not yet considered the extent to which any loss by volatilisation of part of the fertilizer N may stimulate CO2 uptake from the atmosphere, following deposition on natural ecosystems; estimates for this effect are very uncertain (de Vries et al., 2006;

Magnani et al., 2007; Hyv¨onen et al., 2007). We conclude that the relatively large emission of N2O exacerbates the already huge challenge of getting global warming under control.

Appendix A

Comparison between the present and the IPCC method to estimate the global N2O yields

The basis of our methodology is that the newly fixed N entering agricultural systems (synthetic fertilizer N and N from biological nitrogen fixation (BNF)) is regarded as the source of all related N2O emissions, and furthermore these emissions may not all happen in the season of application, but involve longer cycling times (which are nonetheless short compared with the lifetime of N2O in the environment). These emissions can be conveniently considered in three categories:

– direct emissions from N-fertilized soils;
– "secondary" emissions resulting from the complex transformations of N compounds in the various flows within agricultural systems; and
– indirect emissions (in the IPCC meaning of the phrase) arising from leached N leaving agricultural fields and entering water systems, and from volatilized N deposited onto natural ecosystems.

Examples of the "secondary" emission sources are:

– crop residues ploughed in as fertilizer for a successor crop;
– dung and urine from livestock (both grazing and
housed) fed variously on N-fertilized grain crops, feeds containing BNF-N (e.g. soya bean meal, alfalfa, cloverrich pasture and silage in Europe, and tropical grasses with *Azospirillum* associations in Brazil); and

– N mineralized from soil organic matter and root residues following cultivation or grassland renewal.

In contrast, in the IPCC approach, emissions from crop residues and mineralization are included in the "direct" emissions and have the same emission factor (*EF*); separate *EF*s are used for emissions from grazing animals, and the N source here is quantified on the basis of the N excreted, and essentially is treated as a "new" N source, not as fertilizer- or BNF-derived N. The fractions of the N applied to fields that are lost by leaching, runoff and volatilization have additional *EF*s applied to them. The aggregate emissions from agriculture are arrived at by summing all these individual sources. The IPCC's 1% *EF* for direct N2O emissions contains an uncertainty of one-third to 3 times the default value. The default EF for emissions from cattle, poultry and pigs is 2% of the N excreted, with a range of 0.7% to 6% – again, from one-third to 3 times the default value. The EFs for N derived from N volatilization and re-deposition and N derived from leaching and runoff are 1% (uncertainty range 0.2–5%) and 0.75% (0.05–2.5%), respectively. At default volatilization fractions of 10% (mineral fertilizer) or 20% (animal manure), and default leaching fraction of 30%, indirect emissions amount to 0.35–0.45% of N applied. Each of the source terms in the bottom-up, IPCC method is very uncertain. However, their sum is not inconsistent with the total derived by the top-down methodology.

Appendix B

Calculation of cv values

a) Bio-ethanol production from maize:
Yield=2.66 US gallons per US bushel (mean of values for wet and dry milling processes) (USDA 2002, cited in UK Dept for Transport, 2006)

=2.66×3.785=10.07 l ethanol/25.4 kg maize
=7.945 kg ethanol/25.4 kg maize

=0.313 kg ethanol/kg maize.

C content of ethanol (C_2H_5OH, mol. wt. 46) by weight=24/46=522 g/kg.
C content of maize (rC)_=0.44 g/g_=440 kg/t.

cv=(0.313×522)/440=0.37.

b) Bio-diesel production from rapeseed:

– the average oil yield is 45% (450 kg/t rapeseed) (Elaine Booth, SAC Aberdeen, personal communication)
– the average composition of the oil is adequately represented by the triglyceride of the dominant fatty acid,
erucic acid, i.e. $(C_{22}H_{41}O_2)_3(C_3H_5)$, mol. wt. 1052, then

C content of the oil by weight=828/1052=0.787 kg/kg.

Thus the C content of the oil=(450×0.787)=354 kg/t rapeseed.

The conversion to bio-diesel involves conversion to the methyl ester:

$(C_{22}H_{41}O_2)_3(C_3H_5) \rightarrow 3C_{22}H_{41}O_2CH_3$

but the C content of the bio-diesel is almost unchanged from that of the natural oil:

mol. wt. of methyl ester=352, and
C content=(276/352)×450=353 kg/t rapeseed.

Oil content of original rapeseed=45% (450 kg/t), and non-oil components_=550 kg/t, of which

– protein is 40% (_220 kg/t original rapeseed), with a C content of 510 g/kg;
– the remainder (60%, _330 kg/t original rapeseed) is dominantly carbohydrate,
(Colin Morgan, SAC Edinburgh, personal communication)

Thus the C content of the protein fraction in the original rapeseed =220×510/1000=112 kg/t; and the C content of the carbohydrate fraction (for which a C content of 440 g/kg can be adopted, as for grains)=330×440/1000=145 kg/t. The overall C content of the original rapeseed (rC=Coil+Cprotein+CCHO) =354+112+145=612 kg/t.

cv=353/612=0.58.

c) Bio-ethanol production from sugar cane:

Yield is 86 l dry ethanol (density 0.79 kg/l) per tonne sugar cane harvested at a water content of 72.5%, or 247 kg ethanol per tonne dry sugar cane (Macedo et al., 2004, as cited by JRC, 2007).

C content of ethanol (C_2H_5OH, mol. wt. 46) by weight=24/46=522 g/kg.
C content of dry sugar cane is determined by its structural material, cellulose, and its sugar content (polysaccharides: 440 g/kg; saccharose: 420 g/kg), we use rC=430 g/kg

cv=(0.247 × 522)/430=0.30.

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DR MARK SHELDRICK

How to Quickly Control the Thermal Effects of Greenhouse Gases

Summary of Points Addressed

Albedo Effect of painting urban surfaces white. Scope is item 2, part a. Question 1, of Feasibility and Efficacy.

This paper will address the points:

Area Available. Albedo Increase.
Cooling Effect of Albedo Increase across the area. Comparison with effects of CO_2 heating effect.
Financial cost of scheme. CO_2 cost of scheme.
Secondary Effects.

Introduction

This article is about a form of geo-engineering which would be cheap and quick to implement and reverse and with a minimum of side effects on the world, other than those deriving directly from the temperature change produced.

The method proposed is to change the albedo of the built up areas of the globe. Other schemes have been proposed to change the albedo of the planet but these involve affect large areas of the globe that until now have only been marginally affected by mankind. This could have significant side effects. It would be better to restrict significant changes to the parts of the world that have already been significantly changed and are already under mankind's direct control. The changes of albedo in built up areas can be accomplished quickly, controllably and reversibly without significant effect upon the non-built up areas.

Inspirations

This paper was inspired by the article written by Bjorn Lumberg 'Paint it white' for the Guardian Website Guardian.co.uk/commentisfree/ which was about reducing the urban heat island effects. That article was primarily about the local effects, while this paper will be about the global implications.

Other related article about local cooling effects of increased albedo, reported in New Scientist issue 11th October 2008, (No. 2677) page 15 "Hot white roofs are height of cool.", referring to article in Journal of Geophysical Research, DOI: 10.1029/2008JD009912 "Surface temperature cooling trends and negative forcing due to land use change toward greenhouse farming in south-eastern Spain. Pablo Campra of University of Almeria+ Garcia M., Canton Y., Palacios-Orueta A.

Articles about the global effect of painting things white also exist. See White Is the New Green: http://www.redorbit.com/news/science/968210/white_is_the_new_green/index.html Thursday, 14 June 2007.

Painting Rooftops White Would Slow Global Warming: http://sustainablog.org/2008/09/10/painting-rooftops-white-would-slow-global-warming/ and http://www.energy.ca.gov/2008publications/LBNL-1000-2008-022/LBNL-1000-2008-022.PDF

On My Mind: http://www.forbes.com/forbes/2000/0821/6605036a.html

Area Available

The estimated total urban area as a percentage of the world surface varies from 0.15% to 1.0%.
PMUe 2,213,496 Km2 [Poverty Mapping Urban Extents] 1.7% of Land, 0.496% world.
GRUMP 3,485,596 Km2 [Global Rural Urban Mapping Project, Produced by CIESIN] 2.7% of Land, 0.788% world.
BUUA 713,330 Km2 [Boston University Urban Area] 0.5% of land, 0.146% of world.
IGBP 4,745,000 Km2 [International Geosphere -Biosphere Programme] 0.9275% of world.
Wikipedia 1.5% of Land area, 0.438% of world.
Total Land and Sea area: 510,072,000 Km^2, Land area = 148,940,000 Km^2 (29.2%)

This figure is given as a percentage of the total world surface, sea as well as land, as this article is about the global effect. The value varies between the various sources due to different definitions of urban or built up areas. Examples of things exclude are towns of populations less than 50,000, the road and rail network. Many things that are urban/artificial areas are excluded from the estimates given. [http://www.eco-logica.co.uk/pdf/CPRELandTake.pdf UK area occupied by roads 1.17% of land area, similar value for Germany.] For the purposes of this work an arbitrary value of 1.0% of the full world surface area is used, both for simplicity and to include all the smaller urban and artificial areas as well.
Total Urban area usable = 5,100,000 Km^2 (0.01 x 510,072,000 Km^2)

Albedo Effects

This section will estimate what cooling effect is possible from the possible change in albedo of urban and artificial areas.

Earth Current Global Albedo 0.30 from p284 of Fundamentals of Atmospheric Modeling 2nd Edition by Mark Z. Jacobson, Cambridge University Press, 2005, ISBN 0-521-54865-9. (various other sources range from 0.29 to 0.37)

[Liou, K.N., 2002, An Introduction to Atmospheric Radiation, Amsterdam, Academic Press.]

Cloud cover proportion 0.59 [The Encyclopedia of Earth, http://www.eoearth.org/article/Cloud_formation_processes]

This reduces the effective visible area of urban land to (1-0.59) x 1%= 0.41%, of the daylight side.

Estimate of Radiation reflected directly back into space = Albedo x solar constant at Earth's orbit = 0.30 x 1,365 W/m^2=409.5 W/m^2.

But this is for a circular cross-section area of the earth only, which is ¼ of the earth total surface area. This is from the ratio between the area of a sphere = 4.pie.r^2 to the circular cross-section area pie.r^2, a standard geometric relation.

So to average this out over a sphere, divide by four for an average of 102.4 W/m^2. This is being averaged over the globe in order to put it on the same basis as the infrared emissions from the Earth, to enable a more direct comparison with the effect of CO_2.

Examples of Albedo for Various Land Uses

Northern Cities 0.07 Tropical Cities 0.12 Fresh Asphalt 0.04

Worn asphalt 0.12

Fresh Concrete 0.55 Albedo of White Paint 0.88-0.92 (Depending upon age.)

Urban average albedo for Northern cities 0.07. [Fundamentals of Atmospheric Modeling, page 284 for table of Albedo values]

Maximum possible increase is to about 0.87. Change in albedo possible is +0.8 at the limit for urban areas.

A real world example of the effects of change in albedo is given in the reference "Surface Temperature Cooling Trends…" where the change in albedo was +0.25.

Effect of Change in Albedo on Average Heating Effect.

The effect of 0.41% of surface area gaining in albedo by +0.8 would be a global increase of albedo = 0.0041x 0.8=+0.00328.

For the Earth this would result in a change from 0.300 to 0.30328. The albedo difference will be used in the temperature equation as the difference is more reliable than the absolute value due to the variations in estimates on the starting value.

The increase in Albedo possible would effectively reflect = (Albedo Increase) x (Solar constant) = 0.00328 x 1,365 / 4 = 1.12 W/m^2

An extra +1.12 W/m^2 of forcing radiative cooling as an average over the whole globe.

Examples of smaller areas and degree of whitening, which will result in milliwatts/m^2 of cooling:

+0.1 Albedo over whole urban area will give average (0.1/0.8) x 1.12 W/m^2 = 140 mW/m^2 of global cooling.

+0.1 Albedo over 10,000 Km^2 of urban land, the reduced land area ratio works out as: (10,000 / 5,100,000) x 140 = 0.275 mW/m^2 average global effect.

Emissivity Effects

This is the proportion of thermal radiation that an object emits in comparison to a theoretical black body of the same temperature. This is the emission equivalent of albedo. Degree of increase possible less than 1/20th of that of increased albedo as typical values for substances lie in the range 0.92 to 0.98 with the average for planet Earth being about 0.95. Will ignore potential of increasing emissivity as small with respect to main point. But this is the area where green house gases have their influence, in reducing the emissivity effectiveness.

Current CO_2 Situation

This section is to estimate the amount of CO_2 and its effects, to give simple conversion values between effects and quantity.

Atmosphere Total mass 3,000 Billion Metric tonnes of CO_2 (Wikipedia) (2,750+ Billion Metric Tonnes of CO_2, Woods Hole Research Centre: 750+ Billion Metric Tonnes of C). Current Emission rate is 31 Billion Metric Tonnes of CO_2 per Year. (2007)

Preindustrial CO_2 Concentration was about 278 ppm (1750 AD). Current CO_2 concentration 383 ppm (2007)

[Source Global Carbon Project 2008 (**GCP**) http://www.globalcarbonproject.org/carbontrends/index.htm]
NOAA/ESRL Radiative Forcing Estimate 1.7 W/m^2 {1750-2007} [from http://www.esrl.noaa.gov/gmd/aggi/]
+105 ppm by molecule number = 818 Billion Metric Tonnes of CO_2 (producing the Radiative forcing effect of 1.7 W/m^2).
[Derived from figures in carbon cycle chart in Chemistry of Atmospheres, page 18]
1 ppm of CO_2 in the atmosphere weighs 7.79 Billion Metric Tonnes.
1Billion Metric tonnes Net of CO_2 in atmosphere blocks 2.08 mW/m^2 radiation (from 1.7 W/m^2 / 818 Billion Metric Tonnes of CO_2).

Comparisons

Purpose here is to calculate the area required to cancel out ppm's of CO_2, or tonnage of CO_2 emitted.

Note must only cancel out green house effect of **half** (46%) of the CO_2 emitted, as only that proportion stays in the atmosphere for a significant time. The other half (54%) goes into the oceans (and other natural sinks) and a separate effort is required to nullify the acidity effect in the oceans. (GCP)

1 Billion Metric Tonnes of CO_2 in atmosphere, forcing equivalent of 2.08 mW/m^2 requires 75,600 Km^2 of land with an albedo increase of 0.1 to counter it. (10,000 Km^2 of urban land can cool by 0.275mW/m^2 equivalent, so 2.08 / 0.275 = 7.56 times as much land needed). 818 Billion Metric Tonnes of CO_2 in atmosphere, with forcing equivalent of 1.7 W/m^2 requires 12,400,000 Km^2 of land with an albedo increase of 0.5. (= 818 x 75,600 /5) Note: total urban area usable: 5,100,000 Km^2.

Current emissions.

World average of (4.75 Tonnes CO_2/Year per person) x 0.46 = 2.19 Tonnes of CO_2 remaining in atmosphere, requires 33.1 m^2 of land painted to increase its albedo by +0.5, each year per person. (2.19 / 1,000,000,000) x (75,600 x 1,000,000 / 5)

What is the Limit of Mitigation Possible

Here it is estimated just how significant the cooling can be in context of the world development.

Total Urban area of 5,100,000 Km^2 with an albedo increase of 0.5 could produce a cooling effect of 0.7 W/m^2 (140 mW/m^2 x 5)
Enough to counter 337 Billion Metric Tonnes of CO_2 or = 43.3 ppm of CO_2 concentration, roughly reducing the net effective CO_2 concentration to 340 ppm.
(Cooling value of Albedo increase/Warming Effect of 1 Billion Metric Tonnes of CO_2, = 700 mW/m^2 / 2.08 mW/m^2 = 337 ratio.
Atmospheric Concentration = Total tonnage/tonnage for 1 ppm = 337 / 7.79 = 43.3 ppm.)

As atmospheric concentrations are increasing by about 2 ppm per year, this level of mitigation protects against about 20 years of CO_2 emissions. Further protection could be produced by use of increasing urban area over time and increasing the albedo change to beyond +0.5. Or by extending the usage of white greenhouse agriculture.

Costs

The cost of producing the paint for the surfaces that would not otherwise be painted is given a rough calculation. For this both a pound sterling cost and the extra CO_2 emissions cost.

What is the cost of the resources used to paint everything white? We already paint most stuff. Just now require it to be painted in a specific colour. Some extra resources will be used up on items that were not painted previously and on repainting some items sooner than they would otherwise be painted. The calculation in this paper will be for the whole cost of the painting.

Actual resources used in making the paints and applying it will be calculated on a per area basis so that it can be compared to the CO_2 warming prevented. Based on a standard area of 10,000 m^2 (1 hectare), the first calculation is to work out how much paint is needed.

Kilogram's of paint used: 15m^2/litre (Kg) on a smooth surface or 5m^2/litre (Kg) on a rough surface [source, instructions on can of paint]. At least 2 coats are required in practice. Use the average of the two different types of surfaces. 10m^2/Kg per coat with 2 coats = 5m^2/Kg. 10,000/5 = 2,000 Kg /Hectare = 2 Tonnes / Hectare. (Reapplying, 1 coat required, therefore half cost for maintenance)
[Information on paint: Manufacturer's instructions on can of paint] Here the simplifying assumption was made that a litre of paint weighs 1 Kilogram, it is in general denser than that, but not by a large amount.

Financial Calculation of Application

This section calculates the financial resources used to apply paint. By the method of spray painting, an application rate of 25m^2/hour on a rough surface for 1 coat is easily possible. 25m^2/hour on a smooth surface for 2 coats. 400 man-hours/hectare for smooth surfaces and 800 man hours/hectare for rough

surfaces. An average value of 600 man-hours/hectare will be used. This gives a 9,000£ wage cost per hectare at 15£/man-hour.
3£/Litre standard white paint = 6,000£ of paint/Hectare. The price of manufacturing and distribution is all included in shop retail price [Typical price for standard outdoor white paint, UK]. Wholesale prices will be about half of this.
Effective duration of paint = 10 years manufacturer's claim, extendable to 20 years in practice without significant deterioration in moderate climes, but possibly reduces to only 5 years in hostile climates.

Cost for kW hr of Cooling

Assume increased Albedo by 0.5 after allowing for geometry of reflections and complex environmental conditions rather than +0.8.
Planetary geometry and cloud cover will be factors that reduce effectiveness, 10.3 % average effectiveness will be the figure used, a poor figure as we cannot choose to select a particularly sunny area, we are fixed with urban areas (¼ planetary cross section to surface area ratio x 0.41 clear sky proportion = 0.103).
Solar constant x Albedo Increase x Average Effectiveness = 1,365 x 0.5 x 0.103 = 70.3 Watts/m^2 extra reflected back on average.
(Global average from 1% of this as that is the amount of urban area = +0.703 Watts/m^2, whereas the earlier Albedo calc for +0.8 albedo gave a value of 1.12 W/m^2. To directly compare that with the value calculated here: 1.12 x 0.5/0.8 = 0.70 W/m^2.)
Power reflected x Hours in Year = 70.3 x 8,766 = 616 kW hrs/Year-m^2 = Energy removed per year.
1 Hectare for 10 Years, reflects extra 61.6 Million kW hrs for 15,000£ outlay. 41 kW hrs per 1 pence (double cost effectiveness for extended duration maintenance). Approximately 1/500 of the cost of supplying electrical power to customers.

<u>CO_2 Calculation for Application</u>

Lifetime of extra CO_2 in atmosphere 100 Years based on deep ocean cycling and standard assumptions in the literature about green house gases. 1 Tonne of CO_2 for 100 years, blocks (2.08 mW / 1Billion) x 100 x 8,766 = 1.82 x10^{-6} WHr/m^2
(Calc: Radiation Effect for 1 Billion Tonnes x Number of Years x Hours per Year / by that Billion = Watt hrs per m^2 per Tonne)
The global total effect is then = W hr per m^2 per Tonne of CO_2 in atmosphere multiplied by surface area of the Earth.
= 1.82 x10^{-6} x 510 Million Km^2 x 1 Million m^2 per Km^2 = 930 x10^{+6} W Hrs
= 0.93 Million kW hrs per Tonne of CO_2 in atmosphere, per 2.17 Tonnes of CO_2 emitted. (46% of emission remains in atmosphere.)
1 Hectare protects vs 144 Tonnes of CO_2 total emissions by using 2 Tonnes of Paint.
(Total kW hr cooling of paint on 1 Hectare / Total kW hr heating of Tonne of CO_2 emitted = 61.6 Million / (0.93 Million x 0.46))
Therefore 1 Tonne of paint mitigates 72 Tonnes of CO_2 emissions.

<u>Resources Used in Making Titanium Dioxide Pigment, for Extra CO_2 Cost Calculation</u>

Here the calculation involves the physical resources used to make paint pigment TiO_2 and to estimate approximately the weight of CO_2 produced in the manufacture of TiO_2.
The materials that the firm Tiwest requires for each Tonne of Titanium Dioxide produced according to the Department of Resources Development are given in "Downstream Processing" June 1996. [http://www.chemlink.com.au/titanium.htm]
From this it is estimated that the process materials could release up to about 1.47 Tonnes of CO_2 per Tonne of Titanium Dioxide.
[Link to descriptions of sulfate and chloride based processes:
http://www.millenniumchem.com/Products+and+Services/Products+by+Type/Titanium+Dioxide+-+Paint+and+Coatings/r_TiO2+Fundamentals/Titanium+Dioxide+Manufacturing+Processes_EN.htm]
Electricity generation requires 1.53 MW Hr /Tonne. So 1.53 x 1.22 Tonnes of CO_2 per MW hr = 1.87 Tonnes of CO_2 per tonne of product. This gives a combined total of 1.47 + 1.87 = 3.34 Tonnes of CO_2 per Tonne of TiO_2, a high estimate.

Estimates for Various Components of Paint

Paint has many components, the main ones being pigment, binder and solvent.
Typically 33% of paint is actual pigment by weight. 0.33 x 3.34 = 1.1 Tonnes of CO_2 per 1 Tonnes of paint [15-60% range, Plant Engineers Handbook, section 34.2.2, 2002 Dennis A. Snow]. The Titanium Dioxide pigment is the most significant component of white paint with respect to energy usage and CO_2 emissions.

A water based white paint will clearly have limited CO_2 emissions due to the solvent. Emulsion paint solvent is mainly water with chemicals to mix in the binder and pigment into the water forming an emulsion. The CO_2 cost of this is small compared to the pigment and binder. This is because the solvent is mainly water and the chemicals used are small in quantity.

The Binder can be just 25-30% of mass of pigment. A pessimistic adjustment for the CO_2 cost of the binder is to add 30% to the total CO_2 cost, in direct proportion to the amount of binder relative to the pigment.

The total is then 1.43 Tonnes of CO_2 produced per 1 Tonne of paint.

Transportation Costs in CO_2

Transportation of paint is done by the cheapest most efficient means, like ships or rail, as it is a mass product with significant mass. So CO_2 emissions for transportation and distribution is only a small percentage of its mass. Companies do not air freight paint.

Example cost: 0.16 Kg of CO_2 emission per Tonne Kilometre for 40 Tonne trucks. Shipping is 1/10th of this value, as is rail.
[http://www.feasta.org/documents/energy/Aviation_background_briefing.PDF]

1 Tonne of paint shipped 10,000 Km and trucked 250 Km would produce emissions of 160 + 40 = 200 Kg of CO_2. 14% of manufacturing CO_2 cost. For these calculations 200 Kg of CO_2 will be added onto the CO_2 cost of 1 Tonne of paint.

Total Costs

Global financial cost will be Earth Surface Area x % Urban Area x Cost per Hectare / Duration of Paint = 510 Million Km^2 x 100 (Hectares per Km^2) x 0.01 x 15,000 / 10 = 765 Billion pounds per year.

Total of 7.65 Trillion pounds for a full 10 year process to paint all of the urban areas in the world for maximum effect. An average cost of 1,180£ per person across the whole world for the decade.

100 Years of application will cost (10 + 90/2) x 765 Billion pounds = 42.1 Trillion pounds.
Note: Stern Review mitigation costs estimate of 930 Billion Dollars per Year by 2050. [http://www.hm-treasury.gov.uk/sternreview_index.htm]

Net CO_2 benefit of 72 Tonnes per Tonne of paint for cost of 1.63 Tonnes of CO_2 per Tonne of paint. The ratio is then 72 / 1.63 = 44.2 Tonnes of CO_2 mitigation per Tonne of CO_2 used in manufacture and distribution of the paint. Sufficient margin to cope with minor errors in estimates and calculations.

Total production for 1% Earth surface area = 0.01 x 510 Million Km^2 x 100 (Hectares per Km^2) x 2 Tonnes/Hectare per 10 years.
=102 Million Tonnes a Year initially. Half this for maintenance. [Current Production of Titanium dioxide = 4 Million Tonnes a year.]

The CO_2 emissions cost of the paint over the 100 years will be 102 Million Tonnes x (10 + 90/2) x 1.63 = 9.14 Billion Tonnes of CO_2. (9.14 / 7.79) x 0.46 = +0.54 ppm addition of CO_2 to the atmosphere.
Cost of neutralizing 1 Tonne of CO_2 = (Cost of 1 Tonne of paint + Labour) / (CO_2 benefit - CO_2 cost, of 1 Tonne of paint) = (3,000 + 4,500) / (72 - 1.63) = 107£ / Tonne of CO_2.

One significant extra detail is that a lot of urban areas have sloping roofs and sides of buildings which increase the surface area required to be painted per hectare of ground. The overall area needed to be paint would be increased significantly by this. A first estimate would be to double amount of area that needs to be painted for calculations of cost but not effect.

Countering this extra cost will be the economies of scale reducing the unit price of white paint once new production facilities are built, and the replacement saving of not using other types of paint.

Minor Extra effects

For structures where more energy is spent on air conditioning than on heating, there will be a bonus having cooler housing with reduced air conditioning costs. Energy Efficiency Bonus, CRC Handbook of Energy Efficiency page 282.

White roads would need different coloured lane markings, not a problem, there exist paint which enhances grip that can be used for road surfaces. Matt white paint recommended to minimise glare and the need to wear sunglasses.

Black roads would help melt snow fall during daytime but risk refreezing and ice in mornings. Complex situation really: sometimes help, sometimes hinder - depending upon exact conditions. The UK relies on gritting with salt.

Housing in cold climates would benefit from black walls only if they were poorly insulated, so the detrimental effect of having white walls should be small. Benefit more from windows with shades or curtains for night-time. Effects of solar heating on housing is at a minimum in winter and at high latitudes (North and South) when it is most required.

Estimates here are simple and can be improved, especially those on the manufacture costs in CO_2 terms, but these were pessimistic.

No estimates on the effects of inflation is included, all monetary values are in constant 2008 pounds sterling or dollars.

Consequences

Changing of house colouring to more reflective shade will result in colder houses, especially significant in winter. Painting slate roofs white would be a good compromise as only the attics would then face a significant cooling and most attics are not inhabited but are (or can be) isolated from the main house by insulation. The roofs should be insulated in northern climes anyway.

The objective of this exercise is to create a colder planet with colder winters and this will have a detrimental effect on the vulnerable parts of northern populations. Which, despite having warmer winters, are becoming increasingly concerned about the effect of cold weather on the elderly.

Conclusions

Cooling effect from choosing paint colour to be white.
Significant enough to counter global warming for 2 decades.
Maximal cooling effect is 1.12 W/m^2 but unlikely to achieve this in practice.
Controllable and rapid application on global scale possible, but does require global application.
Urban areas only are chosen in order to have minimal effects on the natural world, equivalent to normal current activities.
The 42.1 Trillion Pounds cost for a full 100 year use is less than the value of hazards expected as mentioned in the Stern report, for which a value of around 4 Trillion Dollars per Year was estimated (or 1% of World GDP in 2100 AD, that being some 11x today's of around 35-40 Trillion dollars). However the Stern review costs are for the effects of several hundred extra ppm of CO_2 equiv. while this method of painting only mitigates about 40 ppm.
In practice the actual extra cost of implementation will be significantly less than that calculated here.

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This submission is a personal position.

MARTIN SHERMAN

To: the Royal Society's working group on geo-engineering schemes to mitigate climate change

from: Martin T. Sherman
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To the Royal Society's working group on geo-engineering schemes to mitigate climate change:

I am interested in having the RS assess my invention, **The Tidal Irrigation and Electrical System** (US Patent 6863028) which would fit into the section Greenhouse Gas Reduction Scheme, (a, ii) Methods utilising oceanic biological systems. The plan is a hybrid tidal barrage and OTEC system that utilises the lagoon of a tidal barrage to grow algae. This approach proposes to mitigate climate change by producing power in the terawatt range, generating the source material for bio diesel and by directly absorbing CO2 in a single, intensive process.

For a full flash based audiovisual presentation please go to: http://demo.seavac.org/

For a text based description of the technology and a blog on the surrounding issues please go to: http://www.seavac.org/

The website and demonstration are designed for the general public and will only take a few minutes to see the basic concept and a few minutes more to get some of the detail.

Invited feedback:
(I will limit my answers to my invention and the issues surrounding it)

1) Current state of knowledge regarding the feasibility efficacy and predicted impacts of climate geoengineering schemes:

To my mind the best thinking on tidal barrages can be found in "Enhancing Electrical Supply by Pumped Storage in Tidal Lagoons" by Dr. David J. C. MacKay http://www.inference.phy.cam.ac.uk/mackay/. The tidal barrage is the pump which moves the Deep Oceanic Water (DOW) and therefore its size dictates the power output of the system as well as its carbon capture and biomass potential.

The biomass potential of algae, and therefore its carbon uptake and bio-petroleum potential, can be found in numerous places. Much of this work focuses on maximising a given bioreactors potential through the search for, or the engineering of, a form of algae that most efficiently converts solar energy into and amasses lipids. The TIE System's bioreactor is open to the elements and therefore could never support a monoculture. Seeding of the DOW input to the Artificial Atoll would significantly increase the level of high lipid organisms but this decrease in efficiency can be more than compensated for because of the increase in efficiency as the system grows in size.

Algal schemes can be divided in to those that release a fertilising agent like iron into the ocean and those that attempt to grow algae for use. The effects of uncontained algal blooms and die offs due to open ocean fertilisation have been known to cause a wide range of deleterious effects from 'dead zones' (oxygen poor areas) to large scale releases of neurotoxins. Recently the United Nations has banned further trials of this technology until more detailed research in controlled conditions can be done. Algae schemes that attempt to farm these organisms in contained systems hope to use the biomass for food, fuel, fertiliser and the carbon capture potential. However, all schemes (as far as I know) other than the TIE System lose large amounts of power in pumping the water in which the algal plants live, around the system. Also, algal plants still require micronutrients and fertilising agents that must be introduced and refined by industrial production. Both the pumping of water and the source material (DOW) are supplied by tidal action in a TIE System. This means that as the tidal barrage grow in size, the system cost

decreases. Expressed as $\prod r^2$ multiplied by the tidal flux, the cylinder that is the artificial atoll of the tidal barrage is subject to the same principles as any circle or cylinder; namely that its volume increases out of proportion to its circumference as the object increases in size. So if a TIE System with a captureable tidal flux of 2m has a circumference of 6.28 km it would move 6,283,185 cubic meters of DOW. However, if the circumference was instead multiplied by ten (62.8 km), it would move 628,318,500 cubic meters of DOW. The increase of efficiency is obvious and significant. The quality of this increasing economy of scale is larger than any other scheme I have encountered.

A good overall study of current algal growth schemes can be found at:
http://www.physorg.com/news140013562.html

The other subsections of the invention are all detailed at www.seavac.org. Projections and outputs are to be found in the additionally provided material.

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

I would say that a great deal of 'green washing' (the practice of misrepresenting the efficacy and effects of various technological developments) has been perpetrated against the public by the private sector and governments. The uses of maize as a replacement for petrol and current carbon offset schemes are some of the grossest examples of green washing. Much greater scrutiny is called.

The type of research that should be undertaken should be that which brings our carbon use in to balance. For me, it is far preferable if this means replacing fossil fuels because a scheme that simply ameliorates the side effects of our current energy strategy would be like driving with your feet on the accelerator and the brake at the same time. Also, it is only a matter of time before even the most abundant fossil source, coal, is exhausted. It's better to break the addiction now.

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

The most important ability of any scheme is its ability to be switched off easily incase there is an unforeseen side effect. Simply opening the artificial atoll wall to the surrounding ocean would stop a TIE System from operating.

Again, deployment should be carefully monitored because the market is interested in making money and this can be at odds with actual reductions in greenhouse gases. For instance, the lagoon of the tidal barrage will need to be monitored for signs of eutrophication and excessive emissions of methane. It is pointless if all of the carbon dioxide capture that occurs due to absorption by the algae and all of the petroleum that is offset by the energy production of the TIE System, if the greenhouse effect is made worse due to methane emissions because of the biologic activity in the lagoon.

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

Certainly Canada and Russia stand to do well in post greenhouse world but it seems that most populations will suffer due to sea level rise, biodiversity loss and desertification. I think it is important to consider that we are currently engaging in geoengineering by the use of fossil fuels. The morality of this is not in question so the moral question becomes a cost/benefit analysis. If, for instance, the net balance of humanity would have larger harvests and more comfortable weather, would it be moral to 'interfere' with global temperature rises?

The poorest of this world and wildlife stand to suffer the greatest effects and this leaves the moral imperative on those with the ability to do something, the West, to form and implement a strategy to halt climate change. As an institution of our culture it would need to reflect other institutions for common good with checks and balances to safeguard against corruption, especially as this will involve vast sums of money.

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

The Tidal Irrigation and Electrical System could meet much of the world's demands for electricity and bio-fuel but it does have several obstacles to overcome first. With good reason, it has been considered, by some, pure hubris to build large structures on the mid to near continental shelf, especially in the tropics. Forces of approximately 100 tons per square inch are exerted by the largest waves during the biggest storms. There are numerous examples but the destruction of the Mulberry Harbours of WWII is the classic example of wave/storm damage.

The land regularly overcomes these vast wave forces. Either the shore is soft and the ocean next to it deepens very gradually and the waves lose their energy that way or the shore can be hard and then the ocean can become deep quickly and waves smash themselves against the rocks. I, as the inventor, do not suggest which strategy is best for the TIE System to mimic. It will depend too much on local conditions and cost/benefit analysis to know whether a low inclined "barrier island" approach or a hard wall-like structure or a combination will work best.

The other barrier to the implementation of the TIE System on a world scale is that the best places to build it are in the tropics and this does not fit in with the desire of many nations to be energy self-sufficient within their own borders. This makes sense on a national security level but it remains to be seen if it is possible let alone economically efficient to meet the demands for energy of industry, transport and commercial and domestic residences with the available renewable resources.

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?

Ultimately there will need to be some sort of technological fix. The energy to supply fuel for transport, industry and the rest while still supplying fertiliser, water and food to sustain even current human populations will be difficult to meet without using fossil fuels. Yet we must eventually wean ourselves from them. Climate effects aside (and that's a big aside) they will run out and then we must find a way to power our society.

I think that any project that has a linear increase in scalability of production is doomed to fail. For example, if the total energy budget of a wind turbine is 1000 barrels worth of oil (to manufacture, install and maintain the wind turbine over its lifetime. (This is just an example not accurate figures)) and the average wind turbine generates 1500 barrels of oil of energy before it needs to be replaced then it will take many, many more wind turbines than are necessary for regular consumption to keep pace with the need for replacement. Almost all renewable energy power generation and carbon capture schemes suffer from linear increases of scalability.

As previously stated tidal barrages and therefore the TIE System beats the linear increase in scalability by the simplified equation; Πr^2 multiplied by the tidal flux.

7) Other issues?

Methane, energy storage, land use, filtration methods, electrical infrastructure, wind and wave power are all discussed in detail at www.seavac.org

PROFESSOR KEITH SHINE FRS

Submission to the Royal Society Study on Geoengineering from the Department of Meteorology, University of Reading[1]

10 December 2008

1. Introduction

The Department of Meteorology has a broad range of expertise in aerosol and cloud physics, climate dynamics (in both the troposphere and stratosphere) and radiative forcing of climate change. While it has no research directed specifically to geo-engineering, much of its research is nevertheless very relevant.

We restrict our comments largely to the albedo modification schemes (henceforth AMS). We also avoid comments on the political, ethical, financial or technological feasibility of any proposed schemes, again because this is beyond our expertise.

Our overall conclusion is that the current state of knowledge is such that we could not, even within quite wide bounds, predict the outcome of any large-scale geoengineering experiment with any confidence. This does not preclude, though, the possibility that small-scale experiments could be performed, which could inform our understanding of wider climate issues as well as specifically informing geoengineering.

In our discussions during the preparation of this document, we also considered the question: "if not now, when?". Although we would expect significant advances in climate models over the coming decades which undoubtedly would lead to increased confidence, we note that there are many chronic uncertainties in climate change science; most notably, in the context of this report, is the continued uncertainty in the value of the climate sensitivity parameter (henceforth λ), that measures the response of the global-mean surface temperature to a unit radiative forcing (either reported in K $(Wm^{-2})^{-1}$ or as the equilibrium warming for a doubling of CO_2 concentrations (in K)). There has been no significant narrowing of the range of uncertainty of λ over the past 30 years (traditionally given as about 0.4 to 1.2 K $(Wm^{-2})^{-1}$), and indeed recent work (reviewed in detail in the 4th Physical Science Assessment of the Intergovernmental Panel on Climate Change – henceforth AR4) has even been unable to preclude significantly higher values for λ.

2. Current state of knowledge relevant to albedo modification schemes

2.1 The long lifetime of CO_2: It is well established that pulses of CO_2 emitted into the atmosphere have very long lifetimes – it is estimated that around 40% of any pulse emitted into the atmosphere will remain in the atmosphere for periods exceeding 1000 years. Final recovery in fact takes place on the order of hundreds of thousands of years. This in itself already calls into question any geoengineering scheme. As Archer and Brovkin (*Climatic Change,* 90:283-297, 2008) point out, a sudden halt in any artificial cooling could lead to a sudden large increase in surface temperature from the accumulated CO_2 emissions. Hence, notwithstanding complications that may be identified in other submissions to the Royal Society study, we would *a priori* consider that any geoengineering technique which removed CO_2 from the atmosphere to be more desirable than AMSs.

2.2 A question of balance: AMSs are often posed in terms of balancing radiative forcing due to CO_2 and hence implicitly on balancing global-mean surface temperature. Of course, the climate system is multivariate and balancing global-mean temperatures does not ensure balance of any other climate variable. One important example of this is the fact that CO_2 leads to a surface and tropospheric warming but a stratospheric *cooling*. Most AMSs would at best only balance surface and tropospheric temperatures, and seem likely to leave a strong unbalanced stratospheric cooling, with consequences for ozone chemistry, stratospheric dynamics (which has the potential to influence surface temperature – see

[1] The following contributed to this report: Andrew Charlton-Perez, Lesley Gray, Eleanor Highwood, Giles Harrison, Anthony Illingworth, Manoj Joshi, Keith Shine, Nicola Stuber, Rowan Sutton. Correspondence can be addressed to Keith Shine (k.p.shine@reading.ac.uk) in the first instance. The opinions expressed here are those of the authors rather than the institution.

later) and possibly also stratospheric water vapour concentrations (also see later). Figure 1 shows recent work by Stuber *et al*. (submitted to *Climate Dynamics*, manuscript available on request) in which idealised globally-uniform aerosol layers were imposed on a slab-ocean version of the Hadley Centre climate model. The left panel shows that while, in the model at least, tropospheric aerosols which completely scatter at solar wavelengths (sulphates approximate to this behaviour) could be used to balance (global-mean) tropospheric warming, it would lead to a large unbalanced cooling in the stratosphere. (The right panel illustrates and warns that the situation is *much* more complicated if absorbing aerosols (such as soot) were used; because of impacts on cloud amount and stratospheric water vapour amounts, even the sign of the surface temperature change varies as the height of the aerosol layer is altered – these results are also likely to be very model dependent.)

A further illustration of the difficulty of balance is shown in Figure 2 (from Shine et al., 2005). Depending on the geographical distribution of the forcing, a global-mean balance of surface temperatures could be achieved which would still lead to strong residual warmings and coolings in the individual hemispheres.

Finally, other important climate parameters would be difficult to balance – for example, it is now well established in climate modelling experiments, that the relationship between global-mean surface temperature change and global-mean precipitation change varies between different climate forcing mechanisms (e.g. AR4; Lohmann and Feichter (2005)). The land/sea contrast in surface climate response is also dependent on the nature of the climate forcing imposed (Joshi and Gregory, *Geophys. Res. Lett.,* In Press, 2008).

An increase in CO_2 concentration can cause "indirect" impacts on land surface temperature, which are unlikely to be balanced by an AMS, for two reasons. Firstly, modelling studies indicate that stomatal closure associated with elevated CO_2 reduces plant transpiration, causes an increase in land surface temperature (e.g.: Betts *et al.,* 1997). Secondly, models also indicate that an increase in CO_2 reduces tropospheric clear-sky long wave cooling, which leads to a reduction in precipitation (e.g.: Lambert and Webb, 2008), which further warms and dries the land surface. Additionally, as is well established, CO_2 increases leads to an acidification of the ocean which again will not be compensated for by an AMS.

2.3 Radiative forcing and climate efficacy: We note briefly, as it is well established, that the radiative forcing associated with the cloud albedo effect, which is at the heart of some of the proposed AMSs, is highly uncertain – AR4 gives a range of -0.4 to -1.1 Wm^{-2} for the change relative to pre-industrial times. This uncertainty is small compared to that associated with the so-called cloud lifetime effect, for which AR4 does not even provide an estimate – indeed, a talk by Jean-Luc Brenguier at the NERC Appraise 2008 Annual Meeting[2] raised considerable doubts as to whether we can predict even the *sign* of this forcing from models or field experiments because the links between aerosol and cloud optical thickness or liquid water path cannot be considered separately from the numerous dynamical feedbacks which are likely to counterbalance the expected changes.

An additional uncertainty is that even if a geoengineering scheme could deliver a known radiative forcing, it is now becoming established that the so-called *efficacy* of a radiative forcing varies between climate change mechanisms – efficacy measures the ratio of λ for a given mechanism to the value of λ for a doubling of CO_2. As discussed in AR4 Section 2.8.5 (see especially Figure 2.19), understanding of efficacy is still in its infancy, and the spread of model results for the cloud albedo effect is particularly large.

To summarise, we believe that balancing RF would almost certainly not lead to a balancing of temperature change, even at the global-mean level.

2.4 Cloud albedo modification schemes: Salter *et al.* (2008) describe a strategy to inject a large number of cloud condensation nuclei (CCN) into the atmosphere beneath marine stratocumulus clouds; these extra CCN modify the clouds so that the droplets become smaller but are present in higher concentrations, leading to an increased cloud albedo.[3]

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[2] See also www.jamstec.go.jp/frsgc/whatsnew/2005/0617/pdf/abstract/6_5.pdf

[3] They envisage a fleet of wind-driven 300 ton boats, each pumping 30 kgs^{-1} of sea water into the atmosphere through nozzles to form a spray of 0.8 m diameter droplets at 20m above the sea surface. These droplets then evaporate, each forming a NaCl particle CCN of diameter 0.25 m at a rate of 1.12×10^{17} per second. Salter *et al.* suggest that, in two hours, turbulence would disperse them through a 1km deep boundary layer, and so, assuming

Several aspects warrant further investigation before the feasibility of any such scheme can be properly assessed:

a) Would turbulence really disperse the CCN uniformly through such a large volume? To support the idea that artificially introduced CCN can modify clouds, Salter *et al.* appeal to satellite images of 'ship tracks' or narrow filaments of bright cloud several hundred km long, forming above the exhausts from ships engines. However the very persistence of such narrow filaments suggests inefficient dispersion of CCN.

b) Another suggestion (Latham *et al.*, 2008) is to use droplet charging to produce vertical transport in the permanent global atmospheric electric field. Droplet charging is almost certain to occur in the atomization process, but, as well as facilitating transport of small droplets (in the vertically directed fair weather field of $120Vm^{-1}$, a unit density 0.25 m diameter droplet requires only ~4 electronic charges for the electrical force exerted to equal its weight), any appreciable droplet charging would lead to high electric fields which could also modify the droplet size distributions obtained.

c) The calculations depend critically on the assumed CCN lifetime.

d) How does the flux of particles produced by the spray compare with that produced by natural whitecapping of waves? If the spray nozzles produce $1.12x10^{17}$ drops per second which are dispersed over an area of $7.72x10^{10}$ m^2, then the average flux of spray droplets is $1.5x10^6$ m^{-2} s^{-1}. Norris et al (2007) report a very similar value for the natural flux of sea spray when the wind speed is 10 ms^{-1}; such wind speeds occur over large areas of the oceans making the flux from the nozzles seem very small in comparison.

Note also that there are only a rather limited number of regions of the Earth where such schemes could be implemented. This will have consequences for the geographical pattern of forcing produced. Nevertheless we note that small-scale experiments would likely have inherently little risk and we see no reason to discourage them (on scientific grounds at least), as they would add to our knowledge more generally of cloud-aerosol interactions.

We think it is worth reflecting that even after more than 50 years of weather modification attempts, by injecting various substances into clouds for example to induce rain or to suppress hail, the success or otherwise of these schemes remains a subject of controversy – there has been difficulty in clearly establishing a cause-effect relationship. In view of the many complexities of aerosol-cloud interactions, it may prove similarly difficult to establish the veracity of claims of such AMSs and innovative ideas are likely to be needed to do so.

Unlike some other aerosol types, sea-salt is also capable of substantially affecting radiation at near - infrared wavelengths, its extinction peak continuing out to 4 μm microns (compared to extinction by sulphates which mostly falls below 2 μm micron). The effect of any absorption of radiation by sea salt has not yet been well studied (see e.g. Irshad *et al.*, 2008), but as noted in Section 2.2, the response of the climate to aerosol absorption is likely to be complex, and any predictions are likely to be very model dependent.

Another factor that would need to be examined is whether the dispersion of large quantities of sea-salt into the atmosphere could lead to ecologically damaging deposition away from the immediate source, although the above estimates indicate that this source is likely to be negligible compare to natural whitecapping.

2.5 Stratosphere-based AMSs: Geoengineering by introducing large amounts of sulphur dioxide to the stratosphere has recently received a great deal of attention in the literature (e.g. Crutzen (2006), Wigley (2006)). This method is an obvious starting point for discussions of potential geoengineering approaches,

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the lifetime of a CCN is one day, they conclude that a single boat would be able to fill a volume of atmosphere 1km deep and of area $7.72x10^{10}$ m^2 (~ 280 by 280km) with $9.67x10^{21}$ nuclei, or about 125 per cc. They argue that the spray would increase the cloud droplet concentration from 65 per cc in a pristine atmosphere to 190 per cc. If the cloud had a liquid water content of $0.3gm^{-3}$ and a depth of 300 m, the albedo would be increased from 0.49 to 0.58. For a mean solar input of $340Wm^{-2}$ the reflected flux density would increase by $30Wm^{-2}$.

since a natural analogue exists in the recorded major eruptions of tropical volcanoes; the global temperature response has been both measured and successfully predicted. The most well studied of these events, the 1991 eruption of Mount Pinatubo, had a measurable effect on both stratospheric and tropospheric climate, causing a cooling of up to 0.5 K in surface temperatures following the eruption, with effects lasting up to 2 years after the eruption (see for example Robock (2002), Soden *et al.* (2002), Stenchikov *et al.* (2004)).

Studies of geoengineering by stratospheric aerosol enhancement have largely used similar methods to those used to study the Pinatubo eruption. Mostly these take the form of running climate models of various complexities with a specified aerosol loading in order to calculate the global-mean and local climate responses (e.g. Matthews and Caldeira (2007), Rasch *et al.* (2008), Robock *et al.* (2008)). The broad consensus of such studies is that large loadings of sulphate aerosol would be able to offset CO_2-induced global surface temperature rises (for example the Robock *et al.* study suggests that an equivalent 5 Mt yr^{-1} tropical aerosol forcing would fix global temperature rise at values 0.1-0.2 K above pre-industrial levels).

However, as is expected, the studies differ substantially on their predictions of the regional consequences for dynamical feedbacks to such a scheme. It is expected that only by fully accounting for inter-model differences with a large ensemble of climate models, could robust regional signals be identified.

Additionally, there are potentially some systematic problems with this approach. Firstly, many of the models used to study stratospheric AMSs include only a rudimentary representation of stratospheric dynamical processes. Recent work has shown that changes to stratospheric variability (for example induced by ozone depletion in the southern hemisphere) have the potential to produce significant changes to the tropospheric circulation through dynamical feedbacks (e.g. Baldwin *et al.* (2003), Gillett and Thompson (2003), Joshi *et al.* (2006), Scaife *et al.* (2005)). Son *et al.* (2008) showed that models with a rudimentary representation of the stratosphere and models with a more complex representation of the stratosphere produced tropospheric trends of differing sign in response to future ozone recovery in the Antarctic stratosphere. It therefore seems clear that in order to produce an accurate simulation of the tropospheric response to a stratospheric AMS, studies should first explore and establish the response of the stratospheric climate and circulation to such schemes.

Secondly, the introduction of stratospheric aerosol has the potential to significantly influence ozone depletion in the polar stratosphere. Over the next 50 years, ozone depletion is expected to become progressively weaker as the amount of reactive halogen species in the stratosphere is reduced, leading to eventual recovery to pre-1980s levels by around 2050 (Bodeker and Waugh, 2006). The addition of sulphate aerosols provides additional surfaces for the activation of chlorine compounds from their relatively stable reservoir species, greatly increasing the efficiency of ozone depletion in cold stratospheric seasons (Tilmes *et al.,* 2008). This would both delay the recovery of ozone in the Antarctic and increase ozone depletion during cold winters in the Arctic. There are also numerous possible feedbacks between ozone depletion, polar stratospheric temperatures and their variability which have not been fully explored in a modelling context.

The addition of significant amounts of aerosol to the lower stratosphere is likely to increase the temperature of this region, leading to an increase in stratospheric water vapour (e.g. Joshi and Shine 2003). Changes of this nature would perturb the surface climate both globally (Forster and Shine 1999) and regionally (Joshi *et al.* 2006), in addition to the other feedbacks described above. Additional ozone depletion might also be expected to occur as a result of stratospheric moistening (Stenke and Grewe 2005).

A final unknown is the impact that an additional natural aerosol loading from an, essentially unpredictable, large tropical volcanic eruption would have on a stratosphere with an already heavy aerosol loading.

The topic of "top of atmosphere" albedo modification has been reviewed and modelled elsewhere (Lunt et al 2008). We note that as stated by the authors, even with a global cancellation of positive CO_2-induced forcing and negative albedo forcing, significant regional responses in temperature and precipitation still occur, as is the case with other mechanisms described above.

3. Future research in geo-engineering

Compared to other priorities in climate research in both the basic science (e.g. in radiative forcing, global and regional scale climate change, carbon cycle feedbacks) and in the science relating to impacts and adaptation and more conventional forms of emission mitigation, we do not regard geoengineering science to be a high priority. We would be deeply concerned if there were any significant diversion of resource from these other areas.

If mitigation of climate change is to be undertaken, we would regard the prevention of emissions into the atmosphere in the first place to be inherently more desirable and less risky, at least from an atmospheric science point of view – we suggest that further work on geo-engineering should be modest in comparison, and be viewed as a form of "insurance policy".

Nevertheless, future research in geoengineering is likely to have benefits for the wider understanding of the climate system – indeed, any proposed research in the area of geoengineering ought to be encouraged to state these wider benefits. A modest targeted programme could be instituted by NERC and/or DEFRA/DECC, or else geoengineering could be considered "in scope" for new thematic programmes or research council responsive-mode programmes. In that case, any proposals could be judged on their inherent scientific merits.

Finally we note that while "back-of-the-envelope" climate modelling techniques may be attractive in any initial assessment of geoengineering techniques, these should never be regarded as a replacement for detailed study, using state-of-the-art techniques, to fully assess any consequences, should implementation ever be seriously considered.

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DENIS SKEET

Dear sirs,
I have just caught up with the fact on our National Radio that The Society has been calling for suggestions to counter global warming so these may be considered by a team of specialists in each area.
One I would like to throw into the ring is to utilise all the waste plastic that accumulates around the world, to be moulded into hollow rafts of a square or hexagonal shape with a reflective upper surface, linked to each other with a loose rather than rigid connection to allow movement on the surface of the sea. These obviously are to replace our disappearing ice shelves and reflect sunlight off the surface of the sea.
Such rafts could be manufactured in any country that has the technical capability using a common mould so they could be linked together regardless of their source. They would probably need to be tethered to a land mass along one side and maybe also tethered at their seaward boundary as well. As more rafts were manufactured they could just be added. If such rafts were to eventually cover large areas of the sea, in arctic/antarctic regions it would require that an occasional raft be left out to provide entrance/exit holes for seals, polar bears, walrusses etc. etc.
Such rafts should be made to as large a size as possible to enable various life forms to clamber out onto their surface without sinking them.
This project would need to be an ongoing international event supported by governments to oversee the manufacture, transport and instillation of the rafts as although we have already lost a considerable area of ice, over a long period of time we may be able to reclaim that area and this may assist in reducing sea temperatures.

Yours Sincerely,
Denis Skeet
denskee@xtra.co.nz

BRIAN SPIEGELHALTER

Submission to Royal Society on Geoengineering Climate

From Brian Spiegelhalter – Climate Engineering Consultant

This submission is based on a report that was produced by the author for a major UK engineering company in 2007/8 which in turn was based on his MSc dissertation – 'Climate Engineering: An investigation into the management of net solar radiation to mitigate climate change.' (Spiegelhalter (2006))

Summary
From this work, the key issues concerning geoengineering today are:

- Geoengineering should be given proper consideration to complement CO_2 reduction programmes or to buy time until atmospheric CO_2 can be reduced
- Geoengineering proposals have in general been viewed with considerable reservation and scepticism by the majority of the scientific community.
- Research into Geoengineering should now be given the status and funding equal to that given to current climate change research.
- All of the Albedo Modification proposals could have major climate implications.
- No experimentation or implementation should take place until extensive research has been carried out
- Experimentation and Implementation should only proceed under the auspices of a worldwide authoritative body such as the UN.

Structure of Submission
The current geoengineering proposals are briefly reviewed with the risks and practicalities highlighted. Some conclusions are drawn and finally answers are given for the specific questions posed by the Royal Society.

Review of Geoengineering Proposals

1) Greenhouse gas reduction schemes

a)ii) Methods utilising oceanic biological systems - Ocean Fertilisation.
It is proposed that phytoplankton productivity could be stimulated by fertilisation with micronutrient iron so that photosynthesis would be increased. The absorption of CO_2 would therefore increase and so reduce CO_2 in the atmosphere. (Blain(2007))

Risks: unknown continuing effectiveness and its impact on the oceanic ecosystem.
Practicalities: the scale of iron fertilisation needed to balance the increase in anthropogenic CO_2 would not be feasible.

2) Albedo modification (shortwave reflection/definition) schemes

a.k.a. Net Solar Radiation Management.
It is estimated that a doubling of CO_2 in the atmosphere is to a certain extent equivalent to an increase of the average radiation received at the top of the atmosphere of approx 3.7 Wm^{-2} and so there is a supposition that if a reduction of radiation by this amount could be deliberately engineered then the warming effect of CO_2 could be balanced.

a) Surface-based schemes
The proposals involve the amplification of the terrestrial albedo (reflectivity) including the 'whitening' of human settlements, increasing the surface albedo of grasslands by the selective use of more reflective plants and the placing of reflecting surfaces in deserts.
Risks: Disruption of weather patterns
Practicalities: The management of very large areas of land has considerable geopolitical consequences. The schemes could not be scaled to have a significant effect on global warming.

b) Troposphere-based schemes

In this scheme, the production of aerosols in the troposphere is stimulated such that they act as cloud concentration nuclei (CCN) in low level clouds thereby increasing the amount and longevity of these clouds. As low level clouds reflect incoming solar radiation, this would have an overall cooling effect. The proposal is to increase the CCN by the production of sea-water droplets using droplet disseminators on floating rafts in areas where maritime stratocumulus cloud is common. (Latham (2002), Salter and Latham (2007))
Risks: low environmental impact as it is proposed that the aerosol generators are powered by solar and/or wave motion and the ingredients consist of seawater and air. There is great uncertainty over to what extent the formation of low-level clouds is CCN limited and the radiative impact that increased numbers would have.
Practicality: Approx 40 m^3/s of water would need to be sprayed as small particles over approx 20-30 $x10^6$ km^2 of ocean using about 50 vessels costing a few million pounds each. The technology is unproven and the scalability is doubtful.

c) Upper atmosphere schemes.
This scheme emulates the impact on climate of volcanoes by the injection of artificial sulphate particles into the stratosphere in order scatter solar radiation. Estimates suggest $2.5x10^9$ kg of sulphur, deployed as sulphate particles, would be needed per year with a cost of over $50bn/yr. (Cruzan (2006), Rasch et al (2008),
Risks: an increase in acid rain as the aerosol returns to the surface; the impact on stratospheric chemistry e.g. ozone depletion; and the possible impact on climate due to seasonal and regional imbalances in the cancellation of the radiative effect of greenhouse gases.
Practicalities: The sulphate aerosols would need to be positioned in the tropics at a height of approx 25kms above the surface in order for the aerosol to be distributed globally by the stratospheric circulation. If the aerosol were to be injected at lower levels then the residency time would be short and effectiveness for solar radiation management low.

d) Space based schemes
A device would be deployed in space to block or refract the incoming solar radiation. A very thin screen would be placed at the point in space (approximately 1.5 x 10^6 km from earth) where a body remains in the same position relative to the sun and earth due to the balance of opposing forces. This screen would need to have an area of nearly 5 million square kilometres and is likely to have a mass of approx 20 million tons. (Angel (2006))
Risks: failure in control systems could lead to an inability to maintain or modify the area of the shield. There would be returning space debris.
Practicalities: it would be very expensive and the technology is as yet unproven.

Conclusions
All the solar management proposals could have major climate implications as the cancellation of the impact of the enhanced greenhouse gases would occur only in the average radiation budget for Earth. However initial modelling studies indicate that even on a regional and seasonal basis, the effect of the warming due to the increase of greenhouse gases and the cooling due to the management of solar radiation appear to balance. (Govindasamy and Caldeira (2000))

Although the warming effect, due to the increase of CO_2, could possibly be mitigated by the deployment of solar management schemes, the amount of CO_2 in the atmosphere would still increase. A major impact of this would be that the oceans would become more acidic which would adversely impact marine organisms and ecosystems.

Although geoengineering has been regarded with some scepticism by the majority of the scientific community, there may come a time when despite the many economic and political issues, net solar radiation management programmes and, in particular stratospheric aerosol injection, may need to be considered to complement CO_2 reduction programmes or to buy time until atmospheric CO_2 can be reduced. However, before even limited implementation can be considered, extensive research and modelling of the geoengineering proposals need to be undertaken.

Geoengineering solutions to global warming create major political and ethical issues as the ability to control climate and the consequential probable regional environmental changes, have significant social and economic impacts. Individual countries or businesses may decide to implement schemes for their

own benefit but to the detriment of others and so, assuming continued scientific research, open discussion is also necessary to determine, internationally, if and when geoengineering solutions should be deployed and how they should be controlled.

Royal Society questions

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

Very low levels of knowledge at present but encouraged that work is being undertaken so that discussion of geoengineering can be put on a rational basis.
It is only in the last few years that the topic has become an acceptable area for research by mainstream meteorologists and climatologists. Therefore the level of knowledge is only just beginning to move from prejudice to peer reviewed science.

2. How do you think research into climate geoengineering should be taken forward and by whom?
Research should become mainstream using the best available climate models and should be funded as any other climate study. After all it may be better to spend research funds on finding a potential warming mitigation scheme than on proving warming exists.
It should become part of the academic climate studies and so become a legitimate PhD subject.
A more structured approach to research should be taken as proposed by Cicerone (Cicerone (2006)) but it is likely that this would come naturally if enough of the traditional climate centres took this on board.

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

Factors: Risks
Impact of climate and weather systems as compared with doing nothing including regional and seasonal implications. E.g. Monsoon and droughts
Environmental impacts.
Impact on Biochemistry (Land ecosystems and Ocean pH)
Influence on hydrologic cycle
Controllability
Impact of system failure
Reversibility
How quickly the system could be shut down
Time to return to normal.
Chemical stability. Impact on ozone depletion and UV

Factors: Practicalities
Cost
Timescales: How long until it can be deployed
Effectiveness of geo agent: how good is it
Quantity of geo agent to be deployed
Efficiency of agent – where to deploy, how long will it stay, how will it move
Scale – could it make a significant difference
How would the geo agent be deployed
Maturity of the technology

Responsibility for deployment should lie with the UN but their record to date is poor but at the moment there is not a viable alternative.

4. What do you consider to be the most important political, social, legal or ethical issues raised by climate geoengineering?
Who should control
Who compensates those who suffer – there are bound to be winners and losers and these will be different from the winners and losers of anthropomorphic global warming.

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

The major opportunity is that it might just work and be less worse than doing nothing.
The biggest barrier to geoengineering research is prejudice by the purists who only see a CO_2 reduction solution to global warming even if it is unlikely to happen.

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.
Right alongside.

7. Are there any issues related to climate geoengineering that you consider to be important.
Properly funded research looking at all aspects of geoengineering as a legitimate academic subject so that some of the more extreme schemes that have been proposed can be reviewed in advance of any proposed deployment cf. Planktos.
Even if the research only shows that geoengineering will not work, it will be worth it to put off some of the commercial schemes now being proposed.

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7th December 2008

RAY TAYLOR

Hi Andrew

Thanks for talking on the phone on Wednesday

In a separate email I'm sending the science dossier.

Please let me know if you haven't received this.
(I'm sending it separately in case it's too big for your inbox size limit for attachments.)

This is not my formal submission but I'd be grateful for some advice:
1. Would it be possible/viable/good for all members of the panel to have a copy of the dossier which I'm copying to you in 5 mins?
(It contains references to 112 peer-reviewed publications, extracts from some of them, nice illustrations and full copies of 5 key articles. It's roughy the size of the Radio Times when printed with the key articles.)
I would want to submit references to or copies of more recent articles also.

2. How important is it to have an estimate of the W/m2 ?

(Is this W/m2 averaged out globally, or for a sample region where it is being applied?

Is it over 12 months for projects where there is seasonal variation?

I'm not clear if it should be W/m2 for a single intervention, or W/m2 realistically achievable within ?10 ?50 years or W/m2 achievable within combined GDP of UK/USA/China?or W/m2)

In our case the answer may be: "W/m2 depends on size of land area in the initiative and quality of implementation work and effectiveness of tandem projects over cities, roads,seas and oceans."

Would they be happy with a guestimate based on maximum theoretically achievable? And will they take a guess from anyone? a PhD student? Only professors at large universities? Do they expect detailed justification of the figure in a 4page document? Will they weigh against limited W/m2 "definiteness" factors such as low level of disbenefits, high level of positive side effects and contribution to resilience and adaptation?

Thankyou

Ray

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December 8, 2008

We address one proposed Geo-engineering scheme:

Injection of sulfate particles in the tropical stratosphere, the lowermost stratosphere or the Arctic lower stratosphere.

Expected impact of the on the Earth's climate:
Continuous injections of sulfur particles into the tropical stratosphere enhance the stratospheric aerosol layer across the globe that reflects sunlight. The increasing albedo results in a cooling of the Earth's surface and, therefore, counteracts global warming. The desired response is to slow down or stop the melting of the Greenland ice sheet to prevent sea level rise. Other, similar schemes propose to inject particles in the lowermost stratosphere, or only over the Arctic to produce local cooling above high northern latitudes.
The global scheme:
Feasibility:
Climate geoengineering schemes may be feasible after a large effort of engineering development. Engineering tools are not developed at present. Sulfur needs to be transported up to ~20-25 km into the lower tropical stratosphere to result in a global distribution of particles. Balloon or missiles could be used to transport sulfur in the form of H_2S into the lower tropical stratosphere above 20 km. However, no agreement exists in the literature about the amount of the sulfur injection needed to cool the climate to specific value. Further, the particle size distribution of aerosol particles that will result from an injection of H_2S is unknown for any injection scheme (e.g., Rasch et al.,2008). Different aerosol sizes can affect stratospheric chemistry differently (Tilmes et al., 2008a).

Desired effects:
Cooling of the global climate to a specific temperature. Prevent sea level rise due to the melting of the Greenland Ice sheets. Prevent disruption of local culture and wildlife in high Northern latitudes.

Possible unpleasant side effects:
The reduction of temperature increase is globally possible; however, several studies have indicated local temperatures changes, and changes in precipitation patterns, e.g., a decrease of precipitation in the Tropics as a result of radiative cooling the Earth's climate (Robock et al., 2008, Rasch et al., 2008, Tilmes et al.,2008b).
The impact of large aerosol particles on stratospheric chemistry globally is rather small and will likely not result in catastrophic changes (Tilmes et al., 2008b). However, the potential for very large ozone depletion in winter and spring in high northern latitudes exists, especially in the next 20 years. Also, the recovery of the Antarctic ozone hole will be delayed (Tilmes et al., 2008a). The use of smaller particles might have an even larger impact.
A ramp-up of the stratospheric aerosol amount (Wigley et al., 2007) might result in a smaller effect on the ozone layer before 2050 than described in Tilmes et al. 2008a,b, and Arctic ozone depletion may not be much larger than at present, but such a scheme possibly extends the occurrence of large ozone depletion events beyond 2050 and delays the recovery of the Antarctic ozone hole by 30-70 years.
Another likely side effect is the impact of more diffuse sunlight reaching the Earth's surface in the case of geo-engineering on humans and plants. The long-term effect of albedo reduction on ocean and land biota is unknown.
Any successful geo-engineering scheme that works by increasing albedo will, if stopped, lead to a rapid re-warming of the Earth's temperature, because the climate system will be farther out of equilibrium than when the scheme was put in place. In addition, all schemes that do not attack the basic problem of emission of CO_2 will produce a dependence on continuation of the scheme if warming is to be avoided (while not preventing other undesirable consequences of CO_2 increase, such as ocean acidification).

Unknown side effects:

The impact of an increasing potential for an Arctic ozone hole and the resulting increase in UV radiation on the biosphere is not known. Further, large local deposition of sulfur particles and acid precipitation in high latitudes ore in mid-laitudes due to UTLS exchange processes might occur.
Effectiveness with regard to ongoing melting of Greenland ice sheets is unknown. No advanced sea-ice models exist thus far to estimate the impact of a possible cooling on Greenland ice sheets and the interactions with the atmosphere.
For the Arctic sulfur seeding approach, changes of atmospheric dynamics and regional climate due to local cooling are unknown. The Arctic seeding might result in a particle size distribution that includes smaller (younger) aerosols in the lower polar stratosphere. A larger impact on polar ozone chemistry is possible. As in the case of global enhancement of the aerosol layer, the impact of local deposition in the Arctic is unknown, and the possibility of acid precipitation cannot be ruled out.
Finally, experiments in a coupled model framework indicate that proposed geo-engineering schemes such as injection of sulfur into the stratosphere may be able to mitigate global averaged warming, but may not eliminate climate changes. There are good physical reasons for this, as heat is absorbed differently in the atmosphere due to geoengineering, as well as due to CO_2 present in the atmosphere. Thus this proposal does imply regional climate changes.

Not addressed with this scheme:
Increase of extreme weather phenomena in local areas, increasing ocean acidification, local changes in areas of droughts and flooding.
More frequent extreme weather phenomena are a result of increasing global temperatures due to greenhouse gas increases. Geoengineering will reduce the global temperature, but may not stabilize local temperatures, because greenhouse gases impact the climate differently than the albedo changes (as described above) and discussed in Scheider 2008.

Further research:
We conclude that the only justification for further research to explore an albedo-reduction schemes is that they are emergency options that (perhaps) can be deployed quickly in the face of a catastrophe, like incipient melting of continental ice sheets. However, any practical test cases of the global sulfur seeding approach are not recommended. Test cases may not be worth the expense or risk, especially since we have had a couple of "natural" tests in the last 25 years provided by large volcanic eruptions in the Tropics. Further, a minor injection of sulfur will possibly not show a significant impact that could be studies.
In addition to these objections, aerosol modification schemes do not address other problems of continuous growth of GHG abundance. The only way to find a long-term solution to climate change is to address the problem of increasing greenhouse gases, and that must occur by either: (1) conservation plus a switch to renewable energy sources; and/or (2) a practical and long-term secure method of carbon sequestration.

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N. E. VAUGHAN & T. M. LENTON

A Review of Climate Geoengineering Proposals

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Abstract

We present a review of the geoengineering suggestions for counteracting anthropogenic climate change that have been proposed in the recent literature. Climate geoengineering options can be broadly divided into those that seek to rectify the current radiative imbalance via (1) reducing incoming solar (shortwave) radiation or (2) removing CO_2 from the atmosphere and transferring it to long-lived reservoirs, thus increasing outgoing longwave radiation. For each option, we discuss its effectiveness and potential side effects. Taking the options together, we consider the lifetime of their effects, their roll out time for development and deployment, their reversibility, and the risks associated with failure. In general, measures to reduce incoming shortwave radiation are most effective (in terms of radiative forcing) but short-lived, whilst measures to enhance CO_2 removal gain effectiveness the longer they are pursued. Shortwave geoengineering could rectify a global radiative imbalance, and could do so on a decadal timescale, but ocean acidification and residual regional climate changes would still occur. If the measures failed or were stopped, abrupt warming would occur hence they carry a commitment to maintain them, potentially for thousands of years, or deploy them in conjunction with longwave (CO_2) geoengineering. Longwave geoengineering involves less risk, as it acts upon the primary cause of the radiative imbalance (atmospheric CO_2). It also offers a way to return to a pre-industrial CO_2 level and climate on a millennial timescale, through carbon storage of CO_2 captured from the atmosphere. However, air capture and storage is ultimately limited by the capacity of geological reservoirs, the upper estimates of which fall short of estimated fossil fuel resources. Thus, geoengineering could complement the mitigation of CO_2 emissions, but it is not an alternative to mitigation.

1. Introduction

Ideas of climate modification have a long history (detailed in Schneider, 2001; Fleming, 2006a; Fleming, 2006b), with the term geoengineering first appearing in 1977 as a description of CO_2 `disposal' via injection into sinking thermohaline currents to reduce atmospheric $CO_2$ (Marchetti, 1977). The US National Academy of Science report on global warming published in 1992 included a chapter on `Geoengineering', defining it as ``...large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry.'' (NAS, 1992). However, thus far the term, and the ideas it refers to, are not part of the mainstream climate change discourse. The Intergovernmental Panel on Climate Change fourth assessment report gives geoengineering only a brief mention - with an outline of work on injection of sulphate aerosol into the stratosphere and addition of iron to High Nutrient Low Chlorophyll (HNLC) areas of the ocean (IPCC, 2007a).

The difference between mitigation activities and climate geoengineering can be likened to prevention versus medicine. Mitigation refers to activities that reduce anthropogenic CO_2 emissions, whereas geoengineering interventions aim to mediate the effects of elevated atmospheric CO_2 concentrations. This distinction is not mutually exclusive, for example within Carbon Capture and Storage (CCS) technologies, CO_2 capture on fossil fuel power plant exhausts are considered a mitigation activity whilst ambient air capture is regarded as a geoengineering option. The semantic distinction is also fluid and evolving with a lack of consistent usage by the research and policy communities. Certain measures classed as geoengineering in the NAS (1992) report are now regarded as mitigation strategies, i.e. reforestation and CCS (IPCC, 2007b). Furthermore, the definition of geoengineering is often moulded by authors to justify the inclusion/exclusion of material studied.

The resurgent interest in geoengineering in the last few years has been sparked by recognition that existing mitigation efforts are proving wholly ineffectual at the global scale, as evidenced by post-2000 trends in anthropogenic CO_2 emissions. The rapid rate of emissions growth in recent years, from 1.3 % yr^{-1} in 1990-1999 to 3.3 % yr^{-1} in 2000-2006 (Canadell *et al.*, 2007) was fuelled by increasing carbon intensity of energy provision and a stabilisation or reversal of a previously declining trend in energy intensity, coupled to increases in per capita gross domestic product (GDP) and population (Raupach *et al.*, 2007). Despite increased understanding of climate change (IPCC, 2007a) and various international policy

agreements, no region is decarbonising its energy supply (Raupach *et al.*, 2007). Given that the climate system can respond non-linearly to forcing, there is widespread concern about abrupt and/or strongly non-linear changes that may occur with increased anthropogenic forcing (Lenton *et al.*, 2008). This awareness of potential `tipping points' in the Earth system has led some to call for more serious consideration and research into the possible contribution that geoengineering may be able to make to amelioration efforts (Crutzen, 2006).

A number of factors provide motivation for this review, including; an increased interest in climate geoengineering among policy makers and in the wider discourse on tackling climate change (Tickell 2008); the cavalier attitude towards geoengineering ideas apparent in some quarters (e.g. Apak, 2007, see Johnson *et al.*, 2008 for a response); some exaggerated claims of efficiency based on errors in quantification of effects (e.g. Wingenter *et al.*, 2007, see Vogt *et al.*, 2008 for a response); commercial ventures attempting to profit from emerging carbon markets, based on yet-to-be-proven science (e.g. Young, 2007, see Glibert *et al.*, 2008 for a response); and the lack of whole system assessment, with many suggestions focusing solely on global mean temperature as a metric of change and therefore possibly overlooking potentially substantial impacts on other elements of the Earth system (e.g. Govindasamy & Caldeira, 2000; Matthews & Caldeira, 2007; Bala *et al.*, 2008).

To provide some necessary context, the atmospheric concentration of carbon dioxide (CO_2) has increased dramatically over the last century from a pre-industrial ~280 ppm to present day >380 ppm (Raupach *et al.*, 2007), as a result of anthropogenic emissions from fossil fuel combustion and deforestation (e.g. 8.4 Pg C and 1.5 Pg C in 2006) (Canadell *et al.*, 2007). Methane (CH_4) and Nitrous Oxide (N_2O) have also increased significantly (IPCC, 2007a). The elevated concentration of these (CO_2, CH_4, N_2O) and other (e.g. halocarbons, O_3) greenhouse gases has reduced the flux of outgoing longwave radiation from the Earth to space. Despite some masking from aerosol cooling effects (Andreae *et al.*, 2005) there is a net perturbation of the Earth's radiation budget with a combined anthropogenic radiative forcing in 2005 of +1.6 [-1.0,+0.8] W m^{-2}, which is similar to the concurrent estimate for carbon dioxide (CO_2) alone of +1.66 [± 0.17] W m^{-2} (IPCC, 2007a). Excess radiation entering the troposphere has been the main factor contributing to an increase in global mean surface air temperatures by 0.76 [± 0.19] °C between 1850-1899 and 2001-2005, with most of the warming occurring during the last 50 years at a rate of 0.13 [± 0.03] °C per decade, and current warming occurring at about 0.2 °C per decade (IPCC, 2007a). This is already having a range of effects on the Earth system beyond increasing surface air temperatures, including heating the oceans, reducing ice and snow cover and increasing variability in temperature and precipitation (IPCC 2007a).

Increasing atmospheric CO_2 is expected to be the dominant driver of future climate change. Each doubling of CO_2 concentration would be expected to give a radiative forcing of 3.7 W m^{-2} (formula from IPCC, 2001) although many studies round this off to ~4 W m^{-2}. The actual CO_2 concentration trajectory over this and the coming centuries will be dictated by the CO_2 emissions pathway and the Earth system's transient response. The fraction of CO_2 from anthropogenic emissions that accumulates in the atmosphere (airborne fraction) is determined by the transient response of the ocean and land sinks of CO_2. Recent work suggests that the airborne fraction is currently increasing, due to a reduction in the efficiency of the ocean sink (Canadell *et al.*, 2007; Le Quere *et al.*, 2007), whilst the land carbon sink could become a source in future (Cox *et al.*, 2000; Friedlingstein *et al.*, 2006; Lenton, 2000). Faster rates of emissions growth lead to larger airborne fractions and hence higher transient atmospheric CO_2 concentrations. On a millennial timescale, the steady state atmospheric CO_2 concentration will be determined by the total cumulative emissions of CO_2 and the equilibrium response of ocean and land carbon storage (Lenton, 2000). On timescales of 10^4-10^6 years, sedimentation and weathering processes will return the atmospheric CO_2 concentration toward pre-industrial levels (Lenton & Britton, 2006).

Not only does the Earth system have inherent lags in its response to forcing, but so too does the human system. Stabilising atmospheric CO_2 concentrations demands that the current trajectory of increasing emissions is reversed and emissions decline to match the combined ocean and land sink (Sterman, 2008). Decarbonising the global energy system will likely take >50 years due to political processes, technological development, investment requirements and lifetime of existing infrastructure. If emissions change too slowly, it is likely that the transient pathway of CO_2 will `overshoot' its millennial timescale steady state concentration for a significant period of time (Wigley, 2006; Vaughan *et al.*, submitted).

Given this context, a number of potential roles for climate geoengineering have been suggested. These range from direct alternatives to mitigation, i.e. methods that try to completely counteract anthropogenic radiative forcing indefinitely at a global scale (e.g. Angel, 2006), to more short term focussed strategies (Crutzen, 2006) that, for example, may be used to try to prevent particular tipping elements in the Earth system passing a tipping point (Lenton *et al.*, 2008). Wigley (2006) outlines the potential synergies with mitigation, whereby geoengineering could be used in conjunction with a strong transition to a low-carbon economy, to try and avoid an `overshoot' in atmospheric CO_2 concentrations and global temperatures, or to reduce the rates of change of these parameters.

We draw on the recent published literature to consider a number of geoengineering suggestions (Figure 1); we detail how they work in principle, discuss their potential contribution to the amelioration of anthropogenic climate change, and assess their potential side effects on other parts of the Earth system. At the simplest level, the surface temperature of the Earth results from the net balance of incoming absorbed solar (shortwave) radiation and outgoing terrestrial (longwave) radiation (OLR) (Kiehl & Trenberth, 1997). Geoengineering options attempt to rectify the current radiative imbalance via either (1) reducing incoming solar radiation (Section 2), or (2) increasing outgoing longwave radiation, primarily by removing CO_2 from the atmosphere and isolating it in long-lived reservoirs (Section 3). We consider these approaches in turn, with a further distinction for atmospheric removal, between (a) the enhancement of natural sinks (Sections 3.1 and 3.2) and (b) the creation of engineered ones (Section 3.3). Other climate geoengineering approaches, particularly to increasing outgoing longwave radiation are conceivable (for example, dispersing clouds over the polar ice caps), but we confine our attention to proposals in the recent literature. In the Discussion (Section 4) we consider the relative effectiveness of different geoengineering options and the potential synergies and conflicts between them, and with mitigation and adaptation strategies.

Figure 1 Schematic overview of the climate geoengineering proposals reviewed.

2. Reducing incoming solar radiation

A suite of geoengineering ideas seek to rectify the increasing radiative forcing caused by anthropogenic greenhouse gas emissions by reducing the amount of solar radiation absorbed. Proposals range from reducing the amount of solar radiation reaching the top of the atmosphere, to increasing the reflection of shortwave radiation (albedo) within the atmosphere or at the surface (Figure 1). Typically the radiative forcing due to a doubling of atmospheric CO_2 (3.7 W m^{-2}) is taken as the target to counteract, although actual anthropogenic radiative forcing will continue to vary over time. Each individual idea has specific merits and drawbacks, which will be outlined here. However, they also raise common issues; in particular, reducing incoming solar radiation does not ameliorate ocean acidification caused by rising atmospheric CO_2. Indeed successful planetary cooling would be expected to increase ocean CO_2 uptake, thus amplifying ocean acidification (see Figure 2(d) in Matthews & Caldeira, 2007). Such issues will be returned to in the discussion (Section 4).

2.1 Sunshades in space

A fraction of incoming solar radiation could be reflected away before entering the Earth system, by objects placed in a solar orbit (Angel, 2006), or in an Earth orbit (NAS, 1992; Pearson *et al.*, 2006). To offset a doubled pre-industrial atmospheric concentration of CO_2 would require a decrease in incoming solar radiation of roughly 1.6%, equating to a radiative forcing of -3.7 W m^{-2} (Lenton & Vaughan, submitted). Many studies consider a decrease of 1.8%, which causes a radiative forcing of -4.23 W m^{-2} (e.g. Govindasamy & Caldeira, 2000; Angel, 2006). The required reduction in incoming solar radiation could be achieved by placing a sunshade consisting of multiple `flyers' with a total area of 4.1 million km^2 (revised from 4.7 million km^2) at the L1 Lagrange point (Angel, 2006). The negative radiative forcing effect could be varied by altering the size of the sunshade. An option closer to home would be the placement of mirrors in orbit around the Earth (NAS, 1992), or rings of either particles or multiple spacecraft (Pearson *et al.*, 2006). The calculations presented in the literature are based on a static radiative imbalance, however with the observed trends in emissions to date (Raupach *et al.*, 2007) it is clear that the radiative imbalance is set to continue increasing. For example, if a sunshade was in place today (at the L1 point) to offset the current radiative imbalance of 1.6 W m^{-2} then given that atmospheric CO_2 is rising at 2 ppm yr^{-1}, a surface area of ~31,000 km^2 would need to be added each year. This equates to ~136,000 launches per year of 800,000 space flyers per launch (Angel, 2006). Thus, the area

of shades or reflectors in space would need to increase significantly year on year to keep pace with the current rate of increase in radiative forcing.

After deployment, reflectors in space could quickly (within ~5 years) counteract global warming (Matthews & Caldeira, 2007). There are significant differences in the spatial and temporal pattern of reductions in incoming solar radiation relative to the pattern of decreased outgoing longwave radiation caused by elevated greenhouse gas concentrations (Govindasamy & Caldeira, 2000; Govindasamy *et al.*, 2003; Matthews & Caldeira, 2007; Lunt *et al.,* 2008). Yet modelling work suggests that a prescribed reduction in solar luminosity can get remarkably close to cancelling out a known forcing from increased CO_2 (Govindasamy *et al.*, 2003; Matthews & Caldeira, 2007), although a residual global cooling (Govindasamy & Caldeira, 2000) or warming (Govindasamy *et al.*, 2002; 2003; Bala *et al.*, 2008) often remains. In practice, the cancellation would be imperfect because the radiative forcing to be counteracted would not be perfectly known – even current estimates of anthropogenic radiative forcing carry significant uncertainty. Models predict that the meridional temperature gradient would tend to be reduced, leaving either excess cooling in the tropics (Lunt *et al.*, 2008) or excess warming in the high latitudes (Govindasamy *et al.*, 2003), which is not surprising given that changes in solar forcing affect the energy balance in the tropics more than in the high-latitudes.

The main side effect predicted by existing model studies is a slowing of the hydrological cycle with up to a 2% decrease in global mean precipitation (Govindasamy & Caldeira, 2000; Govindasamy *et al.*, 2002; Bala *et al.*, 2008), which may be most pronounced over land (Matthews & Caldeira, 2007), and/or in the tropics (Govindasamy *et al.*, 2003; Lunt *et al.*, 2008). An overall slowing of the hydrological cycle is consistent with a reduction in top-of-atmosphere (TOA) shortwave radiate forcing having a greater effect on the surface energy balance than the equivalent increase in TOA longwave forcing (Bala *et al.*, 2008). A TOA shortwave radiative forcing of -4.2 W m^{-2} translates to an instantaneous -3.1 W m^{-2} at the surface (using the global average energy balance) whereas +4.2 W m^{-2} TOA longwave forcing causes only ~0.5 W m^{-2} instantaneous change at the surface, and a much larger change in the atmosphere, before temperature and radiation fluxes adjust (Bala *et al.*, 2008). In a successfully geoengineered climate where the TOA radiation forcings approximately cancel and the surface temperature is little altered, the net (shortwave and longwave) change in radiation at the surface is still about -2.5 W m^{-2} and this is balanced by reductions in latent and sensible heat loss (Bala *et al.*, 2008). Reduced evaporation (latent heat flux) in turn causes reduced precipitation. The effect may be attenuated over land because elevated CO_2 tends to reduce evapotranspiration and hence the latent heat flux (Matthews & Caldeira, 2007). Reduced incident shortwave may also disproportionately affect the latent heat flux rather than sensible heat flux (the Bowen ratio), according to observations of historical solar dimming causing reduced precipitation over land, followed by recent solar brightening increasing precipitation over land (Wild *et al.*, 2008). Reduced hydrological cycling in the tropics is consistent with reductions in shortwave radiative forcing being biased to the tropics, whereas an equivalent increase in longwave forcing is more evenly distributed. Shifts in the Inter-tropical Convergence Zone (ITCZ) may cause precipitation to increase in some locations in an otherwise globally drier world (Bala *et al.*, 2008).

A regionally targeted (61°N or 71°N to 90°N) reduction in solar radiation has been proposed to protect tipping elements in the Arctic (Caldeira & Wood, 2008). Model simulations suggest a 21% reduction in incoming solar radiation, applied over 71-90°N would be sufficient to restore Arctic sea-ice to its pre-industrial extent in a doubled CO_2 world (Caldeira & Wood 2008). Such polar-focussed geoengineering only modestly reduces the increased water vapour transport to polar regions caused by elevated greenhouse gas concentrations. Combined with the reduced insolation, Calderia & Wood (2008) noted an increased fraction of precipitation falling as snow, rather than rain. Although polar tipping elements including the Greenland Ice Sheet may benefit from this strategy, others, such as North Atlantic meridional overturning circulation (MOC), might not (Caldeira & Wood, 2008).

Decreasing incident solar radiation would have direct effects on photosynthesis, but so too does elevated CO_2 which fertilises carbon fixation. Existing simulations (using the IBIS vegetation model) suggest the CO_2 fertilisation effect dominates over reduced solar radiation, in affecting global net primary productivity (NPP) in a geoengineered climate (Govindasamy *et al.,* 2002; Naik *et al.,* 2003). Global NPP with doubled CO_2 but a 1.8% decrease in insolation is predicted to be similar to that with just doubled CO_2, and much greater than that at pre-industrial CO_2 (Govindasamy *et al.,* 2002; Naik *et al.,* 2003). NPP is predicted to decline in tropical evergreen and boreal forests but increase in temperate deciduous forests, grasslands and deserts, due to the combination of high CO_2 and low temperature alleviating water-stress in

ecosystems where water limitation is a key determinant of productivity (Naik *et al.,* 2003). Regionally targeted (and therefore greater) reductions in solar radiation would be expected to have larger impacts on regional vegetation. For example, large reductions in solar radiation in the high northern latitudes would be expected to over-cool the summer (and under-cool the winter) affecting many plants in the boreal region which typically respond to integrated summer temperature above a certain threshold (e.g. growing degree days above zero). As yet there are no global studies of the impact of reducing incident solar radiation on the marine biosphere.

2.2 Stratospheric aerosols

The injection of sulphate aerosols into the lower stratosphere to cool the climate draws on the natural but imperfect analogy of large volcanic eruptions such as Mt Pinatubo on 12th-16th June 1991 (Crutzen, 2006). The cooling impact of these large volcanic eruptions is well documented - sulphur dioxide (SO_2) ejected into the stratosphere reacts to form sulphate aerosols, which scatter shortwave and absorb and emit longwave radiation (Stenchikov *et al.*, 1998). A simple model (MAGICC) demonstrates how repetition of the forcing exerted by Mt Pinatubo can counteract increased temperatures, but it does not consider stratospheric chemistry interactions or spatial and seasonal variations between longwave radiative forcing and sulphate injection (Wigley, 2006). Insights into the effectiveness and possible side effects of sulphate aerosols geoengineered have been garnered using observational data from large volcanic eruptions (Stenchikov *et al.*, 1998; Crutzen, 2006), atmosphere-ocean general circulation models (Robock *et al.*, 2008), atmospheric chemistry modelling (Rasch *et al.*, 2008a, Tilmes *et al.*, 2008) and analysis of the radioisotope of Tungsten (^{185}W) relating to atmospheric nuclear testing (Tuck *et al.*, 2008).

To counteract the radiative forcing due to a doubling of atmospheric CO_2 (3.7 W m^{-2}) by increasing the stratospheric reflection of shortwave radiation back to space (assuming no absorption occurs above the stratosphere), requires an average global increase in albedo of 0.012 (Lenton & Vaughan, submitted). The amount of sulphate aerosol required to achieve this depends on the size of the particles and the location of injection, ranging from an estimated 1.5 Tg S yr^{-1} (Rasch *et al.*, 2008a) to 5 Tg S yr^{-1} (Wigley, 2006). Smaller particles (radius ~ 0.1 μm) are more effective because they have no impact in the longwave, while the larger, volcanic-like particles absorb and emit in the longwave (Stenchikov *et al.*, 1998). The residence time and spatial spread of particles in the stratosphere varies greatly with the location of injection (Crutzen, 2006; Wigley, 2006; Rasch *et al.*, 2008b). Residence time and global coverage is maximised when injections occur into the lower stratosphere over the tropics (Oman *et al.*, 2005; Robock *et al.*, 2008; Rasch *et al.*, 2008b). As for the mechanism of injection, artillery guns or balloons have been suggested as a delivery method for SO_2 (Crutzen 2006), however due to microphysical and dynamic processes such a focussed injection point could lead to coagulation of particles and subsequent fallout (Tuck *et al.*, 2008; Rasch *et al.*, 2008b). Consequently, others advocate a dispersed delivery method, such as high level aircraft to deliver the aerosol or precursor payload (Tuck *et al.*, 2008; Rasch *et al.*, 2008b).

Stratospheric sulphate aerosol injection carries some significant potential side effects (Rasch *et al.*, 2008b). Ozone depletion is expected (Crutzen, 2006) with recent modelling work showing a 15 to 60 year extension of the recovery time of the Antarctic ozone hole (dependent on particle size and vertical extension) and Arctic ozone losses of at least 60 to 80 DU (Dobson Units) in 75% of all winters (Tilmes *et al.,* 2008). Sulphate injection modelling showed disruption to the Asian and African Summer monsoons (Robock *et al.*, 2008). The response to volcanic eruptions suggests the Arctic Oscillation would be shifted to a stronger positive phase, associated with stronger westerlies and winter warming over Northern Eurasia and North America (Stenchikov *et al.*, 2002; Stenchikov *et al.*, 2006). The response to the Mt Pinatubo eruption suggests that precipitation over land, runoff and river discharge would all decrease (Trenberth & Dai, 2007), although the Mt Pinatubo eruption particles were a lot larger than those advocated for geoengineering and were injected into the middle and upper rather than the lower stratosphere (Tuck *et al.*, 2008; Rasch *et al.*, 2008a). Model predictions of the effects of a prescribed reduction of incoming solar radiation (Section 2.1), including reduced precipitation, should be broadly applicable to sulphate aerosol loading. A key difference is that stratospheric aerosol loading affects the ratio of direct to diffuse light. This will affect terrestrial (and potentially marine) photosynthesis, as well as emerging technologies that rely on direct light (Rasch *et al.*, 2008b). Increases in acid rain (Crutzen, 2006) are likely to be small, because the stratospheric sulphur loading proposed is minor when compared to tropospheric sulphate aerosol loading (Section 2.3). Further research on side effects is required, particularly into impacts on the biosphere (Rasch *et al.* 2008b). Already it is clear that the uncertainties

surrounding the effects of sulphate aerosol addition to the stratosphere are much greater and more meteorologically complicated than those relating to mitigating CO_2 emissions (Tuck *et al.*, 2008).

2.3 Tropospheric aerosols

Some suggest reversing the current declining trend in tropospheric aerosols as a geoengineering option (NAS, 1992), but we join others in ruling this out due to the serious negative impact on human health, the greater loading required than the equivalent intervention in the stratosphere, and the concern about regional impacts dictating multiple injection locations (Crutzen, 2006; MacCracken, 2006). Sulphate aerosols in the troposphere, increased by anthropogenic emissions of e.g. 54 Tg S yr^{-1} in 2000 (Stern, 2005), are responsible for a significant proportion of the current negative anthropogenic radiative forcing, -0.4 ± 0.2 W m^2 (IPCC, 2007a). This has led to less warming than expected due to current greenhouse gas concentrations. However, the 1980 to 2000 trend in tropospheric sulphate aerosols is one of decreasing emissions in the Northern hemisphere, 64 to 43 Tg S yr^{-1}, and increasing in the Southern hemisphere, 9 to 11 Tg S yr^{-1}, leading to a net global decrease. This trend persists (despite growth of sulphur dioxide emitting activities in some regions) and is attributable in part to national level legislation in a number of developed countries, borne of transboundary or inter-regional pollution problems (Stern, 2005). This pollution causes problems for human health, with increases in cardiac and respiratory morbidity and mortality attributed to exposure to particulate matter (Nel, 2005), and ecology, via sulphuric acid precipitation and deposition (Crutzen, 2006). In addition to an effect on global surface temperatures, declining sulphate aerosol concentrations over the North Atlantic may have contributed to western Amazonia drought (Cox *et al.* 2008). The observed increasing sea surface temperatures (SSTs) in the North Atlantic, owing to greenhouse gas forcing combined with reducing aerosol pollution, affects the North-South SST gradient, which in turn shifts the ITCZ causing reduced dry-season rainfall in western Amazonian (Cox *et al.*, 2008).

2.4 Enhanced cloud albedo

Increasing the reflectivity of low level marine stratiform clouds by mechanical (Latham, 1990) or biological (Wingenter *et al.*, 2007) generation of cloud condensation nuclei (CCN) has been suggested. Increasing CCN increases cloud droplet concentrations, and thus cloud albedo, which is known as the 'first indirect effect' or the 'Twomey effect' (Twomey, 1977; Charlson *et al.*, 1987; Wigley, 1989; Slingo, 1990; Twomey, 1991; IPCC, 2007a). Cloud albedo is a saturating function of cloud droplet concentration (Twomey 1977) so methods to enhance cloud albedo would be most effective in remote marine areas with a 'clean' atmosphere, notably the Southern Ocean. The presence of both natural and anthropogenic sources of CCN, provide an ultimate constraint on the potential effectiveness of geoengineering additional sources of CCN. Present day anthropogenic pollution already provides a globally significant source of aerosols that affect cloud albedo. The current best estimate of the radiative forcing exerted by the cloud albedo effect is -0.7 W m^2 (-0.3 to -1.8 W m^2) (IPCC, 2007a). The sources of these aerosols are sulphate, fossil fuel organic carbon, fossil fuel black carbon, biomass burning and mineral dust, and the loadings of these aerosols have high regional variability.

2.4.1 Mechanically enhanced cloud albedo

The most developed mechanical method proposes the use of fine sea spray generated by remotely controlled vessels with Flettner rotors, powered by wind energy (Salter, 2006; Salter *et al.*, 2008). A proportion of the sea spray generated would be lifted by turbulence to provide the additional CCN. The concept was outlined by Latham (1990) with some initial calculations of magnitude (Latham, 2002), developed more recently (Latham *et al.*, 2008).

Early studies, argued a 50-100% increase in droplet concentration in all marine stratiform clouds would give rise to an increase in top-of-cloud albedo of 0.02, causing a planetary albedo increase of 0.005, and that this would offset a doubling of atmospheric CO_2 (Latham, 2002; Bower *et al.*, 2006). We question these figures and estimate a required increase in top-of-cloud albedo of 0.091 across all regions of marine stratiform clouds is needed to offset a doubling of CO_2 (Lenton & Vaughan, submitted). This is a marked increase over the often cited 0.02, but not inconceivable given that such clouds can range in albedo from 0.3 to 0.7.

Separate calculations of the effect of imposed changes in cloud droplet number concentration suggest that the required increases in cloud albedo could be achieved with plausible additions of sodium chloride aerosol and effective activation of this to CCN (Bower *et al.*, 2006). The results confirm that the change in albedo is principally controlled by aerosol concentration and that enhancing cloud albedo will be most effective in unpolluted air masses (Bower *et al.*, 2006). Further calculations imposing an increase in cloud droplet number concentration from a global average of ~100 cm^{-3} to 375 cm^{-3} (i.e. nearly a factor of 4 increase) show up to -8 Wm^{-2} TOA radiative forcing, and are described as "readily achievable technologically" (Latham *et al.*, 2008).

Claims that this approach is "ecologically benign" (Latham *et al.*, 2008) are rather myopic; increasing reflectivity of clouds reduces light availability at the surface, so one would expect ecosystems to be impacted. There is great spatial variation in the potential magnitude of effect, with radiative forcing predicted to exceed -40 W m^{-2} in some areas such as the tropical east Pacific Ocean (west of South America) and the tropical east Atlantic Ocean (west of Africa) (Latham *et al.*, 2008). These regions have important roles in the El Niño Southern Oscillation and the West African Monsoon (see Section 4). Precipitation may also be effected locally, as increasing cloud droplet number concentration may suppress the production of precipitation (the second indirect or Albrecht effect) (Albrecht, 1989; Bower *et al.*, 2006; IPCC, 2007a). This is not surprising given that the same amount of cloud water is assumed to be distributed over a larger number of smaller droplets. Globally a reduction in incident solar radiation at the surface of the ocean would be expected to decrease evaporation and hence precipitation. If precipitation were reduced in terrestrial environments this would have important implications for water availability.

2.4.2 Biologically enhanced cloud albedo

Wingenter *et al.* (2007) propose fertilising patches of the Southern Ocean (SO) with iron, to stimulate phytoplankton growth and therefore increasing the emission of Dimethylsulphoniopropionate (DMSp). DMSp is a precursor compound for Dimethylsulphide (DMS), which oxidises in the atmosphere to create sulphate aerosols (Charlson *et al.*, 1987). These DMS-derived aerosols are the main source of CCN in remote marine areas (Liss *et al.*, 1997). It has been argued that if 2% of the Southern Ocean were fertilised for one month in the summer, a regional, seasonal cooling of 2 °C is achievable (Wingenter *et al.*, 2007). If realistic, this method could be used to stabilise Antarctic Ice Shelves (Wingenter *et al.*, 2008). However the estimate is based on a 480% observed increase in DMS seawater concentration, from 1.6 nmol m^{-3} to 7.7 nmol m^{-3} recorded during the SOFEx iron-fertilisation experiments (Wingenter *et al.*, 2004) driving a 10% increase in CCN over the Southern Ocean. Assuming this leads to an increase in cloud albedo over the Southern Ocean of 0.008 (Wingenter *et al.*, 2007), and scaled for the fraction of year and the fraction of the Earth's surface affected gives an annual global mean radiative forcing of -0.016 W m^{-2} (Lenton & Vaughan, submitted). However, this is probably an overestimate as the increase in CCN over the Southern Ocean has subsequently been revised downwards to 2.6% (Vogt *et al.*, 2008) or 1.4% (Woodhouse *et al.*, 2008), the former giving 0.6 °C regional cooling for one month (global annual value of 0.005 °C) (Vogt *et al.*, 2008).

A key concern is that only 50% of iron-addition experiments in the Southern Ocean to date have resulted in a positive DMS response (Vogt *et al.*, 2008; Boyd *et al.*, 2007). Indeed modelling of the removal of iron limitation in the Southern Ocean (using the PISCES 3D ocean biogeochemical model) predicts a reduction in DMS emissions to the atmosphere, attributed in part to a shift in ecosystem species assemblage from nanophytoplankton to diatoms, which produce relatively little DMS (Bopp *et al.*, 2008). Furthermore, even if the assumed increase in seawater concentration of DMS is correct, detailed modelling (using the GLOMAP global aerosol model) generates only a 1.4% increase in CCN over the Southern Ocean (Woodhouse *et al.*, 2008), significantly smaller than the 10% suggested (Wingenter *et al.*, 2007). Thus, the effectiveness of this geoengineering option, globally or regionally, is highly uncertain. Verification of any effect would be particularly difficult due to the time delay between DMS emission and its contribution to cloud formation. Elevated CCN are predicted to occur several thousand kilometres downwind of the DMS perturbation because the conversion of DMS to CCN takes several days (Woodhouse *et al.*, 2008).

Possible side effects of successful deployment include those for mechanical enhancement (Section 2.4.1) with potential impacts on ecosystems as with iron fertilisation for carbon drawdown (Section 3.2.2.1). In addition, strong Southern Ocean regional cooling may lead to an increased meridional temperature gradient, strengthening and/or shifting winds and potentially increasing CO_2 outgassing (Vogt *et al.*, 2008). A further consideration is that recent mesocosm experimental work simulating bloom conditions

(by addition of nutrients) indicates that ocean acidification leads to a reduction in marine trace gas emissions, such as DMS (Avgoustidi, 2007; Hopkins *et al.*, submitted), so this geoengineering measure may be ineffective if ocean acidification remains unmitigated.

2.5 Surface albedo

In the global annual mean, the Earth's surface reflects 30 W m^{-2} of the 198 W m^{-2} of solar radiation reaching it (Kiehl & Trenberth, 1997). A number of ideas have been proposed to increase the reflectivity of the Earth's surface, including modification of grasslands, croplands, human settlements and deserts (Hamwey, 2007; Ridgwell *et al.*, submitted; Akbari *et al.*, submitted; Gaskill, 2004).

2.5.1 Increasing grassland and cropland albedo

Proposals to increase the albedo of vegetation have recently focused on grasslands including open shrubland and savannah (Hamwey 2007), and on croplands (Ridgwell *et al.*, submitted). The effectiveness of vegetation albedo modification methods depends greatly on the magnitude of albedo enhancement achievable and the area it is applied to. Hamwey (2007) suggests using either variegated plants, light shrubs or bioengineering grasses and shrubs to increase the albedo of grassland, open shrubland and savannah globally from 0.17 by 0.0425 (25%). Using a static 2-D radiative transfer model an increase in global annual average surface albedo of 0.002626 and a radiative forcing of -0.56 W m^{-2} are predicted. Ridgwell *et al.* (submitted) restrict their proposal to croplands but assume a maximum 0.08 increase in canopy albedo is achievable, from 0.2 (in their model). Lenton & Vaughan (submitted) estimate the radiative forcing of Hamwey's proposal to be -0.64 W m^{-2} and Ridgwell *et al.*'s -0.34 to -0.45 W m^{-2} (range due to differences in cropland area estimates) or for a maximum albedo change of 0.04, -0.17 to -0.22 W m^{-2}. Ridgwell *et al.* (submitted) use a coupled atmosphere-ocean model (HadCM3) with a dynamic global vegetation model (TRIFFID), but cropland is not explicitly represented. A global mean surface temperature change of -0.21 ± 0.08 K is predicted relative to a control run with 700 ppm CO_2. This suggests the actual radiative forcing in the model experiment is -0.26 W m^{-2} (Lenton & Vaughan, submitted).

Research on these measures is very much in its infancy and as such it is difficult to ascertain how effective they may be. No convincing evidence is given that a global 40% increase in cropland reflectivity (Ridgwell *et al.*, submitted) is achievable, whereas the proposed 25% increase in global grassland albedo (Hamwey, 2007) appears more carefully worked out. Still the seasonal and spatial variation in vegetation reflectance and the effect of underlying soil on measured reflectance need to be considered (e.g. Gilabert *et al.*, 2002). Effectiveness will also be restricted by ability to scale up, which is limited by land area and availability.

'Side' effects start with an increase in reflectance reducing the light available for photosynthesis and thus potentially influencing plant yield. Plants with a high albedo generally have lower chlorophyll content and therefore reduced photosynthetic activity, leading to reduced carbon uptake (Hamwey, 2007). Thus, trying to alter global cropland albedo may conflict with food production. Added sources of societal concern are the need to use extensive monocultures and/or genetically modified crops. Furthermore, with less shortwave absorption at the surface, evapotranspiration would generally be expected to decline and with it precipitation (Section 2.1). Effects on cloud cover and precipitation are expected to vary from tropics to temperate regions (Hamwey, 2007) but few details of impacts on soil moisture and precipitation patterns have been given (Ridgwell *et al.*, submitted).

2.5.2 Increasing human settlement albedo

The albedo of urban regions can be increased by using highly reflective roofs and altering the material used in paving roads (Akbari *et al.*, submitted; Hamwey, 2007). Albedo enhancement measures can potentially be extended to all areas of human settlement (Hamwey, 2007). Estimates of the potential effectiveness vary widely, depending mostly on the area assumed to be modified (Hamwey, 2007; Akbari *et al.*, submitted). Hamwey (2007) doubles the albedo of human settlement area from 0.15 to 0.3 (based on work by Taha, 2005 and Jin *et al.*, 2005) and using a 2-D radiative transfer model obtains a radiative forcing of -0.17 W m^{-2}. In contrast, Akbari *et al.* (submitted) calculate that an increase in the albedo of urban roofs and pavements by 0.1 induces a radiative forcing of -0.044 W m^{-2}, based on 1% of the land surface being urban and 25% of this being roof area and 35% paved surface. We estimate the radiative

forcing of Hamwey's suggestion is -0.19 W m^{-2} and Akbari *et al.*'s is only -0.01 W m^{-2} (Lenton & Vaughan, submitted) (because the actual area of urban land according to satellite-derived datasets is much less than assumed). The longevity of these albedo effects is not quantified; highly reflective surfaces would be expected to fade over time (Akbari *et al.* submitted) so it will depend on the frequency that they are replaced. Regardless of their uncertain but probably small global effect, urban albedo alterations have been shown to reduce urban heat island effects (Taha, 2008).

2.5.3 Increasing desert albedo

Gaskill (2004) provides an account of a meeting at the U.S. Department of Energy which included the suggestion to increase the albedo of global desert areas (1.16×10^{13} m^2 deemed suitable). These land areas are suggested because they are largely uninhabited, sparsely vegetated, flat and stable (aeolian deserts are excluded). Such deserts typically have an albedo in the range 0.2 to 0.5, depending on geologic composition (Tsvetsinskaya *et al.*, 2002). Gaskill (2004) suggests an albedo increase over 2% of the Earth's surface from 0.36 to 0.8, with the addition of a reflective surface, made of white polyethylene top surface and an aluminium bottom surface, would give rise to a radiative forcing of -2.75 W m^{-2}. We scale down this estimate to -1.74 W m^{-2} suggesting the reduced incident radiation at the surface may not have been properly taken into account (Lenton & Vaughan, submitted). Although sparsely populated, deserts are not devoid of life and the desert ecosystem would effectively be sacrificed by being covered up. The proposed drastic alteration of the surface energy balance would make the covered deserts a lot less hot during the day. Deserts have an important role for marine productivity as a source of iron through dust supply and inhibition of this essential nutrient may reduce the ocean carbon sink (via inhibition of the biological pump).

2.6 Implementation issues

Development and deployment of a solar orbiting reflector structure would take several decades (e.g. for Angel's (2006) proposal, deployment takes 10 years, with 20 launch sites on a 5 minute cycle). All the orbital options would require a significant lead in time for research, development, deployment and, in many cases, maintenance.

Sulphate aerosols in the stratosphere have a lifetime of ~3 years, so the effect of this geoengineering method is reversed on a ~3 year timescale. In order to avoid rapid cooling it would need to be scaled up progressively, and to avoid rapid warming, it should not be suddenly stopped. Rasch *et al.* (2008) detail a range of areas requiring further research and development, focussing on the amount of sulphate required to achieve a desired level of cooling, including the mechanism for delivery (Section 2.2). Early suggested delivery mechanisms such as artillery or balloons (Crutzen, 2006) are able to be realised more quickly than recent suggestion of distributed delivery mechanisms, however the latter is argued to be more effective (Rasch *et al.*, 2008).

For mechanically enhanced cloud albedo, a detailed consideration of development time and costs for the proposed sea-going vessels asserts that with appropriate funding a first full prototype could be developed in 5 years (Salter *et al.*, 2008). For biological enhancement, implementation would be similar to that proposed for iron fertilisation to enhance carbon export (Section 3.2.2.1). In contrast to biological enhancement (Section 2.4.2) the mechanical method is more predictable and testable as it does not depend on a poorly understood ecosystem response. The sea-going vessel design presented incorporates remote control, therefore if necessary this intervention could be halted immediately. Fertilisation to stimulate blooms could be halted immediately, with the blooms senescing within weeks. For both forms of enhancement, the effects on cloud albedo would last for a matter of weeks, but if the intervention has disrupted ecosystems then the duration of any negative effects would depend on the how this disruption had manifested itself.

For crop albedo modification the constraint on deployment timescale is the selection, or development through genetic modification, of crops or vegetation that achieve the necessary albedo enhancement. Complete with field experiments to verify reflectance effect, this stage is likely to take ~10 years. Deployment once development stages were complete could be reasonably quick, especially if utilising agricultural infrastructure. The materials proposed for urban area (roofs and paved surfaces) and human settlement are available, although the quantity required would impact deployment timescales, as would the dispersed spatial extent of these surfaces and the variations of ownership. There is likely to be

significant decay of albedo affect, requiring either regular cleaning or replacement, depending on materials used. The proposed desert modification material would require periodic replacement (every ~3 yrs) and cleaning. Development of an appropriate film and cleaning mechanisms would take ~10 years and deployment is estimated to take 60 years (Gaskill, 2004). In terms of reversibility, for vegetation alteration once plants are removed the effect of albedo changes would be instantaneous. However, the removal of plants (dependent on method) and the ecosystem changes incurred would have longer lasting effects. Reversing changes in human settlement albedo would depend on the decay rate of the albedo effect and would incur a significant removal time due to the distributed nature of the surface. The desert alteration approach could be optimistically stopped in ~10 years, dictated by the spatial extent of coverage and constrained by the mechanism used to remove the structure. Albedo effects of both would cease as soon as the highly reflective surface was removed. The timescale of recovery from any unintended impacts on ecosystems (vegetation and desert) are not possible to foresee, the duration of these impacts depend upon how the interventions have affected the ecosystem and regional climate.

3. Carbon sink enhancement

The second group of geoengineering options are based on the removal of atmospheric CO_2 by enhancing the existing land or ocean carbon sink or creating new carbon sinks. For any geoengineering option that involves removing atmospheric CO_2, its effect will decay over time, due to the response of ocean and land carbon reservoirs to atmospheric perturbations, and it will also decay if carbon storage is not permanent (Lenton & Vaughan, submitted). Thus, in calculating effects on atmospheric CO_2 we specified timescales of interest. To calculate a corresponding impact on radiative forcing we accounted for the fact that the sensitivity of radiative forcing to changes in CO_2 depends inversely on the absolute concentration of CO_2. In the long-term, the only way to return atmospheric CO_2 to pre-industrial levels is to permanently store (in some combination of the crust, sediments, soils, ocean, and terrestrial biosphere) an equivalent amount of CO_2 to the total emitted to the atmosphere.

3.1 Land carbon sink enhancement

In the pre-industrial and pre-agricultural state of the carbon cycle, more carbon was stored on land than today. Thus there is clearly some potential to enhance the land carbon sink by increasing land carbon stores. The majority of carbon stored on land is in soil (1500 Pg C), not in vegetation (550 Pg C) (Olson *et al.*, 1985; Batjes, 1995). In general, carbon on land has a shorter lifetime (with respect to being returned to the atmosphere as CO_2) than carbon in the deep ocean. Carbon in leaf litter and detritus (~ 90 Pg C) has an average lifetime of only ~2 years. Carbon in global biomass (550 Pg C), which is mostly woody vegetation, and in soil as labile organic carbon (660 Pg C) have an average lifetime of ~50 years. The remainder of carbon in soil (750 Pg C) is in recalcitrant material with a lifetime of ~500 years. Carbon in some lignin compounds and charcoal can last far longer than this, particularly if it is washed to the ocean and deposited in sediments there.

We estimate the long-term potential for increasing conventional vegetation and soil carbon storage to be ~165 Pg C by assuming the reversal of all cumulative land-use change emissions to date. This equates to a long-term radiative forcing of $\approx$ -0.24 W m^{-2} (using formulae in Lenton & Vaughan, submitted). To achieve a larger effect, land carbon stores would have to be increased above their pre-industrial level.

A general concern is that such large scale land use change would be likely to come into conflict with food production requirements (especially with a projected global population of 9.5 billion by 2100). An illustration of these possible conflicts for land area is evident today with first generation biofuel crops. There are also likely to be issues relating to secondary and transboundary impacts such as water availability and intensive fertiliser use. In case of afforestation, dramatic ecosystem shifts would have deleterious impacts on species diversity through loss of habitat.

3.1.1 Afforestation and reforestation

The conversion of land from non-forested to forested, termed 'afforestation' (if it has been without trees for > 50 years), or 'reforestation' (if trees were lost in the last 50 years) currently lies within the mitigation discourse (IPCC, 2007b). However, reforestation was the first geoengineering idea discussed by NAS (1992). Given the distinction made between mitigation and geoengineering earlier (Section 1), these

interventions can be viewed as geoengineering activities, in contrast to avoided deforestation, which prevents anthropogenic emissions of carbon and is therefore a mitigation action.

The most optimistic estimates suggest that 120 Pg C could be accumulated by afforestation and reforestation by 2035 followed by the accumulation a further 63 Pg C in standing plantations by 2060 (i.e. 183 Pg C in total) (Read and Parshotam, 2007). It is assumed that there is no decay of the biomass reservoir on this timescale. Following this scenario, we calculate a radiative forcing in 2050 of ≈ -0.49 W m^{-2} (Lenton & Vaughan, submitted). Given that the value of 183 Pg C stored in plantation biomass in 2060 exceeds estimates of the total amount of carbon that has been lost to date due to land use change (much of it from soil), it is not clear that it could be increased further. Holding the store constant to 2100 (i.e. no further uptake or decay) causes the effect on the atmosphere to decay to give a radiative forcing of ≈ - 0.37 W m^{-2} in 2100 and ≈ - 0.27 W m^{-2} in 3000.

Whilst these numbers look encouraging we question whether they are achievable. They assume that humans can do much better than nature at storing carbon in vegetation biomass. The key assumption appears to be that no carbon is lost during reforestation or afforestation it is only accumulated in biomass. However, although the majority of carbon in global biomass is in trees, soil carbon storage is greatest in some non-forested ecosystems, especially peat bogs and under tundra vegetation. Furthermore, in various tropical and temperate regions, grasslands can have equivalent or greater soil carbon storage than nearby forest. Consequently, afforestation and reforestation in many areas could lead to losses of soil carbon that would partly (or even completely) reverse the gain of carbon in biomass.

The ecosystem shift due to afforestation could have deleterious impacts on species diversity through loss of habitat. Afforestation tends to lower land surface albedo and in high latitudes (with seasonal snow cover) this can outweigh the radiative forcing effect of enhanced carbon storage (Betts, 2000). Forest cover also tends to enhance cloud cover and reflectivity through increasing evapotranspiration and by providing biogenic sources of CCN (Section 2.4.2). Terrestrial vegetation is a source of non-methane volatile organic compounds, some of the oxidation products of which produce secondary organic aerosols (Koppmann, 2007; IPCC, 2007a). Thus afforestation in the tropics should generally lead to climate cooling.

3.1.2 Bio-char

Bio-char is essentially fine charcoal produced by pyrolysis of biomass (combustion largely in the absence of oxygen) which converts roughly 50% of the carbon in the original fuel to charcoal, the rest producing CO_2 (which can be captured and stored). Potentially substantial sources of bio-char include 'slash and char' rather than 'slash and burn' shifting agriculture (up to 0.21 Pg C yr^{-1}), pyrolysis of agricultural, forestry and urban wastes (0.16 Pg C yr^{-1}), and biomass energy production by pyrolysis of some of the products of afforestation, reforestation or other plantations (up to 0.18 Pg C yr^{-1}) (Lehmann *et al.*, 2006). The bio-char produced is then dug or ploughed into soil where it acts as a recalcitrant carbon reservoir and enhances the nutrient content of soils, particularly if applied with ammonium bicarbonate, produced in the process of carbon capture from pyrolysis.

It has been estimated that up to 0.56 Pg C yr^{-1} of bio-char could be produced at present and that this could be significantly increased by up-scaling biomass energy production (Lehmann *et al.*, 2006). Read & Parshotam (2007) detail a scenario for bio-char production that would lead to a radiative forcing of ≈ -0.12 W m^{-2} in 2050 (Lenton & Vaughan, submitted). There is scope to further scale-up this geoengineering option, according to estimates that if projected renewable energy demand in 2100 were met entirely through pyrolysis, up to 5.5 - 9.5 Pg C yr^{-1} of bio-char could be produced (Lehmann *et al.*, 2006). In the long term, the bio-char storage capacity of global cropland is estimated at 224 Pg C and for temperate grasslands 175 Pg C, i.e. ~400 Pg C in total (or a ~25% increase in global soil carbon). Assuming that as it decays, this reservoir is continually refilled, the long-term potential is a radiative forcing of ≈ -0.52 W m^{-2} by year 3000 (Lenton & Vaughan, submitted).

The side effects of bio-char are largely positive, enhancing nutrient retention in soils and thus reducing the need for fertiliser additions and ameliorating eutrophication of aquatic ecosystems. Subsequent agricultural disturbance of any enhanced soil carbon would have little negative effect, as any bio-char entrained into the hydrological system would ultimately settle in ocean sediments, and due to its

recalcitrant nature little loss of carbon is expected. Ongoing bio-char production amounts to massively expanding what is currently a small reservoir of long-lived charcoal in soils.

3.1.3 Bio-energy with carbon capture and storage (BECS)

Bio-energy with carbon capture and storage (BECS) amounts to creating a new carbon sink on land, with potential economic benefits in contrast to the costs of chemical air CO_2 capture and storage, but also potentially undesirable side effects. The term covers a variety of biomass and biofuel production pathways, based around forestry, sugar cane and switchgrass production, followed by capture and storage of the CO_2 produced in the fermentation process and in combustion at power stations.

An optimistic estimate is that with CO_2 sequestration from fermentation starting in 2020 and CO_2 capture from flue gases in 2025, up to 50 Pg C could be sequestered by 2035 and 298 Pg C by 2060 (Read and Parshotam, 2007). These figures assume that biofuels displace oil as the major transport fuels and biomass burning displaces a significant amount of the coal used in electricity production (These displacements are not considered here as they amount to mitigation). Taking this scenario as an upper estimate a radiative forcing of ≈ -0.69 W m^{-2} in 2050 is calculated, increasing to ≈ -1.99 W m^{-2} in 2100. In the long term, with continuing BECS activity, there appears to be the potential to cancel the total emissions from a strong mitigation scenario i.e. a radiative forcing in year 3000 of ≈ -1.43 W m^{-2}, if not more (Lenton & Vaughan, submitted).

However, serious doubt can be cast on the feasibility of the numbers proposed this century and the desirability of the land-use changes they imply. To minimise conflict with food production they would demand extending agricultural land and replacing natural grassland ecosystems with bio-fuel plantations. This in turn could lead to elevated emissions of N_2O that counteracts the CO_2 sink created, in terms of radiative forcing (Crutzen *et al.*, 2008).

3.2 Ocean carbon sink enhancement

The natural, pre-industrial state of the carbon cycle had an excess of carbon in the deep ocean relative to the surface and atmosphere. This disequilibrium was continually maintained by the solubility pump (surface waters moving from low to high latitudes cooling and absorbing CO_2 before sinking to depth) and the biological pump (carbon in biological material sinking to depth). The biological pump is further subdivided into the soft tissue (organic carbon) pump and the hard parts (calcium carbonate) pump. Whilst the soft tissue pump acts to lower atmospheric CO_2, the hard parts pump effectively counteracts a part of it. This is because the reaction that forms calcium carbonate in the surface ocean removes two moles of alkalinity from the water for every mole of carbon, thus releasing one mole of gaseous CO_2. Alternatively, calcium carbonate may contribute to the soft tissue pump by 'ballasting' the transport of organic carbon to depth, but current estimates suggest this is less important than the effect on surface chemistry.

There is a large exchange of carbon between the surface ocean and atmosphere (>90 Pg C yr^{-1} for the 1990s) (IPCC, 2007a). Despite significant temporal and spatial variation in this exchange, the global net annual effect is a sink. The surface ocean currently absorbs about a quarter of the anthropogenic CO_2 that is put in the atmosphere annually (Canadell *et al.*, 2007). The present ocean carbon sink is driven by an anthropogenic excess of CO_2 in the air relative to the sea. The majority of the extra CO_2 entering the surface ocean is then transported to depth by the solubility pump, as shown by the distribution of excess (anthropogenic) CO_2 in the ocean – which is concentrated in down-welling regions (Sabine et al. 2004).

A range of climate geoengineering proposals have been made that attempt to enhance elements of the existing ocean carbon sink. Their effectiveness depends on successfully transporting more carbon to depth. The return timescale of carbon that is remineralized at different depths in the ocean is dictated by the movement of water masses and can range from weeks to millennia. Targeting carbon entrainment into particular water masses will maximise the time that the carbon is kept out of interaction with the atmosphere. However, this requires a detailed understanding of where remineralization is occurring within the vertical profile and of the specific dynamics of the targeted region.

3.2.1 Enhancing the solubility pump

Suggested methods of enhancing the solubility pump focus on increasing the absorption of CO_2 in surface waters by increasing the sinking of CO_2-rich waters (Zhou & Flynn, 2005) or by manipulating surface ocean chemistry (Harvey, 2008).

3.2.1.1 Increasing downwelling

Zhou & Flynn (2005) consider a range of methods aimed at increasing the North Atlantic Deep Water (NADW) production by 1 Sverdrup (Sv, 10^6 m^3 s^{-1}) from its current flow rate of 13-20 Sv. They suggest this could be achieved by cooling surface waters by 1°C, by having large floating barges with pumps that form and thicken sea ice. The authors conclude that enhancing downwelling currents is highly unlikely to be a competitive method of carbon sequestration due to the combination of high costs and uncertainty of effectiveness. By their calculations the increase in downwelling current would lead to a net annual incremental flux of 35 $MtCO_2yr^{-1}$ (0.0095 Pg C yr^{-1}). The potential radiative forcing for this activity in 2100 is ≈ - 0.0019 W m^{-2} (Lenton & Vaughan, submitted). The actual value would be less as ocean storage is not permanent. These calculations suggest the method is wholly ineffectual and not worth further discussion.

3.2.1.2 Increasing ocean alkalinity

Increasing the alkalinity of the oceans, through the addition of carbonate minerals has been suggested as a way to enhance the ocean carbon sink (Kheshgi, 1995; Harvey, 2008). This engineered lowering of pH exploits ocean carbonate chemistry, allowing more anthropogenic CO_2 to be absorbed. The use of sodium carbonate (Na_2CO_3) is ruled out as the global recoverable resources would only offset ~6 Pg C (Kheshgi, 1995). Kheshgi (1995) advocates the use of calcium carbonate ($CaCO_3$) found in abundance in the form of limestone, but processed to the more soluble form lime (CaO). Harvey (2008) presents a detailed account based on using a flotilla of ships to sprinkle finely ground limestone ($CaCO_3$) on areas of the surface ocean where the depth of the saturation horizon is shallow (250 - 500 m) and the upwelling velocity is large (30 - 300 m yr^{-1}). We do not consider the reaction of CO_2 with calcium carbonate ($CaCO_3$) in the high pCO_2 of a gas stream because this directly reduces CO_2 emissions to the atmosphere making it a mitigation option (Rau *et al.*, 2007; Caldeira & Rau, 2000; Rau & Caldeira, 1999).

Harvey (2008) calculates that a sink of 0.27 Pg C yr^{-1} could be achieved after a century of linearly ramping up activity, and if maintained for a further ~400 years it could reduce atmospheric CO_2 by ~30 ppm relative to a strong mitigation baseline of 450 ppm, giving a radiative forcing in 2500 of ≈ -0.36 W m^{-2}. We calculate a weaker removal effect of atmospheric CO_2 giving a radiative forcing of and ≈ -0.025 W m^{-2} in 2100 and ≈ -0.20 W m^{-2} in 2500 (Lenton & Vaughan, submitted).

Mining substantial volumes of limestone will have significant localised impacts, and the net benefit of this approach will be significantly decreased if the energy cost of mining and grinding limestone, land and marine transportation are met by fossil fuels (Harvey, 2008). However, given concerns for ocean ecosystems due to ocean acidification at atmospheric CO_2 concentrations as low as 450 ppm (Cao & Calderia, 2008; Zeebe *et al.*, 2008), the potential benefits of this approach have broader appeal.

3.2.2 Enhancing the biological pump

Trying to enhance the biological carbon pump in the ocean is a limited short-term climate engineering strategy because total export production from the surface layers of the world ocean is only of a similar order ~10 Pg C yr^{-1} to current fossil fuel burning and cannot be greatly increased. A key distinction is that boosting primary production in the surface layer of the ocean does not directly translate into an equivalent long-term sink of CO_2. Instead most of the carbon (and nutrients) fixed in the surface layer of the ocean are recycled there, and much of the CO_2 initially taken up is degassed back to the atmosphere. All that counts for a carbon sink on the annual or longer timescale is any net increase in the sinking flux of carbon out of the surface layer, called export production (or new production). Indeed recent mesocosm experiments have actually shown that in some situations where carbon fixed in photosynthesis increased, the export flux of carbon could decrease, because of an even greater increase in bacterial respiration and thus carbon recycling in the surface layer (Thingstad *et al.*, 2008). Export production is generally set by

the flux of incoming nutrients to the surface layer (or photic zone) of the world ocean. Consequently geoengineering proposals for enhancing the biological pump involve enhancing export production either by directly adding limiting nutrients to the ocean surface (NAS, 1992; Lampitt *et al.*, 2008; Boyd, 2008), or by mechanically enhancing the upwelling of nutrient rich water from below (Lovelock & Rapley, 2007; Karl & Letelier, 2008). In most of the surface ocean, the 'macro-nutrients' nitrogen and/or phosphorus are limiting; on average nitrogen runs out first making it the 'proximate' limiting nutrient, but changes in phosphorus availability trigger corresponding changes in nitrogen availability, making phosphorus the 'ultimate' limiting nutrient (Tyrrell, 1999). In some High Nutrient Low Chlorophyll (HNLC) regions, iron is the limiting nutrient. Existing fertilisation experiments (e.g. iron fertilisation experiments) have shown only a small or insignificant increase in export flux (see Boyd *et al.*, 2007). Here we consider three separate options for enhancing the biological pump but discuss their possible side effects together in Section 3.2.2.4.

3.2.2.1 Iron fertilisation

The most widely discussed biological pump enhancement option and most well research geoengineering idea is the addition of iron to areas of the world ocean where it limits productivity, including the Equatorial Pacific, sub-Arctic North Pacific and Southern Ocean. The advanced understanding about this method is a by-product of scientific investigation of the hypothesis that iron is limiting in these HNLC areas (Martin, 1990). To date 12 iron addition experiments (the majority in the Southern Ocean) and two observational studies of iron supply (from the Crozet islands and Kerguelen Island in the Southern Ocean) have taken place (Boyd *et al.*, 2007, Lampitt *et al.*, 2008). Thus, the effectiveness of this geoengineering option is informed by both experimental and observational data, as well as modelling studies (Jin *et al.*, 2008; Bopp *et al.*, 2008; Amount & Bopp 2006; Zeebe & Archer, 2005).

Jin et al. (2008) calculate that by iron fertilising all iron-limited regions of the Equatorial and North Pacific, a net air-sea flux of 3.4 Pg C could be achieved over 10 years (from a pre-industrial state of the carbon cycle). They further estimate that 0.75 to 0.93 of this would translate into a net export flux across 100 m depth. Following the pattern of their 'standard case' scenario, a roughly constant carbon sink of ~0.275 Pg C yr^{-1} would be expected for 10 years. Aumont & Bopp (2006) calculate the effects of a global removal of iron limitation for 100 years and contrast this with a baseline run of their model forced with SRES A2 emissions. They find a much bigger effect, with export production increasing by 3.5 Pg C yr^{-1} initially, decaying to 1.8 Pg C yr^{-1} after 100 years and causing a 33 ppm reduction in atmospheric CO_2 from ~800 ppm. Zeebe & Archer (2005) make a separate estimate that atmospheric CO_2 could be reduced by up to 15 ppm in 2100. These reductions in atmospheric CO_2 equate to a radiative forcing in 2100 of -0.22 W m^{-2} and 0.11 W m^{-2} respectively. We estimate a radiative forcing in 2100 of 0.20 W m^{-2} based on a stronger mitigation pathway and activity commencing in 2020 (Lenton & Vaughan, submitted). On the millennial timescale, literature estimates of the extra carbon that could be stored in the deep ocean from alleviating iron limitation range over 106-227 Pg C (Aumont & Bopp, 2006), the largest value equating to a radiative forcing of -0.29 W m^{-2} in year 3000 (Lenton & Vaughan, submitted).

Experimental and observational work has yet to ascertain the magnitude of any impact of additional iron on carbon export. Of the eleven studies to report export, only five recorded an increase, the remainder saw no change (Boyd *et al.*, 2007). De Barr *et al.* (2008) argue that the range in export efficiency is due to the range of ocean conditions before addition (phytoplankton abundance and taxonomy, zooplankton, water column stratification and temperature) and weather conditions after addition (light availability and wind effecting mixing depths). Many studies conclude iron fertilisation is a relatively ineffective method of tackling elevated atmospheric CO_2 concentrations (Denman, 2008; Huesemann, 2008) whilst others argue it requires further investigation (Smetacek & Naqvi, 2008; Watson *et al.*, 2008). A combined experimental and modelling study approach is advocated, noting that only modelling can assess long term effects on carbon export, but that models need to be constrained by more detailed observations (especially by longer fertilisation studies over larger areas) (Watson *et al.*, 2008).

Iron fertilisation has a strong commercial interest grounded on emerging carbon markets and carbon offsetting (Chisholm *et* al., 2001; Cullen & Boyd, 2008). The first commercial fertilisation experiments were due to begin this year, but Californian based Planktos Inc. halted operations (Courtland, 2008). Currently active commercial ventures include Climos (www.climos.com) and Planktos Science (www.planktos-science.com). There are a plethora of challenges, contentions and potential synergies between scientific and commercially funded ocean iron fertilisation (Leinen, 2008).

3.2.2.2 Macronutrient fertilisation

Oligotrophic regions (low-nutrient low-chlorophyll (LNLC)) account for ~40% of the surface ocean and are limited by nitrogen and/or phosphorous availability. Low nitrate conditions select for nitrogen fixing bacteria (diazotrophs) when all other nutrients (such as phosphate PO_4^{3-}) are available (Redfield 1958). Therefore it has been proposed to add phosphate to LNLC areas (Karl & Letelier, 2008; Lampitt *et al.*, 2008). Alternatively, nitrogen addition in the form of urea ($(NH_2)_2CO$) has been suggested by a commercial venture, Ocean Nourishment Corporation (www.oceannourishment.com). Plans to begin urea fertilisation in the Sulu Sea, around the Philippines in 2008 (Young, 2007) met with vocal concern from the scientific community (Glibert *et al.*, 2008). This may have been a key driver for the memorandum issued by the United Nations Convention on Biodiversity, that called for large scale fertilisation attempts to be prohibited (with a latter amendment exempting scientific research).

There is a deficit of available nitrogen relative to phosphorus in the world ocean, of on average 2.7 mol kg^{-1} (Anderson & Sarmiento 1994), compared to an average deep ocean nitrate concentration of ~31 mol kg^{-1}. Removing the nitrogen deficit would result in a ~9% increase in the export flux. Estimates of the global export flux vary and depend on the depth at which they are measured (the flux declining with depth due to remineralisation). We estimate that the sequestration flux at 500m depth would be increased by 0.21-0.5 Pg C yr^{-1} by alleviating nitrogen limitation which equates to a radiative forcing in 2100 of ≈ -0.10 W m^{-2}. In the long term, if the whole deficit of nitrogen in the global ocean were removed and converted to carbon, a total of an additional 299 Pg C could be stored in the deep ocean, but at 0.5 Pg C yr^{-1} this would take 600 years to achieve (Lenton & Vaughan, submitted).

Each year $0.39\text{-}0.45\times10^{12}$ mol of phosphorous is mined and added to the land surface which has increased the riverine flux of biologically-available (dissolved and particulate) phosphorus (including sewage) to coastal seas by 0.27×10^{12} mol P yr^{-1}, suggesting a 60-70% transfer efficiency (Mackenzie et al., 2002). If all of this is converted to organic carbon with a Redfield ratio of C:P = 106 then it is already generating a sink of 0.34 Pg C yr^{-1}, mostly in coastal and shelf sea sediments. It has been suggested that mined phosphate could also be directly added to the surface ocean (Lampitt et al., 2008), potentially increasing the conversion efficiency to organic carbon. Regardless of whether this happens, we can expect inadvertent phosphorus additions to increase in future. Extrapolating the linear trend detailed in Mackenzie *et al.* (2002) we estimate a radiative forcing in 2100 of ≈ -0.15 W m^{-2}. On the millennial timescale, the total reservoir of mineable phosphate of 323 - 645 × 10^{12} mol P could readily be drained. Taking the upper estimate of the reservoir size and a 70% transfer efficiency a total of 574 Pg C could be sequestered, giving a radiative forcing in year 3000 of ≈ -0.83 W m^{-2} (Lenton & Vaughan, submitted). This assumes that nitrogen fixation will cause nitrogen availability in the ocean to track increased phosphorus availability (Redfield, 1958; Lenton & Watson, 2000) and that micro-nutrients (e.g. iron) do not limit new production in the (currently coastal) regions to which phosphate is added.

3.2.2.3 Enhancing upwelling

The water below the photic zone / surface layer is generally richer in nutrients due to the remineralisation of material sinking from above; therefore it has been proposed that mechanically lifting this nutrient rich water to the surface would create a carbon sink (Lovelock & Rapley, 2007). However, these deeper waters are also relatively carbon rich (due to remineralisation) and will also tend to outgas CO_2, so it is not obvious that the method will be effective (Shepherd *et al.*, 2007). The critical factor is the preferential remineralisation of nutrients relative to carbon at shallow depths. An absolute increase in upwelling flux of such water should lead to a corresponding increase in export flux (assuming nutrient utilisation remains complete).

Lovelock & Rapley (2007) suggested the use of free floating or tethered pipes to transfer water from below the thermocline to the surface waters. Karl & Letelier (2008) suggest that a controlled upwelling of water from a depth of 300 to 350 m to surface LCLN waters would lead to a 2-staged phytoplankton bloom, based on observational and experimental data from a site in the Pacific (22° 45′ N, 158° W). The commercial venture Atmocean (www.atmocean.com) suggest using wave driven barrels to pump water from 200 m depth to the surface and claim their method could sequester 2 Pg C yr^{-1}, which is a gross overestimate (Lenton & Vaughan, submitted).

We estimate an increase in global export flux of 0.08 Pg C yr^{-1} and sequestration flux of ~0.016 Pg C yr-1 is possible if the upwelling flux could be enhanced by 1 Sv globally in regions which all had and maintained complete nutrient utilisation (assuming pipes from ~500 m depth) (Lenton & Vaughan, submitted). To achieve 1 Sv of upwelling would require 4.32 million pumps of the capacity proposed by Atmocean Inc (http://www.atmocean.com/sequestration.htm). Assuming activity started in 2020, this intervention would cause a radiative forcing in 2100 of ≈ -0.0032 W m^{-2} , maintaining this activity to the year 3000 would give a radiative forcing of ≈ -0.028 W m^{-2} (Lenton & Vaughan, submitted).

3.2.2.4 Side effects

A number of possible side effects arising from attempts to enhance the biological pump component of the ocean carbon sink are highlighted in the literature, including: eutrophication and associated anoxia increasing denitrification, loss of biodiversity and harmful algal bloom development; potential redistribution of the global macronutrient balance, with associated downstream effects on productivity; changing emissions of other climate relevant gases and aerosols, (nitrous oxide, methane, halocarbons, ozone and DMS) with an unknown direction of net forcing; and changes to the community structures and functions in the pelagic ecosystem, which in turn affects the export flux, an important driver of the benthic ecosystem (Lampitt *et al.*, 2008; Glibert *et al.*, 2008). The duration of any side effects is difficult to predict and depends upon the manner and extent of ecosystem disturbance. For example, some species of toxic dinoflagellates have cyst life-cycle phases, potentially enabling blooms to occur in years following fertilisation (Glibert *et al.,* 2008).

3.3 Air capture and storage

A third group of carbon cycle geoengineering options considered briefly in this review, act to remove atmospheric CO_2 by wholly artificial means with subsequent storage in the lithosphere, sediments or the deep ocean. To contribute towards reducing the current radiative imbalance caused by greenhouse gases, it is essential that the captured CO_2 is prevented from interacting with the atmosphere. Chemical free air capture is considered by some prominent scholars in the field not to be a geoengineering approach (K. S. Lackner, oral evidence to HoC ISUCC, 10th November 2008). However, we chose to include it based on our distinction between mitigation and geoengineering (Section 1). The storage of supersaturated CO_2 in underground geological reservoirs such as exhausted hydrocarbon reserves and saline aquifers has been a focus of significant research effort for some time, summarised in the IPCC's Special Report on Carbon Capture and Storage (SRCCS) (IPCC, 2005). In the case of air capture with storage, point source capture is classed as a mitigation action, as the emissions never make it into the global atmosphere, but the capture of CO_2 from the atmosphere by chemical engineering processes (`scrubbing') is considered a geoengineering option. The storage options available to either capture method are the same and have received a thorough review as part of the IPCC SRCCS, however new ideas have emerged since the publication of that report. We therefore focus our review efforts on the capture of CO_2 from the atmosphere (i.e. at background concentration levels) and briefly highlight a novel storage idea that was not included in the IPCC's SRCCS.

3.3.1 Air capture

Carbon dioxide can be removed from the atmosphere using chemical engineering, producing a pure stream of CO_2 gas which is then compressed and transported to a storage site. The capture process involves the use of a sorbent material (such as sodium hydroxide, NaOH) that selectively traps CO_2 (Zeman, 2007; Keith *et al.*, 2006, Elliot *et al.*, 2001). Exposure of the air to the sorbent can be ambient (artificial trees) or an active flow (Keith, *et al.*, 2006). Active flow has a greater energy cost but is not dependent upon wind speed to work cost effectively. The regeneration of sorbent, compression and transport require energy, hence the net effect of this process on atmospheric CO_2 will be less if met by fossil fuels. The capture of CO_2 using bio-energy production (BECS) (Section 3.1.3) also generates pure streams of CO_2 for storage. Both methods of capture remove atmospheric CO_2 and share the same storage mechanisms; however we have discussed BECS with other land carbon options due to the similarity of constraints, such as land availability and possible ecosystem disturbance. BECS is estimated to have a better cost-benefit ratio than chemical air capture (Keith *et al.*, 2006). Air capture with storage has the potential to generate whatever size of carbon sink societies are willing to pay for as it is unlikely to

be limited by land or substrate availability (Keith *et al.*, 2006). The ultimate limitation on this engineering carbon sink is storage capacity (see Section 3.3.2). There are few side effects of air capture, aside from the energy and material costs of the infrastructure required if met by fossil fuels.

An alternative proposed method of free air capture is the application of urea, or ammonium sulphate (plus lime), to all non-agricultural land. The idea is that the ammonia emitted would neutralise carbonic acid in the atmosphere and the resulting products would be stored in the surface ocean (Apak, 2007). However, any large scale application of urea would cause a net positive radiative forcing as ammonia is a potent greenhouse gas, it would also entail a massive energy cost and have a number of unwanted side effects including N_2O emissions, inhibition of methane oxidation and eutrophication (Johnson *et al.*, 2008). This is a counter-productive approach and will not be discussed further.

3.3.2 Storage options

Carbon dioxide entrained by chemical air capture or BECS (Section 3.1.3) as well as mitigation activities such as CCS, will utilise the same storage space. Geological storage options suitable for the injection of supercritical CO_2 include depleted oil and gas reservoirs, enhanced oil recovery methods, deep unused saline water-saturated reservoir rocks, deep unmineable coal seams and enhance coal-bed methane recovery methods (IPCC, 2005). It is likely that 99 % or more of the CO_2 injected into these stores would be retained for 1000 years (IPCC, 2005). The storage capacity of geological reservoirs (oil and gas fields, unmineable coal seams and deep saline formations) is estimated to be 460 - 3,030 Pg C (IPCC, 2005). An alternative to geologic storage is the injection of CO_2 into the ocean; however given the significantly detrimental localised impact this would have on ecosystems, geologic storage is perceived to be preferable. Other geologic storage options, explicitly basalts (also see McGrail *et al.*, 2006), oil or gas rich shales, salt caverns or abandoned mines, are largely ruled out as not having any significant contribution to make (IPCC, 2005). One more recent storage idea is to inject CO_2 into deep sea sediments at a depth where it is gravitationally stable (< 3,000m water depth and a few hundred metres sediment depth) (House *et al.*, 2006). At these high pressures and low temperatures CO_2 stays in the liquid phase and is denser than the overlying pore fluid, CO_2 hydrates should form serving as a cap over the pool of liquid CO_2 in the sediments. Concerns highlighted include the unknown implications of the pore water displaced into the ocean and the importance of site selection as landslide events could release the CO_2. A storage capacity of $>10^4$ Gt $CO_{2(l)}$ (>2700 Pg C) is identified within the economic zone of continental U.S.A. (House *et al.*, 2006). It is proposed that no verification or monitoring would be required - an idea that may not be well received. The suggested sediment depths do not overlap with methane hydrate occurrence (see Harvey & Huang, 1995). Therefore one would expect to avoid any interaction with the methane hydrates such as displacement (i.e. release of methane). If this suggested form of carbon storage stands up to subsequent investigation, then when combined with storage options investigated within the IPCC's SRCCS there may be sufficient capacity to store in excess of all the known fossil fuel resources of ~ 3700 Pg C (IPCC, 2007a).

3.4 Implementation issues

The deployment timeframe for afforestation and reforestation is nearly immediate, dependent on land availability and site selection to assure a net cooling effect, given other climate interaction considerations (Section 3.1.1). The development and deployment of bio-char production varies depending on the particular pathway chosen (Section 3.1.2), ranging from changing agricultural practices to bio-energy in the form of pyrolysis (Lehmann *et al.*, 2006). For BECS, the CO_2 capture component is equivalent to that used in standard CCS (Section 3.3.2) and some of the possible storage options are at a demonstration stage (IPCC, 2005). First generation biomass energy has come under considerable criticism regarding location choice and land use conflicts, however second and third generation biomass energy sources may prove less antagonistic, at the cost of incurring longer development timescales. Afforestation, bio-char production and BECS can all be stopped immediately. Afforestation can be reversed although through deforestation, but carbon stored through bio-char production and BECS would not be reversible (without active extraction).

The development and deployment timescale of carbonate addition does not require any significant advances in technology, as the component elements are currently available. However, the development of the sizeable infrastructure required to achieve a global impact would take a significant amount of time (Harvey, 2008). The ability to stop sprinkling crushed limestone onto the surface ocean is of course

immediate. The impact on ocean chemistry however is not able to be stopped, without further chemical engineering intervention (or increasing rates of CO_2 emissions).

Iron and phosphorus addition experiments conducted in recent years (Boyd *et al.*, 2007; Lampitt *et al.*, 2008) demonstrate that ocean fertilization could be deployed immediately, (but only at smaller scales, achieving the maximum potential effects requires significant infrastructure development). Deployment of enhancing upwelling will take longer than iron or macronutrient fertilisation, as the mechanisms suggested are still at a conceptual stage. For all ocean fertilisation approaches, the major constraint on the development and deployment timescale is the assessment of effectiveness of nutrient addition on export production. Experimental work has yet to demonstrate a consistent response to nutrient addition or to be able to confirm exportation to ~500 m depth. The approach therefore requires significant further investigation. All the methods of ocean fertilisation can be halted immediately, the productivity generated will last a matter of weeks, but any successful export production cannot be reversed. If any ocean fertilisation intervention causes ecosystem disruption then the duration of any negative impacts would depend on the how this disruption has manifested itself.

Air capture is currently at a research and development stage (e.g. Zeman, 2008) whilst geological storage operations are still at a demonstration phase (IPCC, 2005). Some specific designs draw on technologies currently used today in paper and cement industries (Keith *et al.*, 2006). The capture intervention could be halted immediately (dependent on design specifics) but the storage component of the system is harder to reverse.

Table 1 Summary of climate geoengineering proposals and their potential cooling effect

4. Discussion

We have summarised each of the geoengineering proposals in the recent literature, detailing their mechanism, effectiveness, side effects and implementation issues, omitting economic and engineering considerations as these lie outside our expertise and little comprehensive work has been published to date. Our definitions and groupings arise from an Earth system perspective, rather than historical precedent or socio-political acceptance (e.g. inclusion of afforestation and reforestation). Here we take an overview of the results, comparing the different options in terms of effectiveness, implementation timescales, controllability and risks associated with failure. Then we turn to the potential relationships between mitigation, adaptation and different geoengineering options. We consider some previously unforeseen Earth system interactions that might occur due to geoengineering, highlight needs for future research, and touch on the geopolitics of geoengineering.

4.1 Effectiveness

The radiative forcing metric allows direct comparison of the potential of different geoengineering methods on a century timescale (Table 1, columns 2 & 3), but it provides only a limited concept of effectiveness, focussed on global annual mean surface temperature. A ranking of the geoengineering options discussed in this review, based on radiative forcing alone (Lenton & Vaughan, submitted), highlights some broad groupings. Sunshades in space or stratospheric aerosols have the greatest potential to uniformly decrease radiative forcing. Mechanical enhancement of marine stratocumulus cloud albedo combined with a variety of land surface albedo modifications could provide a patchy or partial offsetting of radiative imbalance. Air capture and storage, probably via bio-energy plantations, combined with afforestation/reforestation and bio-char addition to soil, has considerable century-timescale potential to reduce atmospheric CO_2. Nutrient addition options for enhancing the ocean carbon sink are less effective on the century timescale. Proposals to seasonally, biologically enhance cloud albedo over the Southern Ocean, or to increase the albedo of urban areas are globally ineffective but could provide useful regional cooling. Proposals to enhance ocean upwelling or downwelling are wholly ineffective, and carbonate addition to the ocean only becomes effective if sustained for many centuries. In the short term, reducing incoming shortwave radiation, most promisingly by stratospheric aerosol injection, would be more effective at addressing the radiative imbalance than attempting to enhance or engineer the carbon cycle (Figure 2).

Figure 2 Schematic illustrating transient geoengineering impacts

Most modelling studies and basic calculations consider a fixed radiative forcing perturbation and/or an equilibrium response. However, the radiative forcing imbalance geoengineering seeks to remedy is currently increasing at about 0.03 W m^{-2} yr^{-1} (Lenton & Vaughan, submitted) and looks set to continue to increase in line with fossil fuel based global energy provision. As such, to remain effective, geoengineering measures should incorporate the ability to be increased as required. However, most of the options have hard limitations on the size of their effect, and all but sunshades in space have some limitation on their effect (Table 1, column 4). Stratospheric aerosols have considerable potential for scaling up their effect, but it will saturate. Mechanically enhancing cloud albedo has some scaling up potential but it is constrained by tropospheric pollution. All surface albedo radiative forcing effects are really maxima constrained by the area of each surface type. Afforestation effects could be saturated within the century timescale, whereas carbon storage in bio-char could continue to increase, ultimately constrained by the size of soil reservoirs. Storage of liquid CO_2 is ultimately constrained by geological reserve capacity. Ocean carbon sink options are inherently slow in their effects anyway.

Many factors may limit how much of the maximum radiative forcing potential of each option is fulfilled. For certain options, feasibility is not constrained by technological development or high costs, but by the ability to verify an effect has occurred, which in turn requires detailed understanding and monitoring. For example, with ocean fertilisation methods, the stimulation of an algal bloom is relatively easy to monitor using existing satellite methods, which have appropriate temporal and spatial coverage. However, the presence of a phytoplankton bloom does not necessarily translate into an increase in carbon export to depth. The relationship between a bloom and the amount of carbon exported varies greatly depending on initial biological conditions, ocean physical dynamics and subsequent weather conditions (De Barr *et al.*, 2008; Lampitt *et al.*, 2008). This then significantly increases the cost element, as blooms would require much closer monitoring.

4.2 Implementation and effect timescales

Accurate development and deployment timescales can only be obtained through rigorous engineering and economic assessment (Lampitt *et al.*, 2008), but we provide a rough indication of the timescales involved for different options (Section 2.6, 3.4 & Table 1 column 5). Some schemes are further developed than others (e.g. Salter *et al.*, 2008), but most have only sketched out costing and material estimates, based on preliminary understanding of the processes involved. Ocean fertilisation based methods have the shortest potential implementation timescales, in that they are already being tested, but their effects take a long time to accumulate. The majority of options require a lead in time of at least a decade, but sunshades in space and land carbon options would need significantly longer to be fully deployed (Table 1).

Progress defining implementation timescales would contribute greatly to the discourse on geoengineering as an 'alternative' to mitigation. Some claim that geoengineering is a cost effective way of dealing with the impacts of anthropogenic greenhouse gas emissions (Carlin, 2007), but this seems premature given the current state of knowledge. Those who advocate geoengineering as part of a tipping point aversion strategy rely on schemes having a short implementation timescale. Furthermore, given that radiative forcing is currently increasing at about 0.03 W m^{-2} yr^{-1}, geoengineering schemes that have limited maximum potential radiative forcing contributions become even less useful if combined with a lengthy lead in time as their fractional contribution will get smaller.

Different geoengineering options vary considerably in the lifetime of their effect (Table 1 column 6). Those with short lifetimes demand correspondingly more frequent interventions to maintain their effect, and should intervention stop for some reason this carries a corresponding risk of rapid warming (Figure 2). Carbon cycle geoengineering options have significantly longer lifetimes of effect than shortwave options, due to the long lifetimes of CO_2 in the atmosphere and of carbon in the reservoirs to which it is being added. For shortwave options, the shortest lifetimes are associated with the generation of tropospheric CCN, followed by the planting of more reflective annual crops, then the injection of stratospheric aerosols, then other surface albedo modifications, and finally sunshades in space (assuming any placed at the unstable L1 point are able to maintain their position).

4.3 Control

The ability to control the implementation of geoengineering options is important in case of unforeseen side effects, and any selection of geoengineering options should take into consideration the ability to

'undo' the intervention. The capacity to stop the intervention within a year (Table 1 column 7) is potentially available to all options except surface albedo changes (due to the vast spatial extent involved), but the speed at which their radiative forcing effect is undone can be much slower (Table 1 column 6). For example, sulphate aerosols have a residence time in the stratosphere of approximately 3 years, so although the active injection of new particles can be stopped immediately the effects could not be. For carbon cycle geoengineering options, their atmospheric CO_2 and radiative forcing effects would take centuries to millennia to decay after stopping activity (but this is a good thing). Limitations to the controllability of different options (Table 1 column 8) are either inherent in the design of the control mechanism, in the time needed to change a modified surface (human settlements, urban areas or desert), or will be determined by the uncertain response of ecosystem processes. For example, low albedo grasses (including crops) may cross with wild relatives and become very hard to control, or in the worst case scenario become invasive species.

A significant feature of shortwave geoengineering options, particularly sunshades, stratospheric aerosols and mechanically enhancing cloud albedo is the risk associated with stopping the intervention abruptly. Once implemented, and the desired levelling of cooling had taken place, abruptly stopping the intervention would lead to very rapid warming (Matthews & Calderia, 2007) (Figure 2). The degree of warming would be largely determined by the underlying concentration of greenhouse gases, especially CO_2. In the absence of any carbon cycle geoengineering, this will be dictated primarily by CO_2 emissions up to that point. If atmospheric CO_2 concentrations had increased in the time since shortwave geoengineering began, the temperature change would be correspondingly increased. In contrast, carbon removed from the atmosphere through geoengineering methods will remain out of interaction with the atmosphere for the residence time of the carbon store (Table 1).

4.4 Trade-offs between mitigation, adaptation and geoengineering

The limitations of geoengineering and concerns surrounding it are strongly related to the level of future mitigation activity. Combined strategies of mitigation and shortwave climate engineering (Wigley, 2006), or longwave geoengineering with additional shortwave geoengineering for abrupt climate change avoidance (Read, 2008), have previously been suggested. In fact there are a range of possible combinations of mitigation, shortwave geoengineering and longwave geoengineering, leading to different climate change impacts and levels of adaptation (Figure 3). The intention here is not to be exhaustive, but to illustrate the long-term trade-offs that could be made between mitigation, longwave and shortwave geoengineering, and the notable impacts of these choices.

Figure 3 Possible combinations of mitigation and geoengineering and their consequences

Here we consider no mitigation to entail the eventual emission of ~4000 PgC and stabilisation at roughly 4 times pre-industrial CO_2 ($4\times CO_2$), whereas mitigation involves the eventual emission of ~2000 PgC and stabilisation at roughly 2 times pre-industrial CO_2 ($2\times CO_2$). Assuming a mid-range climate sensitivity of ~3°C for each doubling of CO_2, the corresponding global warming (from pre-industrial) will be ~6°C with no mitigation and ~3 °C with mitigation. The latter could still potentially lead to loss of the Greenland ice sheet (Lenton *et al.*, 2008), as would the combination of no mitigation and ~2000 PgC of geoengineered carbon storage.

Geoengineering that rectifies the radiative imbalance by reducing incoming solar radiation reduces the immediate need to mitigate or adapt to climate change. However, this only applies whilst the geoengineering measure is maintained, and if no mitigation activity occurs, the effect will have to increase to match the radiative forcing due to rising greenhouse gas levels (Figure 2). Furthermore, a significant fraction of the effect will need to be maintained for >1000 years, because approximately 20% of the CO_2 added to the atmosphere is only removed by natural sedimentation and weathering processes on timescales of 10,000 to 1,000,000 years (Lenton & Britton, 2006). Balancing the radiative forcing caused by increased atmospheric CO_2 (Figure 4) can restore the global mean temperature close to its pre-industrial level (Govindasamy *et al.*, 2003; Matthews & Calderia, 2007), but there may be residual regional climate changes and decreased global mean precipitation (Bala *et al.*, 2008). Thus, adaptation is not avoided altogether (Figure 3). Ocean acidification driven by rising CO_2 will not be addressed and may actual be increased due to cooling enhancing ocean carbon uptake (Zeebe *et al.*, 2008; Matthews & Calderia, 2007) (Figure 4). Any failure of shortwave geoengineering measures would result in extremely rapid climate change (Matthews & Caldeira, 2007) (Figure 2) and demand greater adaptation (or possibly

even exceed adaptive capability). Equally, if measures were deployed too rapidly, or turned out to be more effective than assumed, then climate cooling and associated changes may be more rapid than those due to current warming, demanding corresponding adaptation.

Figure 4 Relationship between atmospheric CO_2 and shortwave geoengineering required to offset resulting radiative imbalance.

Some specific surface albedo enhancement measures increase adaptive capacity, notably enhancing albedo of urban spaces, which should reduce urban heat island effects. Other measures may reduce adaptive capacity, for example, breeding and selecting crops to enhance surface albedo may be in conflict with selecting strains for optimum productivity in an altered climate, or may alter the surface energy balance in a way that reduces evapotranspiration (and hence also precipitation).

Enhancement of natural carbon sinks or creation of engineered carbon sinks can complement but cannot replace mitigation to reduce the sources of CO_2 (except over many centuries). Reliance on engineered carbon sinks in particular requires sizeable storage capacity. Without mitigation it could ultimately demand ~4000 Pg C storage capacity, and even with mitigation it could demand ~2000 Pg C storage capacity (Figure 3). In the short-term, out to the century timescale, mitigation has the greatest potential to limit the increase in atmospheric CO_2 concentration and corresponding radiative forcing, although it could be complemented by air capture and storage and deliberate enhancement of land carbon sinks. In the longer term, out to the millennial timescale, the first order determinant of CO_2 concentration will be the total amount of fossil fuel combusted without carbon capture and storage. Enhancement of the ocean carbon sink has the potential to significantly lower the final stabilisation level of CO_2 and climate. Ongoing air capture and storage of CO_2 has the potential to progressively reduce it. Bio-char could also provide a substantial carbon store on the multi-centennial timescale. The limited effectiveness of ocean carbon sink enhancement on the centennial timescale, and the potentially disruptive effects of trying to boost export production, suggest that geoengineering might be better directed at protecting the integrity of marine ecosystems, e.g. by carbonate addition to counteract ocean acidification (Harvey, 2008). On land, in contrast, some proposed efforts to increase carbon storage carry 'win-win' benefits of restoring forest ecosystems and soils.

There are potential merits in a shift in balance over time from shortwave to longwave climate engineering measures. Shortwave measures have greater potential effectiveness in the short-term but carry substantial risks associated with failure, whilst longwave measures are less risky but are only really effective in the longer-term. Conceivably, a no mitigation approach could be counteracted with a mixture of longwave and shortwave geoengineering, but some ocean acidification and residual regional climate changes would still be expected to occur (Figure 3).

4.5 Unforeseen Earth system interactions

The possible Earth system interactions and potential side effects of geoengineering interventions should be considered before any activity is sanctioned. We have not attempted to provide an exhaustive list of possible Earth system interactions, concentrating instead on the main concerns. There are ample historical cases where intervention into ecosystem functioning have resulted in unanticipated effects. The Earth is a complex and richly interconnected system, which means that interventions may have unanticipated impacts in unexpected parts of the system. As an illustrative example, simulations of stratospheric sulphate aerosol injection suggest it will deplete stratospheric ozone levels, causing a decadal delay in the recovery of the Antarctic ozone layer (Tilmes *et al.,* 2008). Stratospheric ozone depletion over Antarctica is a key driver of observed changes in the Southern Hemisphere Annular Mode (SAM) in recent decades (Thompson & Solomon, 2002), which is also contributed to by greenhouse gas forcing (Perlwitz *et al.*, 2008). Observed strengthening of Southern Ocean winds has been attributed to the shift of the SAM to a positive state (Perlwitz *et al.*, 2008). The strengthening of these winds is causing a reduction in the efficiency of the Southern Ocean carbon sink (Le Quere *et al.*, 2007). Thus, there is the potential for stratospheric sulphate aerosol geoengineering to negatively affect the efficiency of existing sinks of anthropogenic carbon.

A further illustration of the interconnected and potentially complex response of the Earth system is exemplified by a recurring feature in geoengineering modelling work to date. As already discussed, a number of geoengineered model worlds (with high CO_2, but pre-industrial temperature), exhibit a

decrease in global mean precipitation, reflecting much greater variations in regional precipitation patterns. Simulations of the effect of reducing the solar constant and of the impact of increasing CCN over marine areas, show a recurring pattern of increasing the Atlantic North-South gradient in sea surface temperature (SST), with cooling in the South Atlantic relative to the North Atlantic (e.g. Figure 2(a) in Lunt *et al.* (2008) and Figure 3 in Latham *et al.* (2008)). The North-South gradient of Atlantic SST is a major controlling factor in West African Monsoon (WAM) activity, being well correlated with precipitation in the Sahel (Peyrille *et al.*, 2008). Furthermore, increasing the Atlantic North-South SST gradient has been correlated with a reduction in dry season rainfall in western Amazonian (Cox *et al.*, 2008). Thus, residual regional temperature changes in a geoengineered world (high CO_2, reduced temperatures) may have impacts on globally important 'tipping elements' of the Earth system, such as the West African Monsoon and/or Amazon rainforest (Lenton *et al.*, 2008).

These examples illustrate that rectifying a global radiative imbalance caused by elevated atmospheric CO_2 concentrations does not necessarily eliminate significant climate changes, and may bring about unforeseen Earth system responses, which in turn may have the potential to change the magnitude of the initial radiative imbalance.

4.6 Future research

Existing research into geoengineering options has been very limited; most published papers scope out theoretical concepts and conclude with extensive lists of issues requiring investigation. Those ideas that have been subjected to further investigation have been approximated in numerical models (ranging in complexity and scope), with perturbations to particular parameters in order to emulate geoengineered changes to the Earth system. Modelling studies are the limit of investigation into geoengineering to date with the exception of ocean fertilisation, afforestation, bio-energy with carbon storage and chemical air capture and storage. Research aimed at better understanding biogeochemical cycling, through controlled experiments adding limiting nutrients to the oceans has been conducted for a number of years. One by-product has been insight into the potential for geoengineering. Although generally not classed as a geoengineering option for historical and cultural reasons, afforestation and reforestation has also undergone significant investigation.

There is an emerging consensus that geoengineering options need to be investigated and that this can be done without any deleterious unintentional impacts via the use of modelling (Cicerone, 2006). Modelling largely avoids the ethical constraints and conundrums surrounding actual geoengineering activity. Many geoengineering papers conclude by identifying particular facets of their proposal that require more detailed model based investigations (such as Latham *et al.* (2008) for mechanical CCN production and Watson *et al.* (2008) and Smetacek & Naqvi (2008) for iron fertilization). However, although numerical modelling is a powerful tool for the investigation and synthesis of observed data, theoretical relations and assumptions about Earth system processes, models are as fallible as the assumptions and data they are encoded with. Modelling will never incorporate all the complexities of the Earth system, its ecology, biogeochemical cycling, and human systems, or the complete range of spatial and temporal scales over which these various factors act.

Many advocate a combined approach, highlighting the need for experimental and observational investigation particularly for geoengineering options such as ocean fertilisation (Lampitt *et al.*, 2008, Watson *et al.*, 2008; Smetacek & Naqui, 2008), for which experiments have already been conducted (Boyd *et al.*, 2007). However, field experimentation of geoengineering options is not always feasible and given the potential regional or global impacts, is likely to come up against social and political objections. Natural analogues can provide some insight into the possible impacts of particular geoengineering interventions, such as the eruption of Mt Pinatubo for stratospheric sulphate aerosol injection. However the imperfections of the analogy (different particle size and injection height) and therefore limitations of the insight must be recognised (Rasch *et al.*, 2008b).

4.7 Geopolitical

A thorough understanding of the current and potential future international political and legislative implications of geoengineering is sorely needed, and long overdue (Schneider, 1996; Orbach, 2008). Mitigation requires the majority of nations and individuals to comply in order to be effective, whilst geoengineering does not. Taking sulphate aerosols as a case in point, the actual total cost of injecting ≤ 5

Tg S yr^{-1} into the lower stratosphere falls well within the financial capabilities of the most economically developed countries and even extremely rich individuals (Crutzen, 2006). This type of intervention would have significant global, and regionally variable, impacts. The problem is then ethically, socially, politically and legislatively very different to mitigation, and knowledge gained from the mitigation discourse is not necessarily transferable to geoengineering. However, mitigation negotiations to date do amply illustrate that whatever the recommendations regarding geoengineering from the physical or economic sciences, in/action will ultimately be dictated by political processes.

Some have already argued that shortwave geoengineering measures are preferable to mitigation because they could be undertaken quickly (for example, to avoid climate tipping points). A key component of this argument is the speed of implementation, as geoengineering can be enacted by one nation (or individual) thereby circumnavigating the slow process of attaining international consensus (the bane of mitigation agreements to date). Thus a single actor could potentially exert a significant effect on global temperature and climate, in turn affecting the global population. This could be framed as an aggressive act, as once global temperatures are lower, stopping the intervention would cause very rapid warming. For these reasons, it is foreseeable that international consensus would be required by all parties, before such intervention were deemed acceptable (see Zugspitze Declaration, 2008). This then nullifies the argument that geoengineering is preferable to mitigation, based on speed of implementation, because geoengineering would still require global consensus.

5. Conclusions

Geoengineering is best considered as a potential complement to the mitigation of CO_2 emissions, rather than as an alternative to it. Shortwave geoengineering can rectify a global radiative imbalance, and can do so on a decadal timescale. However, ocean acidification and residual regional climate changes would still occur and the intervention could bring about unforeseen Earth system responses that may in turn increase the radiative imbalance. Shortwave measures are not an alternative to mitigation, and would have to be deployed in conjunction with longwave (CO_2) geoengineering or maintained on timescales >10,000 years in order to avoid extremely abrupt warming if they failed, or when the intervention stopped. Longwave geoengineering involves less risk than shortwave geoengineering, as it acts upon the primary cause of the radiative imbalance (atmospheric CO_2) and has limited capacity for 'failure'. However, these measures are only really effective in the longer term. It will not be possible to return to a pre-industrial climate on a millennial timescale without the creation of engineered carbon sinks, e.g. carbon storage with CO_2 captured from the atmosphere, either by bio-energy or chemical processes. However, air capture and storage is ultimately limited by the capacity of geological reservoirs, the upper estimates of which fall short of estimated fossil fuel resources.

Geoengineering could be conducted by one nation or individual and would incur global (and regionally variable) impacts. The geopolitical implications of this are poorly understood. It is foreseeable that global consensus would have to be attained before any large scale geoengineering were undertaken. The majority of geoengineering options require significant amounts of research, particularly into effectiveness and side effects. However, much of this research is hampered by the global scale nature of the geoengineering proposals. The difficulties of verifying effects, coupled with inevitable acceptance issues amongst the global population, could impose a significant (if not terminal) constraint on the possible role of geoengineering in avoiding dangerous climate change.

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Figure 1 Schematic overview of the climate geoengineering proposals reviewed

Black arrowheads indicate short wave radiation, white arrowheads indicate enhancement of natural flows of carbon, grey downward arrow indicates engineered flow of carbon, grey upward arrow indicates engineered flow of water, dotted vertical arrows illustrate sources of cloud condensation nuclei and dashed boxes indicate carbon stores. Not to scale.

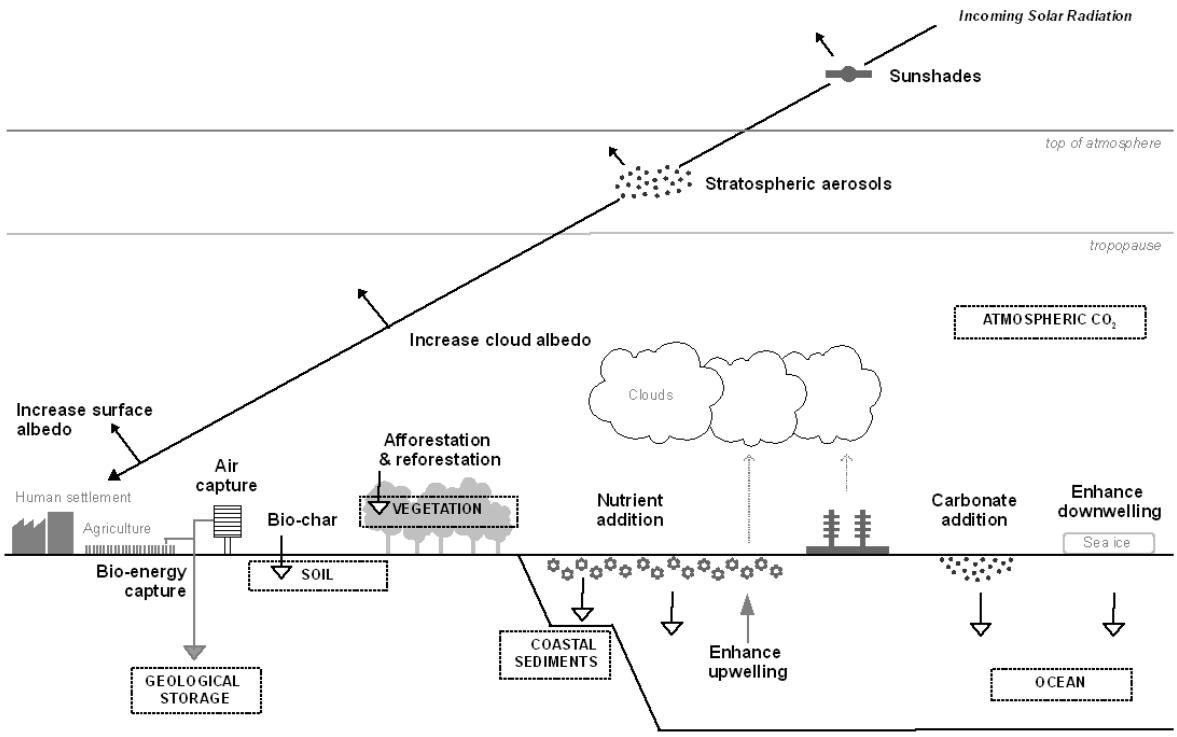

Figure 2 Schematic illustrating transient geoengineering impacts

The impact of shortwave geoengineering only and longwave geoengineering only strategies on global temperature and atmospheric CO_2 concentration from ~1900 to 2500 are illustrated. Grey lines represent temperature change. Solid line shows temperature change for a doubling of atmospheric CO_2 (560 ppm). Dash dotted line shows the impact of longwave geoengineering. Dotted line shows the impact of shortwave geoengineering (with and without failure/intervention cessation). Black lines show change in atmospheric CO_2. Solid line represents atmospheric CO_2 concentration pathway that stabilises at 560 ppm. Dashed line shows the impact on atmospheric CO_2 concentration of longwave geoengineering.

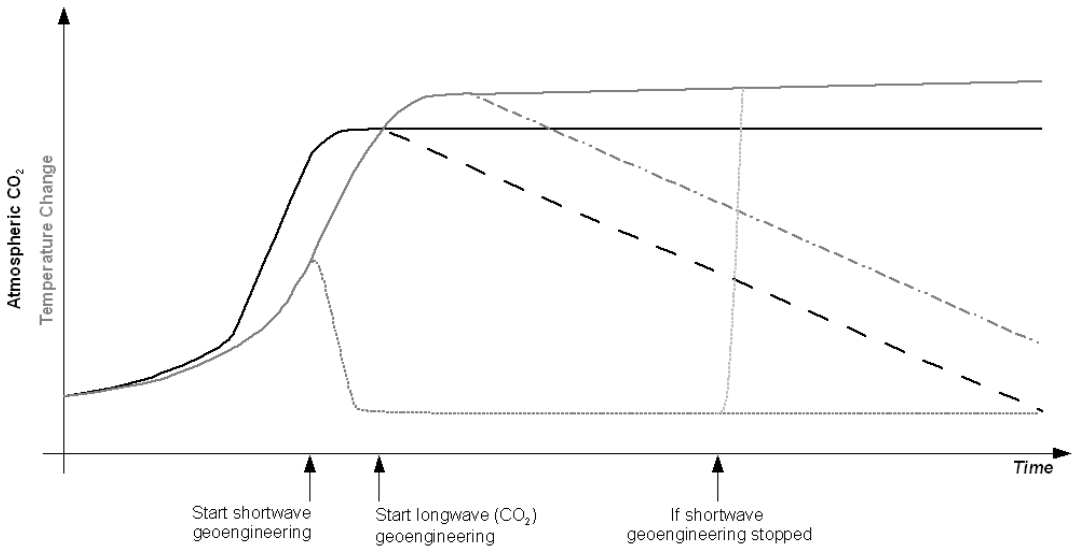

Figure 3 Possible combinations of mitigation and geoengineering and their consequences

Here we use a black circle (●) to denote high, grey circle, (●) medium, and white circle (○) zero/pre-industrial. Ball park figures can be assigned to these, for carbon emitted or stored by longwave geoengineering, ● ≈ 4000 Pg C, ● ≈ 2000 Pg C, for shortwave geoengineering, ● ≈ 3.2 % and ● ≈ 1.6 % reduction in incoming solar radiation, for atmospheric CO_2, ● ≈ 4 x pre-industrial, ● ≈ 2 x pre-industrial concentration, for global temperature change (assuming a mid range climate sensitivity) ● ≈ 6°C, ● ≈ 3°C. Qualitative measures are given for other climate changes and half circles denote residual regional climate changes.

				Consequences			
	Carbon emitted	Shortwave geoengineering	Longwave (CO_2) geoengineering	Atmospheric CO_2	Global temperature change	Other climate changes	Notes
No mitigation	●	○	○	●	●	●	Extensive climate change
	●	○	●	●	●	●	Probable loss of Greenland Ice Sheet
	●	○	●	○	○	○	**Requires 4000 PgC storage capacity**
	●	●	○	●	●	●	Maintenance of intervention required
	●	●	●	●	○	◗	Maintenance of intervention required
	●	●	○	●	○	◗	Maintenance of intervention required
Mitigation	●	○	○	●	●	●	Probable loss of Greenland Ice Sheet
	●	○	●	○	○	○	**Requires 2000 PgC storage capacity**
	●	●	○	●	○	◗	Maintenance of intervention required

Figure 4 Relationship between atmospheric CO_2 and shortwave geoengineering required to offset resulting radiative imbalance.

Grey shading illustrates the uncertainty of the Earth system response. Note logarithmic scale on the y axis. Current atmospheric CO_2 and radiative forcing of +1.66 W m^{-2} are shown with grey arrows.

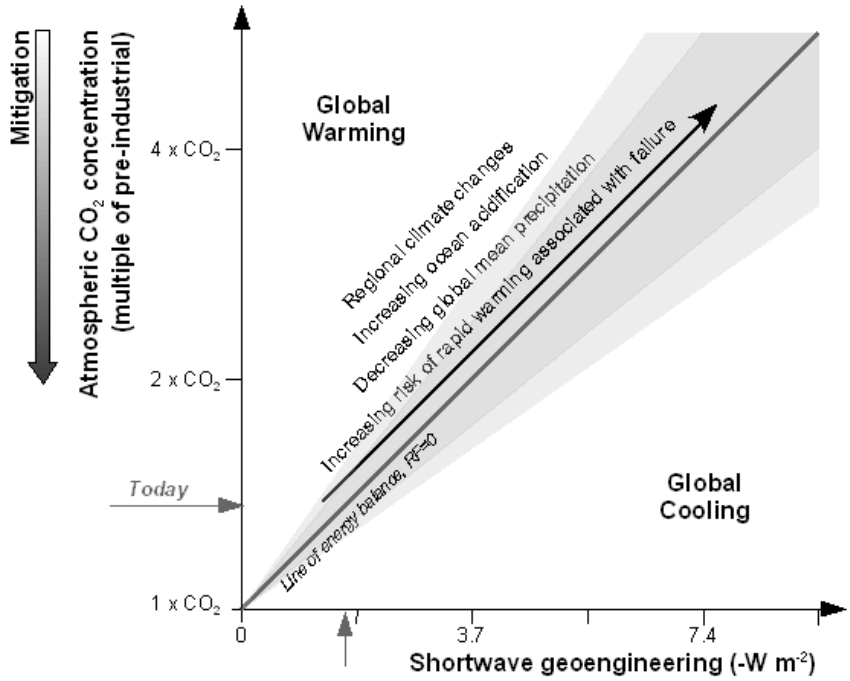

Table 1 Summary of climate geoengineering proposals and their potential cooling effect

Climate Geoengineering Proposal	Radiative Forcing		Limitation to effect	Deployment time	Lifetime of effect	Controllability	
	Published	Estimated[9]				Switch off < 1 year	Limitation
	W m^{-2}	*W m^{-2}*		*years*	*years*	*yes /no*	
Sunshades in space	-4.23 (1)	-3.71	None	>20	~ 20	Yes	Control mechanism
Stratospheric aerosols	~3 (2)	-3.71	Saturation	~10	~ 3	Yes	Particle residence time
Increase cloud albedo							
Mechanical	-3.7 (3)	-3.71	Tropospheric pollution	~ 10	<< 1	Yes	Control mechanism
Biological	-0.025 (4)	-0.016		~ 1	<< 1		Ecosystem changes
Increase surface albedo							
Grassland	-0.59 (5)	-0.64	Surface area	~ 10	~ 10	No	Ecosystem changes
Cropland	-0.26 (6, 9)	-0.44			~ 1		
Human settlements	-0.17 (5)	-0.19			~ 10		Surface replacement
Urban areas	-0.044 (7)	-0.010			~ 10		
Desert	-2.75 (8)	-1.74			< 10		
Land carbon sink							
Afforestation & reforestation		-0.37	Land area availability	~ 50	~ 100	Yes	Ecosystem changes
Bio-char (soil carbon)		-0.40			> 1000		
Bio-energy & storage (BECS)*		-1.99			> 1000		
Ocean carbon sink							
Enhanced downwelling		-0.0019	Ocean physics	~10	~ 500	Yes	Control mechanism
Carbonate addition		-0.025	Ocean chemistry	~ 1			Control mechanism
Iron addition		-0.2	Limitation by other nutrients and denitrification	~ 1			Ecosystem changes
Nitrogen addition		-0.1		~ 1			
Phosphorus addition		-0.15		~ 1			
Enhanced upwelling		-0.0032		~ 10			
Engineered sink							
Air capture & storage			Storage capacity	~10	> 1000	Yes	Storage security

Notes *BECS can be considered an example of air capture and storage. Carbon sink options RF estimates are for 2100 (Lenton & Vaughan, *submitted*).
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Royal Society geoengineering submission
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Introduction
Examined in this paper are two schemes for albedo modification over the oceans. Both are briefly introduced and explained. The relative advantages and shortcomings of the two schemes are then noted (from an atmospheric perspective), before moving on to a general discussion about albedo modification and its implications. The principle focus throughout is on the atmospheric rather than oceanic science. Potential impacts on the oceans are noted qualitatively where relevant however.

The Wingenter iron fertilization / marine albedo scheme
It is now well known that large areas of the Earth's oceans are iron limited, the Southern Ocean being the prime example. There have been several cases of iron fertilization experiments (e.g. SOFeX) that have observed increases in marine phytoplankton primary productivity. This response of the ocean biota to alleviation of iron limitation has been suggested as a way of sequestering atmospheric CO_2 (Martin *et al.*, 1990). This has proved a controversial suggestion, not least because the actual effect on a marine ecosystem is very poorly understood, and the long term sequestration of any CO_2 is by no means guaranteed.

A variation of this iron fertilization idea was highlighted by Wingenter *et al.* (2007). The authors proposed that an increased flux of the gas dimethyl-sulphide (DMS) could also result from iron seeding (based on results in Wingenter *et al.* (2004)). In the atmosphere, DMS is oxidised and contributes to sulphate aerosol. Wingenter et al. proposed that increased sulphate aerosol would result in higher concentrations of cloud condensation nuclei (CCN) in the atmosphere and hence also increased cloud droplet number (CDN) concentrations. Such a geoengineering solution would therefore increase the planetary albedo through the aerosol indirect effects and is essentially a deliberate attempt to manipulate the CLAW mechanism (Charlson *et al.*, 1987).

Specifically, the scheme calls for fertilization of approximately 2% of the Southern Ocean, which after dilution would cover 5% of the Southern Ocean. Wingenter *et al.* (2007) predict that fertilization would result in an increase in concentration (and also sea-air flux) of DMS by 20% (when integrated over the entire Southern Ocean). The authors empirical relationships to predict a 10% increase in the number of CCN, and a 0.8% increase in albedo over the Southern Ocean. This projection leads to an estimated 3 Wm^{-2} decrease in energy reaching the surface, and a 2 °C cooling over the Southern Ocean. Lower temperatures in this region could slow the melting of the Antarctic ice and slow the expansion of sea-water due to warming.

An iron fertilization scheme of this type would be considerably smaller in size and hence cost less than a scheme leading to CO_2 sequestration.

General problems with cloud albedo modification
The geoengineering option outlined above attempts to alter cloud radiative properties by changing the microphysical properties of marine clouds. For a fixed cloud water content, increasing the number of cloud droplets will reduce the mean radius of the droplets in the cloud, with a corresponding increase in the total surface area of those water droplets. This leads to an increased cloud albedo. This is the first aerosol indirect, or Twomey, effect. The second aerosol indirect (Albrecht) effect concerns cloud lifetime. Smaller cloud droplets will have a lower collision and coalescence rate, thus slowing down the rate at which they grow to form raindrops. The implication of a lower raindrop formation rate is longer cloud lifetime. Both increased albedo and longer cloud lifetime would serve to reduce the amount of shortwave radiation arriving at the Earth's surface, hence cooling the area underneath the clouds.

Perhaps the first and possibly greatest criticism of albedo modification schemes is that they don't deal with the cause of climate change, i.e. increased longwave absorption in the atmosphere as a result of an increased concentration of greenhouse gases. Increasing albedo reduces the amount of shortwave energy reaching the Earth's surface, hence cooling the surface. Other impacts of increased greenhouse gas concentrations are not dealt with, e.g. ocean acidification.

Another significant problem with the albedo modification schemes noted here is that only local or regional cooling can be achieved because the shortwave radiative effect of the cloud modification is limited to directly below the cloud. There are very specific oceanic regions where the modification will be potentially

effective. The global impact of highly localised cooling needs to be carefully considered because of potential feedbacks on atmospheric circulation.
It is often stated that one advantage of geoengineering by cloud modification is that that the effects can be terminated very quickly. However, the reduction in solar radiation at the surface will result in a cooler ocean mixed layer. The recovery time of ocean temperature is at least as long as the period of forcing. The timescales of recovery have not been investigated.

The second aerosol indirect effect, also known as the lifetime or Albrecht effect, is debated. As already noted, increases in cloud lifetime are proposed to occur as a result of reduction in size of cloud droplets, due to decreased precipitation efficiency. There is a complicating factor however. A smaller cloud droplet is also likely to undergo increased evaporation because of its smaller size, in effect reducing cloud lifetime. Thus a competition between decreased precipitation and increased evaporation controls cloud lifetime. Xue *et al*. (2008) model this effect, and find that initially increasing the number of cloud droplets (from an unpolluted cloud) leads to an increased lifetime (or cloud fraction) as a result of suppressed precipitation. However, a concentration is reached where the cloud droplets become small enough for the dominant influence to become evaporation, thus decreasing cloud lifetime. Cloud lifetime can actually be decreased to less than the unpolluted cloud lifetime.

Specific problems with the Wingenter *et al*. scheme

In addition to the general problems related to albedo modification outlined above, there are other concerns. Vogt *et al*. (2008) highlight that not all iron fertilization experiments lead to an increase in DMS concentrations; some experiments have in fact shown a decrease. The increase in DMS concentration estimated by Wingenter is at the high end of observed responses. The actual response of the marine ecosystem to iron seeding is very difficult to predict, as there are complex interactions within the system, and data is sparse.

The calculation of CCN, CDN, albedo and temperature response is very basic in Wingenter *et al*. (2007). A comprehensive evaluation would require the use of a microphysical aerosol model to resolve the aerosol indirect effects. For estimates of climate impacts, a climate model would also be needed.
A detailed microphysical aerosol model was used by Woodhouse *et al*. (2008) to simulate the impact on CCN of the proposed Wingenter scheme, see Table 1.

	Wingenter et al., 2007	Model
DMS flux change	+20 %	+8.0 %
CCN (> 25 nm) change	+10 %	+1.29 %
CCN (> 35 nm) change	-	+ 0.04 %

Table 1. The relative change in DMS production and CCN over the Southern, as predicted by Wingenter *et al*., 2007 and a microphysical aerosol at 1 km altitude. From Woodhouse *et al*., 2008.

The model results predict that the Wingenter *et al*. (2007) predictions are very optimistic. The modeled change in CCN number is modest compared to what is predicted. Calculations of change in CDN and albedo were not performed by Woodhouse *et al*, although a similar model run in a coupled climate model is planned for the future.

Potential feedbacks and changes in the surface ocean as a result of albedo modification

Any changes in the atmosphere could also lead to changes in the surface ocean below. As already noted there will be changes in the amount of shortwave radiation reaching the surface ocean that may induce changes in local or regional circulations and hence winds. Any change in wind can also alter the flux of sea-salt, DMS and organics to the atmosphere as fluxes of these are known to be highly dependent on windspeed. This has the ability to further alter the aerosol and clouds.

An increased cloud lifetime implies reduced precipitation. Over land this will have important consequences. Over the oceans, the implications are possibly less clear, but might affect life at the surface.

The effect of less shortwave energy (sunlight) as a result of increased albedo is clearer. Less sunlight could mean lower rates of photosynthesis. It would also mean lower sea-surface temperatures and reduced

evaporation. Greater turbulent mixing (and hence nutrient availability) could also result due to reduced stratification. The effect on marine life could be significant.

Principal conclusions

- Wingenter estimate of response of CCN and climate to an altered DMS flux is very optimistic. Follow-up assessments using detailed global aerosol models suggest a modest response in CCN of approximately 1%.
- Mass and number resolving model necessary for determining microphysical responses to albedo modifying geoengineering schemes.
- There are a host of potential consequences both in the atmosphere and in the surface oceans. These need to be explored and tested with detailed regional and global climate models.

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Carbon sequestration via wood burial and storage

Summary

- **Concept** A forest management scheme is proposed in which certain dead or live trees are harvested via collection or selective cutting, then buried in trenches, stowed away in above-ground shelters, or submerged under deep water. The largely anaerobic condition under a sufficiently thick layer of soil will prevent the decomposition of the buried wood. Because a large flux of CO2 is constantly being assimilated into the world's forests via photosynthesis, cutting off its return pathway to the atmosphere forms a net carbon sink.
- **Theoretical potential** A sustainable long-term carbon sequestration potential is estimated to be 10 ± 5 GtC y-1. The potential is largest in tropical forests (4.2 GtC y-1), followed by temperate (3.7 GtC y-1) and boreal forests (2.1 GtC y-1).
- **Cost** A first-order cost estimate is $14/tCO2 ($50/tC). The cost is low because CO2 is removed from the atmosphere by the natural process of photosynthesis.
- **Potential environmental impacts** such as nutrient lock-up, disturbance to forest floor and habitat, and other unintended consequences, which nevertheless appear manageable and require research. Various factors such as conservation and competition with other wood usage will likely set limits so that only part of the full potential can be realized.
- **Synergies** Wood burial and storage can be practiced in conjunction with other activities to achieve co-benefits or reduce negative impact, including: (1) burying/storing downed wood from deforestation, instead of burning; (2) extending indefinitely the ability of reforested land to take up carbon; (3) burying post-consumer wood; (4) burying excess fuel load on forest floor to reduce fire danger; (5) burying/storing wood damaged by storms and insect infestation.
- **Potential role for climate mitigation** The technique is low tech, easy to monitor, distributed, safe, and reversible. It requires little government intervention except for carbon accounting and monitoring, as long as market incentives are provided through climate change policy or voluntary means.

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1. Concept
The terrestrial biosphere takes up 60 GtC (Gigaton carbon) each year by photosynthesis as net primary productivity, which turns over into litterfall and soil carbon as leaves fall and trees die. These are subsequently decomposed by microorganisms, and eventually go back to the atmosphere as CO2. Under steady state, the net carbon flux is near zero. However, if we can siphon even a small fraction of this fast cycle to a long-term storage, we have the hope of creating a sustainable carbon sink that can potentially rival the fossil fuel emission, currently at 8 GtC y-1.
The proposal here is to collect dead wood on the forest floor or selectively cut live trees in a way that minimizes the disturbance to the forest. The coarse woody material is then buried in trenches dug on the forest floor or stored in sealed shelters above ground. The largely anaerobic condition under a sufficiently thick layer of soil will prevent the decomposition of the buried wood. As the forest continues to take up CO2 by photosynthesis, the net effect is a carbon sink. Details can be found in Zeng (2008).

2. Implementation strategy
The implementation of a wood burial scheme will involve three major steps:
(1) Enabling access to the forest if not already in place;
(2) Site selection, trench digging for burial or building a shelter for above ground storage.
(3) Selective tree cutting or the collection of dead wood followed by trimming, shortening and burial or storage, repeated at an appropriate return interval.

In situ burial is preferred to minimize transportation cost and associated CO2 penalty. The burial needs to be below the organic horizon and rooting zone with sufficiently thick soil cover to ensure anaerobic condition. Shelter storage needs to be completely surrounded by resistant material to prevent the invasion of fungi, insects, plants and animals and regular maintainance and monitoring are needed. It is also possible to submerge logs under water, but it may have more limited capacity as water bodies with anaerobic conditions are not wide spread.

3. Cost
The cost is estimated at $50/tC ($14/tCO2) based on data from logging industry. It is low compared to CCS because wood burial is free air capture with near-zero cost because it is done by the natural process of photosynthesis. When implemented at global scale, many factors will vary from location to location such as technology and labor costs. The cheapest will be the forests that are already under intense management where roads and machinery are in place. The price may increase as the total area of forests utilized this way increases. The operation of machinery will consume some fossil fuel and emit CO2. These factors need to be evaluated.

4. Scale of operation
Even if only half of the estimated potential (5 GtC y-1) is carried out in the next few decades, the scale of such a world-wide operation would be enormous, as illustrated in the scenario below. If each trench has a 500 tC capacity (a dimension of 40m × 10m × 7m), then the number of trenches needed for a 5 GtC y-1 sequestration rate would be 10 million per year, i.e., one trench every 3 seconds. Assuming it takes a crew of 10 people (with machinery) one week to dig a trench, collect/cut and bury wood over a 100 hectare area, 200,000 crews (2 million workers) and sets of machinery would be needed. This estimate is admittedly simplistic and the task could be quite labor-intensive if it is to be carried out in dense or steep-sloped natural forests.
The plausibility of this operation may be viewed from an economical point of view. A $50/tC cost for wood burial corresponds to $250 billion per year at a 5 GtC y-1 sequestration rate. This is only 0.5% of world total GDP of $48 trillion in 2006. Obviously, labor and machine costs can be very different in different countries. The job opportunities provided by the operation and other positive impact on the economy will be attractive in many regions especially the developing countries.

5. Potential issues
Decomposition of buried wood Because of the low oxygen condition below soil surface, the decomposition of buried wood is expected to be slow. This is supported by the observation of extremely slow decomposition of woody material such as furniture in landfills where wood products are found to be well preserved after many years of burial. Methane generation under anaerobic condition may be minimal because methanogenic bacteria do not attack lignin. Ancient wood can be preserved for thousands of

years in undisturbed archeological sites. Indeed, the current proposal can be viewed as creating 'graveyards' for dead trees worldwide.

Nutrient lockup One potential drawback of wood burial is that nutrient in wood will be locked away. Fortunately for our purpose, the nutrient content of wood is low because of the structural component consists mainly cellulose-lignin carbonhydrates. For instance, typical carbon to nitrogen ratio (C:N) is 20:1 for leaves, but 200:1 for wood.

The ultimate question is whether internal fixation and external input are fast enough to compensate for the loss rate due to burial lockup. Globally speaking, the nitrogen lock-up due to a 10 10 GtC y-1 burial is about 1/5 of natural plus anthropogenic nitrogen deposition rate, thus it does not appear to be a problem big enough to hold back the wood burial proposal. However, our current understanding of such issues is limited, and more research in this area is needed.

Habitat loss and disturbance to forest floor and soil

Competition with other wood usage Current world total wood consumption is about 0.9 GtC y-1. Compared to the 10 GtC y-1 coarse wood production rate, there will be additional capacity for carbon sequestration.

6. Co-benefits with other activities

Reforestation and afforestation: making the carbon sink long-lasting Reforestation is a widely embraced carbon sequestration technique. However, as forest and underlying soil mature, the carbon sink becomes saturated. Reforestation followed by sustainable wood burial will extend the lifetime of such land carbon sink indefinitely.

Deforestation: cutting off the CO2 source

Post-consumer wood: making waste a carbon sink

Fire suppression: burying the fuel

Catastrophic damages: storm blowdown, insect infestation Wood from catastrophic death that would otherwise decay can be collected and buried. Examples include the damaged trees by Hurricane Katrina in southeastern US during 2005, and the dying pine forests of western US and Canada by bark beetle infestation.

7. Conclusions

Coal was formed by the burial of ancient plants in anaerobic conditions such as swamp and peatland. The proposed wood burial method is essentially a first step of a fossil fuel formation process, only drastically *accelerated* by active human management. It is ironic that the whole climate change problem is caused by the human *accelerated* release of the fossil fuel carbon pool. Thus it will not be surprising if this method turns out to be the most 'natural' way to undo fossil fuel CO2 emission.

The wood burial technique uses natural tree growth to capture CO2 from the air at nearly no cost, thus making it significantly more economical than other carbon capture methods. For storage, past focus has been on geological formations and in the ocean. Storing carbon by wood burial under soil will not only cut down atmospheric CO2, but also relieve the CO2 burden on the ocean where acidification is of major concern. The traditional carbon sequestration techniques tend to be industrial scale, while the present proposal is a distributed approach. This has both advantages and disadvantages that need to be sorted out. It is likely that many of these methods will be practiced to some degree, but the merits of wood burial make it an attractive option: low tech, low cost, distributed, easy to monitor, safe, reversible, thus a no-regret strategy. On the other hand, forest is a precious resource Nature endowed upon us that serves many critical ecosystem functions and human needs. Care needs to be taken in pursuing such a strategy at large scale.

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