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# Geo-engineering Options for Mitigating Climate Change

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## Foreword

There is overwhelming scientific evidence that climate change is happening and that human activity is the primary cause. Global temperature has risen by about 0.8°C since 1900 and much of this warming is due to the human-induced increase in greenhouse gases in the atmosphere. The signs of warming are widespread – from melting glaciers and Arctic sea ice, to the poleward shift in plant and animal ranges.

If emissions of greenhouse gases continue unabated, global temperatures could rise by up to another 6°C by the end of the century. Rising temperatures will bring changes in weather patterns, higher sea levels and increased frequency and intensity of extreme weather. These changes would, in turn, have significant impacts on biodiversity, food and water supplies, human health, international security and the global economy. The effects will be felt everywhere, but the impacts are likely to be greatest in the poorest communities, who are least able to cope with the changes that climate change brings.

Avoiding dangerous levels of climate change is the greatest environmental challenge facing the world today. In order to avoid widespread and significant impacts, we must make rapid and drastic cuts in global greenhouse-gas emissions. To keep global temperatures below 2°C above pre-industrial levels – the limit for avoiding dangerous climate change proposed by the European Union – global emissions must peak within the next decade and decrease by more than 50% compared to 1990 levels by 2050. This is considered to be economically and technically feasible, but the challenge is great and it will require concerted urgent global action.

Developing and deploying methods for emissions abatement, and adapting to unavoidable change, are the overwhelming priorities for tackling climate change. However, some have suggested that climate change could, in addition, be limited or ameliorated through large-scale manipulation of the global environment. Such geo-engineering approaches tend, however, to raise other environmental risks and often suffer from significant disadvantages such as high cost, limited practicality and lack of political acceptability. Thus geo-engineering approaches are not an alternative to reducing greenhouse-gas emissions, but they cannot be totally ignored either, when we may need all the weapons in our armoury to fight climate change. Some geo-engineering options could, for example, be used to ‘buy time’ to reduce greenhouse-gas emissions if the global community was unable to achieve quickly enough the emissions reductions required to avoid dangerous climate change.

As a first step, it is important that we fully understand what the possible options are and what limits they may have. As a result, DECC has produced this preliminary assessment of some of the more high-profile geo-engineering options that have been proposed so far. This assessment incorporates numerous comments received from scientific experts and other interested parties, and aims to stimulate further comment and discussion. It also offers preliminary conclusions about the individual schemes assessed, but it is clear that further research and analysis will be needed before geo-engineering techniques can even be contemplated as a policy tool to limit the scale or effects of climate change.

I am grateful to all those who have contributed to this paper and hope that it will encourage the research community to consider further work on assessing the feasibility of geo-engineering as an additional means for mitigating climate change.

**Professor Robert Watson**

Joint Acting Chief Scientific Advisor for DECC

## Executive Summary

Geo-engineering, defined here as intentional large-scale manipulation of the global environment, has been suggested as a means of mitigating the effects of anthropogenic greenhouse-gas (GHG) emissions on climate, without necessarily reducing emissions. The topic is currently attracting significant interest. However, to date there has been relatively little research into the feasibility and effects of such large-scale manipulations and there are wide-ranging concerns about their implementation.

This DECC paper, which was prepared during 2008<sup>1</sup>, is intended to provide a preliminary assessment of a number of geo-engineering options that have been proposed so far. It is informed by comments received from a range of scientific experts and interested parties. The paper is not intended to be exhaustive, rather it aims to provide an initial foundation to stimulate comment and discussion. It focuses on the high profile geo-engineering schemes, rather than attempting to discuss all possible options.

These schemes are categorised under: 1. alteration of the Earth's radiation balance; and 2. removal and storage of atmospheric CO<sub>2</sub>. For each option, we include: a brief over-view of the scheme; an outline of current understanding of its potential effectiveness, impacts, technical feasibility and cost; and a preliminary assessment of its strengths, weaknesses, opportunities and threats. Given the limited information currently available for most geo-engineering options, the paper does not provide any quantitative assessment or comparison of effectiveness, economic or societal cost/benefit, or associated bio-geophysical risks. Whilst we recognize that socio-political issues may be crucial for delivery of geo-engineering options, this paper does not attempt to consider them.

There are large uncertainties regarding the effectiveness, impacts, technical feasibility, cost and risks of all the geo-engineering schemes considered and it is premature to draw firm conclusions on the feasibility of implementing them. We make some preliminary conclusions about individual schemes, however, which reflect the views of the parties consulted. 'Air capture' schemes potentially have fewer detrimental side effects than other options, but their effectiveness in net CO<sub>2</sub> capture is still uncertain. Injection of aerosols into the stratosphere or troposphere, surface albedo modification, ocean iron fertilisation and 'air capture' schemes have the advantage that they could be implemented gradually and altered relatively easily. Options involving space shades/mirrors (high risk and an unlikely prospect in the near term) or injection of aerosols into the stratosphere or troposphere, have the disadvantage that rapid climate change could result if they were stopped abruptly. Ocean pipes and cultivation of marine algae were considered to have limited feasibility. Schemes that change the Earth's radiation balance have the disadvantage that they do not counter ocean acidification or other negative effects of increasing CO<sub>2</sub> concentrations. The climate system and ecological impacts of most, if not all of the schemes considered, are currently highly uncertain and as such they would be associated with high environmental risks.

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<sup>1</sup> This paper was completed under Defra sponsorship, prior to the creation of DECC

Although the priorities for tackling climate change should continue to be overwhelmingly focussed on emissions abatement and adaptation to unavoidable change already underway, we consider some further research into the feasibility of using geo-engineering options could be merited. If research goes ahead, we have identified a number of desk, field, laboratory and climate model-based studies as priorities for the research community to consider.

## 1. Introduction

This paper has been prepared by the Climate and Energy: Science and Analysis Division of the Department of Energy and Climate Change, as a preliminary assessment of geo-engineering options to mitigate the effects of anthropogenic greenhouse-gas (GHG) emissions on climate. A draft document was sent to a number of scientific experts and a range of interested parties in the U.K. for input and critique in February 2008, with the aim of developing a more detailed understanding of the various options<sup>2</sup>. Wherever possible, the comments received have been incorporated into this revised document and are referenced with a letter and a number (e.g. [A1]), where the letter refers to the reviewer and the number refers to a specific comment made by that reviewer.

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<sup>2</sup> Note that the scientists and interested parties consulted may not be representative of wider communities because most of those consulted have a specific interest in geo-engineering [cf. C6].

## 2. Aims

Geo-engineering, defined here as intentional large-scale manipulation of the global environment, has been suggested as a means of mitigating the effects of anthropogenic greenhouse-gas emissions on climate, without necessarily reducing emissions.

This paper aims to provide a preliminary assessment of a number of the geo-engineering schemes that have been proposed. It discusses these schemes under two main headings: alteration of the Earth's radiation balance; and removal and storage of atmospheric CO<sub>2</sub>. For each option, it provides: a brief over-view of the scheme; an outline of the current understanding of its potential effectiveness, impacts, technical feasibility and cost; and a preliminary assessment of its main strengths, weaknesses, opportunities and threats (SWOT).

The paper is not intended to be exhaustive, rather it aims to provide an initial foundation from which to stimulate comment and discussion. In particular, it focuses on high profile geo-engineering schemes, rather than attempting to discuss all possible options. It does not discuss schemes that aim to capture and store carbon dioxide (CO<sub>2</sub>) from point sources such as power stations (which are conventionally known as 'Carbon Capture and Storage' (CCS) options) or schemes that aim to increase the length of time that carbon stored in non-atmospheric reservoirs is isolated from the atmosphere (such as the addition of 'biochar' to soils<sup>3,4</sup> [G2, Q5] or the disposal of agricultural crop waste<sup>5</sup> in the ocean [M30, Q6]), because these are not routinely considered 'geo-engineering'. In addition, due to the limited information that is currently available for most geo-engineering options, the paper does not attempt to provide a quantitative assessment or comparison of the effectiveness, economic or societal cost/benefit, or bio-geophysical risk associated with the options considered<sup>6</sup>. Finally, while recognizing that socio-political issues (such as public acceptance and international political co-operation) may be critical in delivering geo-engineering options [e.g. M3, S7, U4, X10], the paper does not address these considerations in any detail.

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<sup>3</sup> Read, P., 2008, Biosphere carbon stock management: addressing the threat of abrupt climate change in the next few decades: an editorial essay, *Climatic Change*, 87, 305-320

<sup>4</sup> See: <http://www.nature.com/nature/journal/v442/n7103/full/442624a.html#B3> for more information on this scheme.

<sup>5</sup> Metzger, R.A., Benford, G. and Hoffert, M.I., 2002, To bury or to burn: Optimum use of crop residues to reduce atmospheric CO<sub>2</sub>, *Climatic Change*, 54(3), 369-374.

<sup>6</sup> A review paper in preparation by Nem Vaughan and Tim Lenton aims to provide a quantitative comparison of the effectiveness (e.g. W/m<sup>2</sup> reduction in radiative forcing on a defined timescale) and economic cost of different geo-engineering options [F13].

### 3. Background

Geo-engineering to address climate change is currently a high profile issue, attracting significant scientific and media interest, and geo-engineering of the climate has been discussed for some time<sup>7</sup>. Despite this, there has been relatively little research into the effects, technical/economic feasibility, risks or societal implications of such large-scale manipulations. DECC has not, so far, undertaken any research into geo-engineering; its limited assessments of the topic have been informed by:

- the IPCC's Fourth Assessment Report (AR4), published in November 2007, which concluded that geo-engineering options are largely unproven and potentially high risk<sup>8</sup>;
- DECC-funded science undertaken at the Met Office Hadley Centre; and
- informal comment from the U.K. climate science community.

There are many potential concerns about the implementation of geo-engineering schemes. They include the fact that our understanding of the Earth system is incomplete, making it impossible to understand fully the potential impacts of any geo-engineering scheme [e.g. E1, T1]. Also, geo-engineering schemes based on changing the Earth's radiation balance do not counter the other negative effects of increasing CO<sub>2</sub> concentrations, such as ocean acidification (which could have significant detrimental effects, including threats to marine productivity and biodiversity) [e.g. C5, M2, Q7, AB1, AG4]. If implemented, many geo-engineering schemes would also need constant maintenance to retain their effect, which could be extremely expensive and/or impractical [e.g. M38]; and, in the event of funding for maintenance ceasing to be available, the environmental implications could increase significantly. It is also clear that the consideration of geo-engineering options could divert funding, public attention, and specialist engineering expertise away from other policies and projects, including those aimed at reducing greenhouse-gas emissions [e.g. R1, S4, U2]; and that gaining public acceptance and international agreement on geo-engineering schemes could be difficult [e.g. S2, S6, X10, X11]. In some cases, it is unclear how funding for schemes could be generated, particularly where there are significant uncertainties around the extent of the mitigation effect or of other environmental consequences, or where it is unclear how the developer of a technology would be able to reap an economic benefit.

Despite these concerns, many of the parties we have consulted feel that further research into the effectiveness, impacts, technical feasibility, cost and risks of geo-engineering options is warranted [D1, H3, J7, Q8, Z5, AE1, AG2]. These options could offer a means of 'buying time' to reduce greenhouse-gas emissions while avoiding dangerous climate change (on local to global scales) [e.g. D20, AB4, AG2], and it may thus be prudent to carry out further research into their feasibility. It is also

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<sup>7</sup> For example, Kellogg W.W. and Schneider S.H., 1974, Climate Stabilization: For Better or for Worse?, Science, 186, 1163-1172.

<sup>8</sup> The IPCC AR4 concluded that "geo-engineering options, such as ocean fertilisation to remove CO<sub>2</sub> directly from the atmosphere, or blocking sunlight by bringing material into the upper atmosphere, remain largely speculative and unproven, and with the risk of unknown side-effects". It further stated that "reliable cost estimates for these options have not been published".

worth mentioning that geo-engineering schemes could have beneficial side effects<sup>9</sup>, such as increases in agricultural and forest productivity due to CO<sub>2</sub> fertilisation (in the case of schemes that do not reduce atmospheric CO<sub>2</sub> concentrations) and/or increases in diffuse radiation (in the case of schemes that modify the properties of the atmosphere) [V1], as well as detrimental side effects [cf. M2].

The view that more research into geo-engineering is warranted is reflected by an increase in the number of workshops being held on the topic. For example, the Tyndall Centre co-hosted a meeting on geo-engineering in Cambridge in January 2004 [Q2]. NASA Ames Research Center and the Carnegie Institution for Science also sponsored a workshop on the use of solar radiation management to mitigate climate change in November 2006<sup>10</sup>. The Harvard University Center for the Environment sponsored a climate geo-engineering workshop at the American Academy of Arts and Science in November 2007<sup>11</sup>. There was also a session on the topic at the Fall Meeting of the American Geophysical Union in December 2007. A meeting on geo-engineering was also planned for Autumn 2008 in Germany. In addition, the Royal Society is now undertaking a study into geo-engineering, which is expected to report in Summer 2009, and has published a special issue of *Philosophical Transactions of the Royal Society A*, on geo-engineering<sup>12</sup>. A group (including Paul Valdes, Dan Lunt and Andy Ridgwell) has also been established at Bristol University to evaluate geo-engineering options [J7]. However, with a few exceptions which are indicated in this report, DECC does not regard geo-engineering as a priority for public funding for research.

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<sup>9</sup> This was noted by the IPCC AR4.

<sup>10</sup> Workshop report available at: <http://event.arc.nasa.gov/main/home/reports/SolarRadiationCP.pdf>

<sup>11</sup> Many of the participants at this meeting felt that understanding geo-engineering options warrants a significantly greater research effort, particularly in view of the fact that significant anthropogenic climate change has already taken place, and the limited progress that has been made so far in reducing greenhouse-gas emissions. A number of key concerns were also acknowledged by participants, however, including the risk that implementing geo-engineering schemes could curtail efforts by governments and industry to reduce greenhouse-gas emissions, and the fact that there are many unknown variables (for example, effectiveness, technical feasibility, cost) and risks associated with these approaches. See: Kintisch, E., 2007, "Scientists say continued warming warrants closer look at drastic fixes", *Science*, 318, 1054-1055.

<sup>12</sup> Launder, B. and Thompson, J.M.T. (eds), *Geoscale engineering to avert dangerous climate change*, Theme Issue of *Phil. Trans. R. Soc. Lond. A*. Published online 1<sup>st</sup> September 2008. Available here: <http://publishing.royalsociety.org/index.cfm?page=1814>



## 4. Geo-engineering approaches

A number of geo-engineering options for mitigating the effects of anthropogenic greenhouse-gas emissions on climate have been proposed. In this paper, we consider a number of proposals, under two main headings: **(i) alteration of the Earth's radiation balance**, which involves either reducing the amount of sunlight that reaches the Earth using space shades/mirrors, or increasing the proportion of incident sunlight that is reflected back into space using stratospheric aerosols, tropospheric aerosols or changes in the land/ocean surface; and **(ii) removal and storage of atmospheric CO<sub>2</sub>**, which involves capturing CO<sub>2</sub> from the atmosphere through ocean fertilisation (using iron addition or ocean pipes), marine-algae cultivation, electrochemically-induced increases in ocean alkalinity or 'air capture' schemes (such as 'synthetic trees').

### 4.i. Alteration of the Earth's radiation balance

Schemes that involve modifying the Earth's radiation balance aim to offset the effects of increasing greenhouse-gas concentrations on climate<sup>13</sup> by reducing the amount of solar radiation that reaches the edge of the Earth's atmosphere, or by reducing the fraction of incoming solar radiation that is absorbed by the atmosphere and/or surface (i.e. increasing the Earth's albedo). These schemes would not prevent other effects of increasing atmospheric CO<sub>2</sub> concentrations, such as ocean acidification [e.g. Q7, AG4] and plants becoming more productive (in certain conditions), which could have significant feedback-effects on climate.

A number of studies have explored the effectiveness and impacts of schemes that aim to alter the radiation balance of the Earth. In particular, climate models have been used to explore the effects of 'dimming' the Sun [A10, AC1], which gives an indication of the effects of schemes that would reduce the amount of solar radiation reaching the Earth's surface (such as space shades or stratospheric aerosols). These experiments confirm that it would, in theory, be possible to modify the Earth's radiation balance to offset completely the effects of increasing greenhouse-gas concentrations on global annual average temperature<sup>14</sup>. However, even if this were possible in practice, these schemes could still be associated with significant climate changes because: (a) the temporal and spatial distributions of the forcing effects of greenhouse gases on climate differ from those of sunlight; and (b) elevated CO<sub>2</sub> has effects on the climate system that are not reduced by the geo-engineering schemes (such as increasing the water-use efficiency of terrestrial plants). Some modelling work indicates that the climatic changes associated with the schemes would be small (relative to the unperturbed world)<sup>14</sup> [C21, Q16], but other studies have found more significant changes, including decreases in precipitation over vegetated land surfaces (particularly in the tropics), a decrease in the meridional temperature gradient, a

<sup>13</sup> Greenhouse gases increase atmospheric and surface temperatures by decreasing the amount of outgoing long-wave radiation that leaves the atmosphere.

<sup>14</sup> Govindasamy, B. and Caldeira, K., 2000, Geoengineering Earth's Radiation Balance to Mitigate CO<sub>2</sub>-Induced Climate Change, *Geophysical Research Letters*, 27, 2141-2144

decrease in Arctic sea ice extent, and a decrease in the amplitude of the El Niño/Southern Oscillation (ENSO)<sup>15,16,17</sup>.

Modelling work has shown that temperature would respond rapidly if these options were implemented quickly<sup>16</sup> [A6, B9], so there may be little harm in delaying their deployment until 'dangerous' climate change is imminent. If they were stopped abruptly, however, either due to failure or policy decisions, rapid climate change could result because the 'masking' effect of geo-engineering would be removed<sup>18</sup> [B1, B9, F9, AB3]. Such rapid climate change could have severe impacts on both human and environmental systems<sup>16</sup>.

#### **4.i.a. Space shades / mirrors**

There are a number of proposals that aim to mitigate climate change by reducing the amount of solar radiation reaching the Earth's atmosphere using space shades or mirrors. These usually involve injecting material into the L1 Lagrange point, which lies 1.5 million kilometres away from the Earth towards the Sun [L1, O2, Q11]. Some of the proposals involve the injection of material into space from Earth (which would require significant amounts of energy), while others suggest that space-based resources (from the Moon or asteroids) could be used to obtain the materials, process them and inject them into the desired position (the rationale being that the energy required to mine, manufacture and launch from the Moon would be much less than on Earth, although these proposals are beyond current space engineering experience and are unlikely to be achievable in the foreseeable future) [L1].

These options would be expensive to implement and might be difficult to modify or remove. Once in space, however, they might be relatively cheap to operate and maintain (compared to other geo-engineering options) — although it is worth noting that material placed at the L1 Lagrange point would need active control and management to prevent it drifting sideways [Q11], as well as being susceptible to damage by meteoroids/space debris [O2] and degradation over time [F3]. Significantly more work is required to assess the practicalities (including deployment and maintenance requirements, cost etc.) of these options, and it appears to us that they are not near-term solutions.

It has been suggested that some of these schemes could be coupled with solar power generation, which might improve their cost-efficiency and provide an alternative to carbon-based fuels [AC2]<sup>19</sup>. Specifically, space shields could be partially covered with solar cells to generate electricity for terrestrial use (~1.4 MW of

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<sup>15</sup> Govindasamy, B., Caldeira, K. and Duffy, P.B., 2003, Geoengineering Earth's radiation balance to mitigate climate change from a quadrupling of CO<sub>2</sub>, *Global and Planetary Change*, 37, 157-168.

<sup>16</sup> Matthews H.D. and Caldeira K., 2007, Transient climate-carbon simulations of planetary geoengineering, *PNAS* 104, 24, 9949-9953.

<sup>17</sup> Lunt, D.J., Ridgwell, A., Valdes, P.J. and Seale, A., submitted, "Sunshade World": a fully coupled GCM evaluation of the climatic impacts of geoengineering.

<sup>18</sup> One study (ref. 14) found that if a geo-engineering scheme that decreased incoming sunlight to compensate for the increase in radiative forcing according to the A2 emissions scenario was put in place in 2000 and failed in 2075, warming rates 20-times greater than the current rate occurred after failure. The warming rate was 10-times greater than the current rate if the scheme was in place under the same conditions but failed in 2025 [cf. B4, B9].

<sup>19</sup> DECC understands that this option is currently being investigated in the United States [AC2].

solar energy would be incident on each square kilometre of shield [L2]). The efficiency of collecting solar energy and beaming it to Earth (for example, by microwave) would be low (probably ~10% at best) and the cost would be high [L2, O1], but it has been suggested that this means of simultaneously generating electricity and reducing the amount of solar energy received by the Earth might be worth closer examination [L2].

Two proposals involving space shades/mirrors are:

**Reflective mesh** — A superfine reflective mesh of aluminium threads ~25 nanometres thick could be positioned between the Earth and the Sun to reduce the amount of sunlight that reaches the Earth (it has been estimated that a 1% reduction in solar radiation would require ~1.5 million km<sup>2</sup> of ‘mesh’ mirrors).

**Orbital ‘sunshades’**<sup>20</sup> — Trillions of thin, almost transparent disks ~50 centimetres in diameter could be launched from Earth to near the L1 Lagrange point to shade the Earth. It has been calculated that this scheme would reduce the amount of solar radiation reaching the Earth by ~1.8%. The proponent of the scheme estimates that it could feasibly be developed and deployed within about 25 years, at a cost of several trillion U.S. dollars<sup>20</sup>.

Preliminary SWOT analysis – Space shades / mirrors	
<b>Strengths:</b> <ul style="list-style-type: none"> <li>• Potentially a long-term solution</li> <li>• Potentially low maintenance</li> <li>• Rapid cooling effect if deployed quickly [A6]</li> </ul>	<b>Weaknesses:</b> <ul style="list-style-type: none"> <li>• Potentially expensive to deploy</li> <li>• Potentially energy-intensive to deploy</li> <li>• Potentially difficult to modify or remove [M9]</li> <li>• Technology needs to be developed</li> <li>• Probably long timescale to implement</li> <li>• Susceptible to impact damage from meteoroids/space debris [O2]</li> <li>• No CO<sub>2</sub> mitigation</li> </ul>
<b>Opportunities:</b> <ul style="list-style-type: none"> <li>• Development of new technology</li> <li>• Use climate models to assess potential</li> </ul>	<b>Threats:</b> <ul style="list-style-type: none"> <li>• Uncertain climate system impacts</li> <li>• Uncertain ecological impacts</li> <li>• Could add to space debris, potentially threatening satellites [M9]</li> <li>• Failure could lead to rapid temperature rise/climate change</li> <li>• Ocean acidification (via increased CO<sub>2</sub>)</li> </ul>

#### 4.i.b. Stratospheric aerosols

This technique aims to cool the Earth’s troposphere and surface by increasing the backscattering of radiation in the stratosphere (which increases planetary albedo)

<sup>20</sup> Angel, R., 2006, Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1), PNAS, 203, 17184 – 17189.

using airborne sub-microscopic particles such as sulphate, metals, dielectrics, resonant scatterers or dust [A12]. These aerosol particles would be created by releasing aerosol precursors into the stratosphere. This could be done by: releasing precursors at the Earth's surface and allowing them to be carried into the stratosphere; firing them into the stratosphere from the Earth's surface; or delivering them into the stratosphere using high-altitude balloons or aircraft [B2] (possibly by addition to aviation fuel, which could reduce the cost of delivery [Q15]). Injection could either take place in the tropics (with the aim of obtaining global coverage) or in the Arctic (with the aim of reducing warming in this region, which is particularly vulnerable to anthropogenic climate change).

There are a number of uncertainties about the potential impacts of these schemes on the environment<sup>21,22</sup>. In particular, the effects of stratospheric aerosols on the climate system are not fully understood [AD4] — although they are known to affect circulation patterns, stratospheric ozone concentrations (which affect climate) [AD2] and upper tropospheric cloud formation (a particular concern is that these schemes could increase the cover of high cirrus clouds in the tropics, which could increase warming). Changes observed after volcanic eruptions (which can inject aerosols into the stratosphere) suggest that the climatic response to stratospheric aerosol forcing is regionally variable [AD3]. In particular, they indicate that there may be significant decreases in precipitation over land<sup>23</sup> (which could lead to drought) and changes in the North Atlantic Oscillation (which could lead to warmer winters over Eurasia) [B6]. The potential impact of the schemes on ecosystems also remains uncertain, but aerosols can affect photosynthesis by increasing the amount of diffuse solar radiation and decreasing the amount of direct solar radiation [A14] and can cause environmental pollution.

**Sulphate aerosols** — The most widely-discussed proposal in this category involves the injection of sulphate aerosols into the stratosphere<sup>24</sup>. It has been estimated that this scheme would require ~1.5 to 3 teragrams of sulphur to be added to the stratosphere each year to counter the effects of a doubling of CO<sub>2</sub> levels<sup>25</sup>, although another study suggested that ~5 teragrams of sulphur per year might be needed to mitigate future warming<sup>26</sup> [cf. B3, F4]. The aerosols could be produced: either by injecting sulphur dioxide into the stratosphere, where it would be converted into sulphuric acid droplets; or by releasing long-lived sulphur compounds such as carbonyl sulphide (OCS) at the surface [AD1]. Unlike in the troposphere, sulphate aerosols in the stratosphere do not get washed out within a few weeks, but have a residence time of ~1 to 2 years<sup>24</sup>. Consequently, they are transported further in the

<sup>21</sup> Professor Ken Carslaw, University of Leeds, is working to assess the impact of changes in lower stratospheric composition on the climate system (project entitled 'The lower stratosphere: interactions with the tropospheric chemistry/climate system' - Ref: NE/E017150/1). This project will use the UKCA model to — amongst other things — explore the scientific implications of geo-engineering schemes based on stratospheric aerosols, including the potential contribution of sulphate aerosols to acid rain [AD5].

<sup>22</sup> We understand that Alan Robock (Rutgers University) and colleagues have received an NSF grant to evaluate the efficacy and possible consequences of geo-engineering proposals involving the injection of aerosol particles into the stratosphere.

<sup>23</sup> Trenberth K.E. & Dai A., 2007, Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering, *Geophysical Research Letters*, 34, doi:10.1029/2007GL030534

<sup>24</sup> Crutzen P., 2006, Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?, *Climatic Change*, 77, 211-219.

<sup>25</sup> Rasch, P.J., Crutzen, P.J., and Coleman, D.B., 2008, Exploring the geoengineering of climate using stratospheric sulfate aerosols: The role of particle size, *Geophysical Research Letters*, 35, doi:10.1029/2007GL032179.

<sup>26</sup> Wigley, T.M.L., 2006, A Combined Mitigation/Geo-engineering Approach to Climate Stabilization, *Science*, 314, 452-454.

stratosphere than in the troposphere and thus have greater coverage of the globe, particularly if they are injected at the tropics [C27]. It might, however, be difficult to produce a spatially-uniform change in the radiative properties of the stratosphere using the methods of aerosol-precursor delivery that have been proposed<sup>27</sup>.

Under this option, if greenhouse-gas concentrations continued to rise, increasing quantities of sulphur would need to be injected continuously into the stratosphere to mitigate temperature change, which may not be sustainable in the long term. Also — as noted above — if failure occurred, rapid climate change could result<sup>28</sup>. The climatic impacts of the scheme also remain uncertain. A study that simulated the injection of sulphate-aerosol precursors into the stratosphere using a General Circulation Model found that injection at the tropics produced sustained cooling over most of the world, but also disrupted the Asian and African summer monsoons, with detrimental effects on food supply<sup>28</sup>. The scheme could also lead to significant reductions in stratospheric ozone concentration (particularly in the Arctic)<sup>10</sup>. An additional risk is that aerosols would be washed out of the atmosphere, causing acid rain [AD5]. The effect of fallout over a few decades is likely to be small compared to the impacts of acid rain in the recent past [C32], but the magnitude of this effect still needs to be quantified [AD5].

Preliminary SWOT analysis – Stratospheric aerosols	
<b>Strengths:</b> <ul style="list-style-type: none"> <li>• Potentially short timescale to implement</li> <li>• Potentially rapid cooling effect<sup>15</sup> [A6]</li> <li>• Easy to modify or reverse<sup>29</sup></li> </ul>	<b>Weaknesses:</b> <ul style="list-style-type: none"> <li>• Continuous implementation required until GHG emissions are reduced</li> <li>• Probably regionally variable effects on climate</li> <li>• No CO<sub>2</sub> mitigation</li> </ul>
<b>Opportunities:</b> <ul style="list-style-type: none"> <li>• Use climate models to assess potential</li> </ul>	<b>Threats:</b> <ul style="list-style-type: none"> <li>• Uncertain climate system impacts</li> <li>• Uncertain ecological impacts</li> <li>• Fallout may contribute to acid rain (sulphate aerosols) [AD5]</li> <li>• Uncertain effects on stratospheric ozone</li> <li>• Failure to maintain could lead to rapid temperature rise/climate change</li> <li>• Ocean acidification (via increased CO<sub>2</sub>)</li> </ul>

#### 4.i.c. Tropospheric aerosols

**Seawater spray** — Professor Stephen Salter<sup>30</sup> has suggested that the albedo of low-level clouds could be increased by spraying seawater into the troposphere [A18, D8]. The scheme would involve seeding low-level marine stratocumulus clouds with

<sup>27</sup> Brewer, P., 2007, Evaluating a technological fix for climate, PNAS, 104, 9915-9916

<sup>28</sup> Robock, A., Oman, L., and Stenchikov G., Submitted to JGR, Regional Climate Responses to Geoengineering with Tropical and Arctic SO<sub>2</sub> Injections. Available at: <http://climate.envsci.rutgers.edu/pdf/GeoengineeringJGR7.pdf>

<sup>29</sup> Dickinson, R., 1996, Climate engineering a review of aerosol approaches to changing the global energy balance, Climatic Change, 33, 279-290.

<sup>30</sup> See papers in: <http://www.see.ed.ac.uk/~shs/Global%20warming/Albedo%20control/>



droplets of seawater ~1 micrometer in diameter using special spray generators floating on the sea surface. These droplets would act as cloud condensation nuclei and thereby increase the number of water droplets in the clouds, which would in turn increase their albedo [A18]. As seawater droplets pumped into the atmosphere would only remain there for a few days, continuous aerosol production would need to be maintained until reductions in greenhouse-gas concentrations were achieved. Correspondingly, however, the short residence time of the droplets means that this option could be ‘turned off’ rapidly [D6, D22, H9, M12, P2].

It has been suggested that this technique could counter the warming effect of a doubling of the atmospheric concentration of CO<sub>2</sub> [cf. D9], but there are uncertainties regarding the extent to which such an adjustment of cloud properties could offset greenhouse gas-induced warming, and about how localised the cooling effect would be. These uncertainties could be explored further using climate models [A21, A22].

The potential side-effects of the technique also remain uncertain. There could be a decrease in rainfall at sea due to the decrease in the average size of water droplets in the clouds affected, but this effect might also lead to more rainfall over land [D19]. The scheme might also change the spatial pattern of radiative heating (due to the fact that it can only be implemented in certain regions). In particular, it could increase the contrast between land and sea temperatures. The technique might also cause sea salt to crystallise in the atmosphere in regions without clouds, which could allow chemical reactions that release reactive halogens (such as bromine) to occur on the crystal surfaces, potentially reducing ozone concentrations in the troposphere and possibly even the stratosphere [AD6]. It is also possible that some of the sea salt would be deposited via rainfall over land, increasing salt input to terrestrial ecosystems [AD7].

Attempts have been made to assess the cost and technological requirements of this option, and it has been claimed that they are relatively low [cf. D21, D31]. More work is required, however, to fully assess the practicalities of the scheme (including cost, structure, safety and maintenance). In particular, it remains uncertain whether aerosols could be generated in the quantities required to affect global temperature using available technology and at a reasonable cost [Q18, R3].

Preliminary SWOT analysis – Tropospheric aerosols	
<b>Strengths:</b> <ul style="list-style-type: none"> <li>• Easy to modify or reverse [D6, D22, H9, M12, P2]</li> <li>• Potentially simple technology</li> <li>• Potential for flexible, targeted geographical use [cf. A23]</li> </ul>	<b>Weaknesses:</b> <ul style="list-style-type: none"> <li>• Effectiveness uncertain</li> <li>• May be of limited geographical scope</li> <li>• Continuous implementation required until GHG emissions are reduced [D24, M12]</li> <li>• No CO<sub>2</sub> mitigation</li> </ul>
<b>Opportunities:</b> <ul style="list-style-type: none"> <li>• Use climate models and field studies to assess potential</li> <li>• Potential to learn about cloud/aerosol effects and processes [D15, P3]</li> </ul>	<b>Threats:</b> <ul style="list-style-type: none"> <li>• Uncertain climate system impacts</li> <li>• Uncertain ecological impacts</li> <li>• Failure to maintain could lead to rapid temperature rise/climate change</li> <li>• Ocean acidification (via increased CO<sub>2</sub>)</li> </ul>

#### 4.i.d. Surface albedo

Changes in the albedo of the Earth's surface can affect climate by changing the energy budget of the lower atmosphere<sup>31</sup> and it has been proposed that land and/or ocean albedo could be increased to mitigate climate change. It is unlikely that such schemes could have a significant effect on climate at the global scale (partly because even modest global warming is expected to lead to significant loss of sea ice and snow cover — which will significantly decrease surface albedo — and it would be difficult for these schemes even to 'keep up' with these changes [M14]). They may, however, be useful in mitigating the effects of anthropogenic climate change at local to regional scales. The potential effects of these schemes on climate could be explored using field studies and climate models [A24].

Several options for changing land cover to enhance surface albedo are discussed below. Schemes aimed at increasing the albedo of the ocean surface — including the deployment of floating reflective objects such as white plastic tiles [M15] — are not explored in detail here, due to the limited information that is available about them.

**Albedo of artificial surfaces** — By deploying highly reflective white cement and titanium-oxide-based paints and films on surfaces in urban areas in the United States, several studies have demonstrated that baseline urban albedo can be increased by 100% or more, depending on the specific land cover mix<sup>32</sup>. Furthermore, it has been estimated<sup>33</sup> that doubling the albedo (from 0.15 — a typical urban value — to 0.3) of all 'artificial' surfaces in human settlements using this 'whitening' process would decrease the annual global average radiative forcing by  $0.17 \text{ W m}^{-2}$  (which is ~10% of the radiative forcing caused by the increase in  $\text{CO}_2$  concentration between 1750 and 2005). 'Whitening' would be cheap to implement, but the surfaces would require regular cleaning to maintain their albedo<sup>34</sup> and the aesthetic impact would be significant if implemented on a large scale. On a smaller scale, the roofs of buildings could also be covered with vegetation (so-called 'green roofs'), which would cool surfaces by increasing both albedo (compared to standard materials) and latent heat loss<sup>35</sup>. Field experiments have shown that green roof surfaces can reduce peak surface-temperatures by more than  $30^\circ\text{C}$  compared to dark impervious surfaces, and energy balance modelling indicates that 'green roofs' are as effective at cooling as the brightest possible 'white roofs'<sup>35</sup>. Green roofs might be more visually acceptable than white surfaces, but they would probably be more expensive to implement and would also require regular maintenance<sup>35</sup>. They do,

<sup>31</sup> For example, regional-scale replacement of natural forests by agricultural crops in the continental United States over the past two centuries has significantly increased surface albedo and reduced radiative forcing of the climate (Bonan G.B., 1997, Effects of land use on the climate of the United States, *Climatic Change*, 37, 449-486). It has also been shown that large-scale boreal and temperate afforestation programmes could be associated with increased radiative forcing arising from decreases in surface albedo, which could offset the carbon sequestration effects that underpin such programmes (Betts R., 2000, Offset of the potential carbon sink from boreal forestation by decreases in surface albedo, *Nature*, 408, 187-190).

<sup>32</sup> Taha, H., 2005, Urban surface modification as a potential ozone air-quality improvement strategy in California – Phase one: Initial mesoscale modelling, Public interest energy research program, Report CEC-500-2005-128, Sacramento, CA, California Energy Commission.

<sup>33</sup> Hamwey, R., 2007, Active amplification of the terrestrial albedo to mitigate climate change – An exploratory study, *Mitigation and Adaptation Strategies for Global Change*, 12(4), 419-439.

<sup>34</sup> Bretz, S. and Pon, P., 1994, Durability of High Albedo Coatings, Recent Research in the Building Energy Analysis Group at Lawrence Berkeley Laboratory, Issue #5, <http://eetd.lbl.gov/Buildings/RRResearch/Albedo.html>.

<sup>35</sup> <http://www.roofmeadow.com/technical/publications/GaffinetalPaperDC-0009.pdf>

however, have other environmental benefits, such as increasing biodiversity and helping to control rainfall runoff and, unlike most other options, are well understood and deployable now.

**Albedo of ‘natural’ surfaces** — The amount and/or type of vegetation cover could be changed to increase planetary albedo. For example, crops bred or genetically modified to produce extra-hairy leaves reflect more near-infrared wavelengths back into space than non-hairy strains. Super-hairy strains of soya that reflect 3 to 5% more sunlight than conventional strains have already been bred<sup>36</sup> (although the effect of growing these strains on crop yields also needs to be considered [cf. A25]). It has been estimated<sup>33</sup> that increasing the surface albedo of all grasslands (which currently cover ~30% of the land surface) by 25% would decrease the annual global average radiative forcing by  $0.59 \text{ W m}^{-2}$  (which is ~37% of the radiative forcing caused by the increase in  $\text{CO}_2$  concentration between 1750 and 2005). This value is high because a large proportion of the land surface is occupied by grasslands, but only a fraction of this area could feasibly be modified, so the maximum effect is likely to be significantly smaller in practice.

The albedo of natural surfaces could also be changed using artificial materials. It has been suggested, for example, that a large area of one or more of the Earth’s deserts could be covered with white material (such as plastic polyethylene film). It has been estimated<sup>37</sup> that ~170,000  $\text{km}^2$  of land per year would need to be covered with a material with an albedo of ~0.8 to mitigate the effects of greenhouse-gas emissions over the next ~60 years (assuming no significant reduction in emissions), which would result in a total covered area of ~10 million  $\text{km}^2$  (an area approximately 40-times the size of the United Kingdom). The same source suggests that this scheme could be implemented at a total cost of ~16 trillion U.S. dollars. There are a number of limitations and risks associated with this scheme. It could have serious detrimental effects on desert ecosystems and would reduce dust production, which could affect climate and harm marine ecosystems (because dust acts as an important source of nutrients in some areas). The cover would also be difficult to install and maintain (it would need to be repaired and cleaned, and replaced every 2 to 3 years if currently-available materials were used).

Preliminary SWOT analysis – Land surface albedo	
<b>Strengths:</b> <ul style="list-style-type: none"> <li>• Potentially easy to implement</li> <li>• Potentially relatively low cost (compared to other options)</li> <li>• Technologically feasible</li> <li>• Easy to modify or reverse [M14]</li> </ul>	<b>Weaknesses:</b> <ul style="list-style-type: none"> <li>• Probably limited effect on global climate (limited geographical scope)</li> <li>• No <math>\text{CO}_2</math> mitigation</li> </ul>
<b>Opportunities:</b> <ul style="list-style-type: none"> <li>• New plant modifications</li> <li>• New surface material development</li> <li>• Use climate models and field studies to assess potential</li> </ul>	<b>Threats:</b> <ul style="list-style-type: none"> <li>• Uncertain climate system impacts (particularly on regional scale)</li> <li>• Potential impacts on the biosphere in the case of changing amount/type of</li> </ul>

<sup>36</sup> New Scientist, 5 January 2008, p12.

<sup>37</sup> <http://www.global-warming-geo-engineering.org/Albedo-Enhancement/Introduction/ag1.html>



	vegetation and covering desert areas [I3] • Ocean acidification (via increased CO <sub>2</sub> ) [A27, Y2]
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## 4.ii. Removal and storage of atmospheric CO<sub>2</sub>

Schemes to remove and store atmospheric CO<sub>2</sub> aim to mitigate the effects of increasing greenhouse-gas concentrations on climate directly<sup>38</sup>. They may also have the benefit of directly tackling other effects of increasing atmospheric CO<sub>2</sub> concentrations, such as ocean acidification [M16].

### 4.ii.a. Ocean fertilisation

Ocean fertilisation involves the addition of nutrients to the surface ocean to stimulate phytoplankton blooms. The phytoplankton take up CO<sub>2</sub> and fix it into biomass. When they die some of this 'captured' carbon sinks into the deep ocean, where it can remain isolated from the atmosphere for centuries [cf. X2]. As well as capturing CO<sub>2</sub>, it is possible that ocean fertilisation could, as a secondary benefit, produce dimethyl sulphide (although this depends on which algae are favoured by the extra nutrients), which might increase the albedo of low-level clouds over tropical oceans by providing a source of cloud condensation nuclei [X4] (cf. ref. 39). This secondary effect is likely to be very small [M26], however, and if it does occur it is likely that it would often be associated with the release of carbon (through viral lysis and zooplankton grazing), which would counter the potential benefits [K4].

A number of different ocean fertilisation schemes have been proposed. These can be divided into: those that involve the addition of nutrients from outside the ocean (for example, supplying fertiliser — either in the form of 'waste' nutrients such as sewage or in the form of fertiliser manufactured for the purpose<sup>40</sup> — from land to the ocean through pipes); and those that involve the redistribution of nutrients within the ocean (for example, ocean pipes).

#### Ocean iron fertilisation

Addition of soluble iron to the surface ocean is the most widely-considered option for ocean fertilisation. Small amounts of soluble iron are critical for supporting phytoplankton growth, and the supply of this micro-nutrient limits production in about a third of the ocean<sup>41</sup> (including the Southern Ocean and parts of the Pacific), where the concentrations of unused macro-nutrients (nitrate, phosphate and silicate) are perennially high. The addition of iron to these areas — the so-called 'High Nitrogen,

<sup>38</sup> Interest in these schemes has been prompted recently by the \$25 million Virgin Earth Challenge prize, announced in February 2007, for "a commercially viable design which results in the removal of anthropogenic atmospheric greenhouse gases so as to contribute materially to the stability of Earth's climate", see: <http://www.virginearth.com/>.

<sup>39</sup> Charlson, R. J., Lovelock, J. E., Andreae, M. O. and Warren, S. G., 1987, Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. *Nature*, 326, 655-661.

<sup>40</sup> Commercial exploitation of ocean fertilisation through the addition of macro-nutrients from the land to the ocean has been developed by Ocean Nourishment™ ([www.oceanourishment.com](http://www.oceanourishment.com)), which plans to manufacture fertilizer (specifically, urea) that would be piped to the shelf edge.

<sup>41</sup> Boyd et al., 2007, Mesoscale Iron Enrichment Experiments 1993-2005: Synthesis and Future Directions, *Science*, 315, 612-617.

Low Chlorophyll' regions — could thus increase productivity and draw down atmospheric CO<sub>2</sub> as described above [X3, M38].

The efficiency with which ocean iron fertilisation sequesters atmospheric CO<sub>2</sub> to the deep sea remains uncertain<sup>42</sup>, but field programmes and modelling studies indicate that it is likely to be low<sup>41,42</sup> because a large proportion of the CO<sub>2</sub> taken up by marine phytoplankton appears to be returned to the atmosphere through remineralisation in surface waters before it is exported to the deep ocean [K2, M20, Q20, R5]. It should also be noted that there is a theoretical upper limit to the amount of CO<sub>2</sub> that could be removed from the atmosphere using iron fertilisation, which is determined by the factors that limit biological production after iron is added (for example, the supply of macro-nutrients or light), as well as the fact that the use of macro-nutrients in fertilised areas could decrease macro-nutrient availability elsewhere, decreasing CO<sub>2</sub>-drawdown in these regions [M38, M39]. A study using a global ocean biogeochemical model found that the maximum effect of ocean iron fertilisation on atmospheric CO<sub>2</sub> concentration (assuming massive, continuous addition of iron to the entire ocean) would be a ~30 ppm reduction over 100 years (which is ~32% of the increase in atmospheric CO<sub>2</sub> concentration that took place between 1750 and 2005)<sup>43</sup> [M19, M38, M39].

Iron fertilisation would also have to be maintained continuously to have a lasting effect (and, correspondingly, there would be an increase in atmospheric CO<sub>2</sub> concentration if it was stopped) because any carbon sequestered by ocean fertilisation would be returned to the atmosphere quite rapidly<sup>43</sup> [M21]. Furthermore, the process could have significant biogeochemical and ecological impacts (including oxygen depletion of the intermediate and/or deep ocean, altered trace gas emissions, changes in biodiversity, and decreased productivity in other oceanic regions)<sup>42,43</sup> [K13, Q21, Q36].

More work is required to explore the potential and risks of ocean iron fertilisation, and a group of scientists recently suggested a number of research programs that could contribute to this goal<sup>42</sup> (note that NERC supports work on this topic and there is appropriate U.K. expertise for additional investigations<sup>44</sup>). Despite the uncertainties associated with this option, at least one company (Climos, [www.climos.com](http://www.climos.com)) is seeking to develop commercial ocean iron fertilisation with the aim of generating carbon credits. Planktos ([www.planktos.com](http://www.planktos.com)), another company that was exploring this option, recently announced that it has indefinitely postponed its ocean iron fertilisation project because it was unable to raise sufficient funds [H11, K1].

<sup>42</sup> Buesseler et al., 2008, Ocean Fertilisation – Moving Forward in a Sea of Uncertainty. *Science*, 319, 162.

<sup>43</sup> Aumont, O. and Bopp, L., 2006, Globalizing results from ocean in situ iron fertilisation studies. *Global Biogeochemical Cycles* 20, GB2017, doi:10.1029/2005GB002591.

<sup>44</sup> Current NERC-funded research in this area includes the U.K. contribution to the Surface-Ocean/Lower Atmosphere Study (SOLAS), <http://www.nerc.ac.uk/research/programmes/solas/>. The SOLAS Scientific Steering Committee produced a position statement that expressed concern about prospective large scale ocean fertilisation (available at: <http://www.uea.ac.uk/pipermail/solas.info/2007/000066.html>). Although UK SOLAS is not directly involved in geo-engineering, there is indirect UK SOLAS interest in the topic, with studies on relevant natural processes — specifically, the effects of natural dust inputs on marine productivity. NERC also supports the Oceans 2025 work, <http://www.oceans2025.org/researchthemes.php>, which includes the study of biogeochemical processes and hydrodynamic modelling relevant to iron fertilisation and other marine geo-engineering options.

Preliminary SWOT analysis – Ocean iron fertilisation	
<b>Strengths:</b> <ul style="list-style-type: none"> <li>• Potentially relatively cheap (compared to other options)<sup>45</sup></li> <li>• Technologically feasible</li> <li>• Easy to modify or stop</li> <li>• CO<sub>2</sub> sequestration</li> <li>• Reduces ocean acidification</li> </ul>	<b>Weaknesses:</b> <ul style="list-style-type: none"> <li>• Efficiency likely to be low [K2, M20, Q20, R5]</li> <li>• Carbon stored is eventually released [M21]</li> <li>• Risk of violating international marine agreements/regulations, e.g. London Convention/Protocol on wastes (although this may be a less significant problem if the schemes are shown to be useful and not harmful [H16])</li> <li>• Difficult to control effects [K12]</li> </ul>
<b>Opportunities:</b> <ul style="list-style-type: none"> <li>• Use climate models and field studies to assess potential</li> <li>• Research on marine ecosystems and carbon cycle</li> </ul>	<b>Threats:</b> <ul style="list-style-type: none"> <li>• Potential risks to marine ecosystems [K13, Q21]</li> <li>• Potential increase in nitrous oxide (GHG) emissions</li> </ul>

## Ocean pipes

Recently publicised in the scientific press<sup>46</sup> and media, this proposal involves pumping nutrient-rich water from 100 to 200 metres-deep to the surface layer using floating pipes fitted with valves<sup>47</sup>. It is thought that this might stimulate phytoplankton blooms in nutrient-poor surface layers, which would capture carbon in the same way as ocean iron fertilisation. It is also possible that the process would have a direct cooling effect, as cold water is transported from the deep ocean to the surface [X6].

The efficiency of this proposal remains uncertain [K9, Y3], but it is widely thought that it would be low or negligible [cf. J4, M29, Q20]. Specifically: (a) it is uncertain whether the nutrients that are up-welled would have a fertilizing effect [C38]; (b) it is likely that only a small proportion of any organic carbon produced would be exported to the deep ocean (see above); and (c) any carbon export that does occur could be fully offset by CO<sub>2</sub> flux from up-welled water to the atmosphere, due to the high concentration of dissolved CO<sub>2</sub> in the water [M23, M29, Y3] (this effect could also increase surface ocean acidification [Y3]). In addition, even if the process were efficient, it would require a very large number of pipes (probably millions [K9, X7]) to have a significant effect on atmospheric CO<sub>2</sub> concentrations, and these would potentially pose a significant hazard to both shipping and marine life (which could become entangled or collide with the structures or their buoys, mooring lines etc.) [X7].

<sup>45</sup> Buesseler, K.O. and Boyd, P.W., 2003, Will Ocean Fertilisation Work? Science, 300, 67-68.

<sup>46</sup> Lovelock, J.E. and Rapley, C.G., 2007, Ocean pipes could help the Earth cure itself, Nature, 449, 403.

<sup>47</sup> An American company, Atmocean ([www.atmocean.com](http://www.atmocean.com)), proposed a similar concept before the recent publicity [X5].

Preliminary SWOT analysis – Ocean pipes	
<b>Strengths:</b> <ul style="list-style-type: none"> <li>• Potentially relatively cheap (compared to other options)</li> <li>• Technologically feasible</li> <li>• Low maintenance</li> <li>• CO<sub>2</sub> sequestration</li> <li>• Reduces ocean acidification</li> </ul>	<b>Weaknesses:</b> <ul style="list-style-type: none"> <li>• Efficiency likely to be low/negligible [J4, M29, Q20]</li> <li>• Carbon stored is eventually released [cf. M21]</li> <li>• Pipes may be prone to drift</li> </ul>
<b>Opportunities:</b> <ul style="list-style-type: none"> <li>• Use climate models and field studies to assess potential</li> <li>• Research on marine ecosystems and carbon cycle</li> </ul>	<b>Threats:</b> <ul style="list-style-type: none"> <li>• Could increase atmospheric CO<sub>2</sub> and/or acidify upwelling areas [Y3, Y5]</li> <li>• Potential risks to marine ecosystems [Q21]</li> <li>• Large number/distribution of pipes (would probably need millions) may be threat to shipping or <i>vice versa</i> [X7]</li> </ul>

#### 4.ii.b. Cultivation and storage of marine algae

Bulk cultivation and storage of marine algae could theoretically be used to reduce the atmospheric concentration of CO<sub>2</sub>. Algae can be cultured using nutrient concentrations many times (~100) higher than those available in the natural environment, and it has been estimated that ponds ~1 metre deep covering ~0.1% of the land surface area could remove ~1 GtC yr<sup>-1</sup> from the atmosphere [Q28] (which is ~24% of the average annual increase in atmospheric CO<sub>2</sub> concentration between 2000 and 2005).

Work has already been carried out on the cultivation of marine algae (mainly for biofuel production). Shell/HR Petroleum are developing a pilot plant for biofuel production in Hawaii<sup>48</sup> and Plymouth Marine Laboratory has developed a small-scale photobioreactor<sup>49</sup>, for example. It remains unclear, however, whether algal biomass could be stored in sufficient quantities to significantly affect atmospheric CO<sub>2</sub> concentrations, mainly because there would be practical problems associated with its storage (including preventing its decomposition) [cf. A38]. It has been suggested that some of the carbon ‘captured’ by the algae could be stored in ‘bioplastics’ generated from chemicals synthesised by the algae [I8], or that small-scale storage could be combined with other activities (such as biofuel production) [cf. M37]. These options seem more feasible than bulk storage of algal material [cf. Z2], but they have not been explored in detail.

<sup>48</sup> See [www.webwire.com/ViewPressRel.asp?ald=54866](http://www.webwire.com/ViewPressRel.asp?ald=54866) for a press release on this scheme

<sup>49</sup> This is currently displayed at the Science Museum, see the following links for further details: <http://www.nerc.ac.uk/research/highlights/2007/algae.asp>, and [http://www.pml.ac.uk/data/files/Biofuel%20Exhibition\\_Oct07.pdf](http://www.pml.ac.uk/data/files/Biofuel%20Exhibition_Oct07.pdf)

Preliminary SWOT analysis – Cultivation and storage of marine algae	
<b>Strengths:</b> <ul style="list-style-type: none"> <li>• CO<sub>2</sub> sequestration</li> <li>• Reduces ocean acidification</li> <li>• Technology for cultivation available</li> <li>• Easy to modify or stop</li> </ul>	<b>Weaknesses:</b> <ul style="list-style-type: none"> <li>• Storage may be impractical and/or expensive</li> <li>• Probably limited scale</li> <li>• High initial costs of establishing facilities [K13]</li> </ul>
<b>Opportunities:</b> <ul style="list-style-type: none"> <li>• Combine with biofuel and/or petrochemical feedstock [I8] production</li> </ul>	<b>Threats:</b>

#### 4.ii.c. Electrochemical increase of ocean alkalinity

A scheme has been proposed to increase the amount of atmospheric CO<sub>2</sub> absorbed by the ocean by increasing the alkalinity of seawater using an electrochemical reaction<sup>50,51</sup>. Specifically, it has been proposed that chlorine and hydrogen gas could be removed from seawater by passing an electric current through it. This would increase the alkalinity of the ocean by producing sodium hydroxide, and would thereby increase CO<sub>2</sub> absorption from the atmosphere. The chlorine and hydrogen produced could be combined in fuel cells to form strong hydrochloric acid, which could be neutralized by reacting it with silicate rocks, and then returned to the sea. It has been suggested that the process could be powered using energy sources that are too remote to be useful for other purposes, such as solar and geothermal power<sup>50</sup> [M34], possibly in locations such as mid-ocean volcanic islands, where there would also be a supply of basic rocks<sup>52</sup>.

This proposal would require further investigation, however, to determine whether the energy inputs required would have the net effect of increasing, not decreasing, atmospheric CO<sub>2</sub>. It might also be more efficient to instead use the geothermal or solar energy directly, as an alternative to carbon-based fuels — although this would depend on whether the energy source was available where it could be used and on whether it was fully exploited (i.e. if there was more energy available than could be used directly, it could be used for this process) [Q33]. The practicalities of the scheme (including cost, technology etc.) also require further investigation. Finally, the scheme could have detrimental impacts on the marine environment, because the basic solution produced around the treatment plants could contain chlorinated by-products, which could harm sea life<sup>51</sup>.

<sup>50</sup> House, K.Z., House, C.H., Schrag, D.P., and Aziz, M.J., 2007, Electrochemical Acceleration of Chemical Weathering as an Energetically Feasible Approach to Mitigating Anthropogenic Climate Change, *Environ. Sci. Technol.*, 41 (24), 8464–8470.

<sup>51</sup> See: [http://pubs.acs.org/subscribe/journals/esthag-w/2007/nov/science/ee\\_mitigate.html](http://pubs.acs.org/subscribe/journals/esthag-w/2007/nov/science/ee_mitigate.html)

<sup>52</sup> Shepherd, J., 2008, Journal Club, *Nature*, 451, 749

Preliminary SWOT analysis – Electrochemical increase of ocean alkalinity	
<b>Strengths:</b> <ul style="list-style-type: none"> <li>• CO<sub>2</sub> sequestration</li> <li>• Reduces ocean acidification</li> <li>• Large-scale availability of materials</li> <li>• Easy to modify or stop</li> </ul>	<b>Weaknesses:</b> <ul style="list-style-type: none"> <li>• Effectiveness unproven (might emit more CO<sub>2</sub> than would be saved)</li> </ul>
<b>Opportunities:</b> <ul style="list-style-type: none"> <li>• Development of more efficient electrolysis and/or fuel cells</li> </ul>	<b>Threats:</b> <ul style="list-style-type: none"> <li>• Local impacts on marine ecosystems</li> </ul>

#### 4.ii.d. 'Air capture'<sup>53</sup>

'Air capture' involves the direct removal of CO<sub>2</sub> from the atmosphere by absorption in an alkaline solution, followed by its release in a concentrated stream and subsequent storage<sup>54</sup> (the CO<sub>2</sub> could also be converted into fuel<sup>55</sup>, but this option is not discussed here because it does not result in net draw-down of CO<sub>2</sub>). In one version of the process, CO<sub>2</sub> is absorbed in an alkaline solution, converted into lime, and then released in an oxygen-fired kiln. In an alternative version, an electrical voltage is applied across the carbonate solution to release the CO<sub>2</sub> (this is a simpler process, but requires more energy). An advantage of 'air capture' over traditional CCS technology (i.e. capture from point sources) is that the sites of carbon capture are independent of the sites of carbon emission, and could thus be located near carbon storage sites and/or renewable energy sources that are not fully exploited (cf. section 4.ii.c.).

This proposal requires further investigation to determine whether the energy inputs required would have the net effect of increasing the atmospheric concentration of CO<sub>2</sub>. Energy is needed to construct, maintain and operate the facilities, produce the feedstock chemicals required, and release and store the CO<sub>2</sub> [A35, I5, R6, AG5]. Some of these processes are energy-intensive — it has been estimated that ~1100 kWh would be needed to produce 1 ton of sodium hydroxide [R6], for example, although less energy-intensive alternatives are being explored [C41]. Ideally, the process would be powered using renewable energy, such as solar or geothermal power — although it has been estimated that the thermo-chemical process could still lead to a net reduction in atmospheric CO<sub>2</sub> concentration if it was powered by fossil fuels<sup>56</sup>. It has also been suggested that heat produced during electricity generation could be used to power the process, which could reduce the electricity required by ~50%<sup>54</sup>. The feasibility of storing large quantities of CO<sub>2</sub> also needs to be explored further.

**'Synthetic trees'** — The most well-known 'air capture' option involves so-called 'synthetic trees' — structures with a large surface area that are coated with a

<sup>53</sup> It could be argued that 'air capture' schemes should not be classified as 'geo-engineering' because they do not involve 'manipulation' of the Earth system. These schemes are, however, often classified as geo-engineering options because they involve intentional, potentially large-scale alteration of the environment, and we have therefore chosen to include them in this paper.

<sup>54</sup> See: <http://www.realclimate.org/index.php?p=532>

<sup>55</sup> See: <http://www.nytimes.com/2008/02/19/science/19carb.html>

<sup>56</sup> See: <http://www.livescience.com/environment/071120-carbon-soak.html>



chemical that reacts with CO<sub>2</sub>. Air is passed over the structure to remove CO<sub>2</sub> from it, and the CO<sub>2</sub> is subsequently released for storage<sup>57</sup>. Professor Klaus Lackner<sup>58</sup> of the Earth Institute at Columbia University has designed a 30 metre-tall ‘artificial tree’ (although various structures could be used [Q25]) that is claimed to strip 90,000 tonnes of CO<sub>2</sub> from the air each year — equivalent to the output of about 20,000 cars or the carbon sequestration effect of about 1,000 real trees. The structures could be placed in any area with sufficient ventilation (including caves), so the aesthetic impact could potentially be low [A37, M31]. A working prototype (based on the same principles but using a different design) has been built at Carnegie Mellon University, Calgary<sup>59</sup>.

Preliminary SWOT analysis – Synthetic trees	
<b>Strengths:</b> <ul style="list-style-type: none"> <li>• Relatively simple technology</li> <li>• Potentially few side effects [cf. U3]</li> <li>• Easy to modify or stop</li> <li>• CO<sub>2</sub> sequestration</li> <li>• Reduces ocean acidification</li> </ul>	<b>Weaknesses:</b> <ul style="list-style-type: none"> <li>• Effectiveness unproven (might emit more CO<sub>2</sub> than would be saved)</li> <li>• Feasibility of CO<sub>2</sub> storage remains uncertain</li> <li>• Potentially high maintenance</li> </ul>
<b>Opportunities:</b> <ul style="list-style-type: none"> <li>• Flexibility in location/coverage</li> <li>• Impact assessments</li> </ul>	<b>Threats:</b> <ul style="list-style-type: none"> <li>• Large-scale escape of CO<sub>2</sub> from storage</li> </ul>

<sup>57</sup> See: <http://www.physorg.com/news96732819.html>

<sup>58</sup> Recent work by Professor Lackner and colleagues has not been published because they have formed a private company to develop the technology [Q24].

<sup>59</sup> See: <http://www.ucalgary.ca/%7EKeith/Misc/Stolaroff%20AGU%20Dec%202005%20talk.pdf> and <http://cdmc.epp.cmu.edu/co.pdf>

## 5. Other considerations

In order to assess the feasibility of geo-engineering options, a number of factors will need to be taken into account. In addition to environmental effects, social, political and economic issues will all need to be considered. For example:

- There should be a measurable benefit that unambiguously outweighs the impacts arising from the full lifetime energy costs, carbon emissions and other adverse consequences involved in establishing, maintaining and decommissioning the relevant technologies.
- The magnitude of the manipulation must be controllable, and it must be easy to 'switch off' the effect (in the event of unforeseen consequences).
- There must be very wide public acceptance and international agreement on the acceptability of geo-engineering schemes [S7, U4, X10]. The following political issues must be addressed if geo-engineering is to be carried out on a globally-significant scale:
  - i. There needs to be high public trust in both the science/technology and the competence of the implementing bodies (private sector, national governments or international agencies) [X11], which may be difficult to achieve [S2, S6, X12]. It is, therefore, important that the factors that influence public understanding, risk perception and acceptance of such options are understood and taken into account before attempting to implement them [cf. S1-S9].
  - ii. Geo-engineering actions by one country must not be regarded as an infringement or incursion on the territory of another (although it is worth noting that greenhouse-gas emissions have such effects [C52]). This may be particularly relevant to atmospheric manipulations, which affect national airspace and need to be large-scale to have significant effects.
  - iii. Political commitment needs to be sustained over the period for which geo-engineering is required.
  - iv. Even if there is international acceptance that a net global benefit will result, it must be recognised that disadvantages may occur for some countries. Multi-billion dollar compensation could be involved between winners and losers (for example, the latter suffering floods or droughts potentially attributable to geo-engineering). The ethical and legal frameworks for such arrangements do not yet exist, and are unlikely to be straightforward. (It is worth noting, however, that this concern is unlikely to be significant for geo-engineering options that significantly reduce CO<sub>2</sub> concentrations and thus directly reduce the impacts of greenhouse-gas emissions [C53].)
- The way in which the cost of the scheme would be met must be considered (particularly as the benefits would ideally be shared by all) [S3].
- If CO<sub>2</sub> reductions obtained through geo-engineering schemes were to be traded as carbon credits in carbon trading schemes, the principles and practices for verifying the value of such credits must be agreed between the scientific, commercial, and regulatory communities [H20]; and we would need to avoid situations where climate benefits were rewarded whilst any adverse environmental effects (such as



biodiversity impacts), which might not be experienced by the developer or deployer of the technology, were not paid for.

- Considerable resources would probably need to be expended to offset even a small fraction of predicted climate change. While this benefit could complement other measures, the possibility that geo-engineering options could divert attention and resources away from more fundamental solutions to global warming [S4] (i.e. emissions reductions and avoiding deforestation [F11]) must be considered.

## 6. Conclusions

It is clear from the assessment of geo-engineering options presented here that there are large uncertainties regarding the effectiveness, impacts, technical feasibility, cost and risks of all the schemes considered. As a consequence of these uncertainties, we feel that it is premature at this stage to draw firm conclusions on the feasibility of implementing the schemes discussed [cf. A42, C54, J1, M35]. However, the following preliminary conclusions can be drawn:

- options involving space shades/mirrors (particularly those that involve significant engineering in space) are unlikely to be available in the near future and (as they stand at present) would be high-risk compared to other options because they would be difficult to modify or remove;
- ocean pipes are probably not a feasible geo-engineering option because they are unlikely to remove significant quantities of CO<sub>2</sub> from the atmosphere (and could result in CO<sub>2</sub> release);
- cultivation and storage of marine algae is unlikely to be a feasible option for mitigating climate change on a large scale due to practical difficulties associated with storing algal biomass, but it might be possible to combine small-scale storage operations with other processes, such as biofuel production;
- options involving space shades/mirrors and injection of aerosols into the stratosphere or troposphere have the disadvantage that rapid climate change could result if they were stopped abruptly (either due to failure or policy decisions);
- injection of aerosols into the stratosphere or troposphere, surface albedo modification, ocean iron fertilisation and 'air capture' schemes have the advantage that they could be implemented gradually and modified or stopped relatively easily;
- 'air capture' schemes potentially have fewer detrimental side effects than other options, but their effectiveness in terms of net CO<sub>2</sub> sequestration/release remains uncertain.

The challenge of significantly reducing greenhouse-gas emissions is great and the risks associated with failing to do so are high. There is therefore an argument for carrying out further research to assess the feasibility of using geo-engineering options as a means of avoiding dangerous climate change (on local to global scales), in order to 'buy time' for reducing greenhouse-gas emissions; although, given the significant doubts over feasibility, it is essential that we do not rely on the availability of geo-engineering options. Research into the scientific, technological, economic, and socio-political aspects of geo-engineering options would be necessary to bring deployment closer to reality. Priorities for those funding and conducting such research could include:

- Field-based studies to explore the effects (desired and undesired) of (i) changing surface albedo and (ii) spraying seawater into the troposphere.
- Model- and laboratory-based studies to understand the atmospheric chemistry (particularly ozone) involved in injecting sulphate aerosols into the stratosphere.
- Climate model-based studies to explore the effects of (i) changing surface albedo, (ii) spraying seawater into the troposphere, and (iii) injecting sulphate aerosols into

the stratosphere. A particular priority in this regard could be to use more 'realistic' scenarios (such as simulating aerosol injection using fully-coupled General Circulation Models that include atmospheric chemistry, rather than using 'solar dimming' to represent the effects of aerosols). Simulations could also explore the effects of different options for applying the schemes, such as Arctic vs. tropical and pulsed vs. continuous injection of sulphate aerosols into the stratosphere.

- Climate model-based studies to determine the optimal 'mix' of geo-engineering schemes (i.e. the combination that maximises desirable effects and minimises detrimental effects).
- The use of observational data to validate climate model results (for example, the use of satellite data to validate simulations of changes in surface albedo).
- Research into the net effect on atmospheric CO<sub>2</sub> concentrations of schemes that require significant amounts of energy to implement — particularly (i) electrochemically increasing the alkalinity of the ocean, and (ii) 'air capture' schemes such as 'synthetic trees'.
- Research to assess the technical and economic feasibility of options, particularly where the science is relatively well-understood (such as changes in surface albedo).
- Research into the socio-political feasibility of options, particularly for schemes that involve modification of privately-owned property (such as increasing the albedo of urban surfaces) and schemes that would probably require universal political agreement to implement (such as space shades/mirrors and injecting sulphate aerosols into the stratosphere).

However, it is clear that, given the significant uncertainties around geo-engineering options, research funding has a high probability of not leading to the development of useable technologies. Public support for geo-engineering research should therefore be understood in the context of the wider effort to tackle the impacts of climate change, the priorities for which should continue to be overwhelmingly focussed on emissions abatement and adaptation to unavoidable change. DECC currently has no plans for significant research funding on geo-engineering; however, if other parties, countries and institutions wished to develop a shared approach, DECC would be interested in sharing expertise, and in helping to develop an initial detailed scoping study.