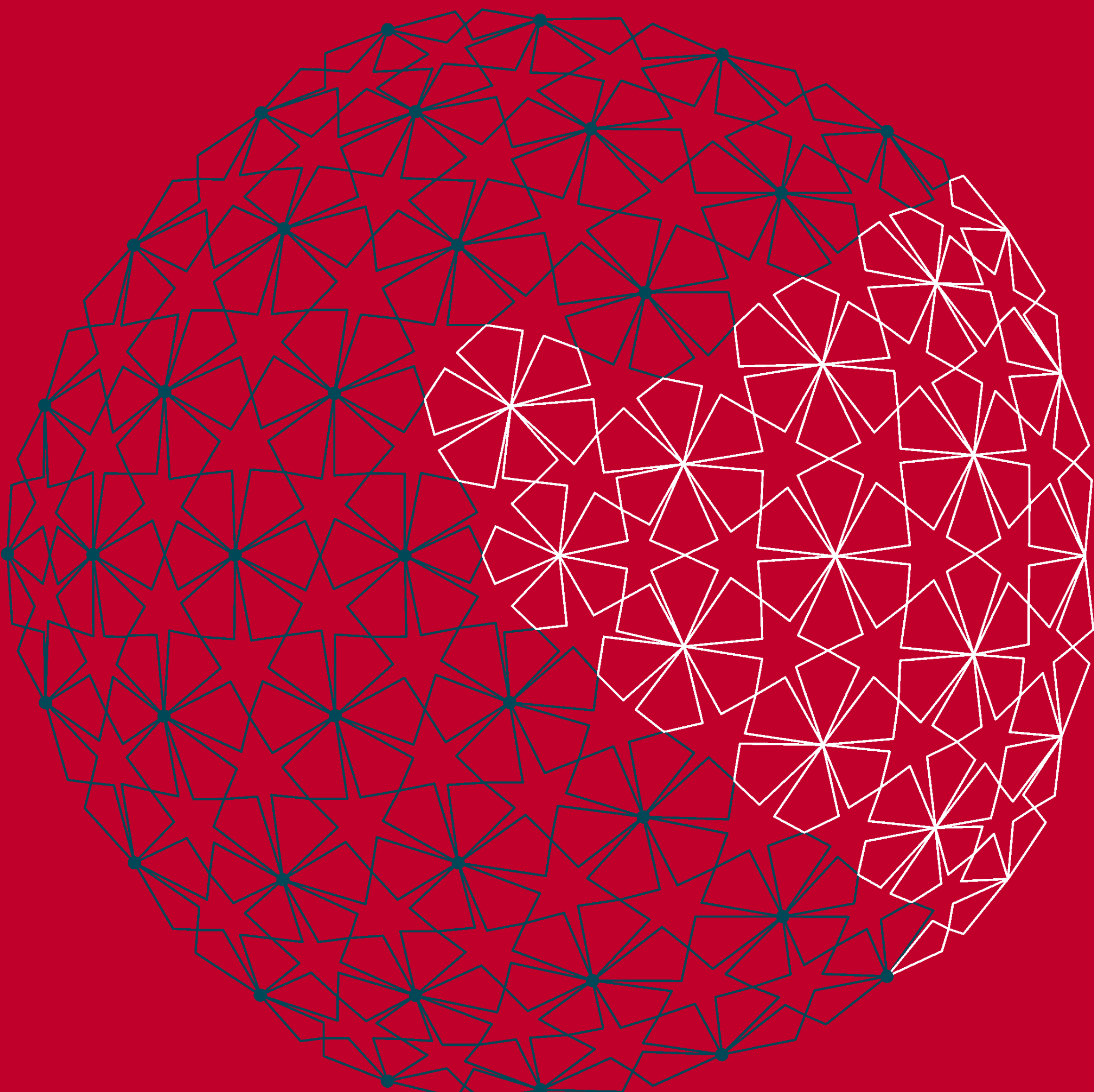
Geoengineering the climate

Science, governance and uncertainty

September 2009



EXCELLENCE IN SCIENCE

THE ROYAL SOCIETY

Cover image from DaisyBall model, by Ginger Booth, http://gingerbooth.com, Copyright © Yale University 1997–2008. The cover image comes from the Daisyworld model developed by Dr. James Lovelock and Professor Andrew Watson, both Fellows of the Royal Society. This conceptual model illustrates the tight coupling between climate and the biosphere through the connection between surface reflectivity and temperature—white daisies reflect more and absorb less solar radiation than do dark daisies thereby keeping the Earth cooler. This is the principle on which Geoengineering by the reflection of solar radiation is based. Daisyworld has been instrumental in drawing attention to the tight link between the Earth's surface climate and the presence of living organisms. See: Watson, A. J. and Lovelock, J.E. (1983). Biological homeostasis of the global environment: the parable of Daisyworld. Tellus 35B, 284–289.

Geoengineering the climate: science, governance and uncertainty

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Geoengineering the climate: science, governance and uncertainty

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Foreword

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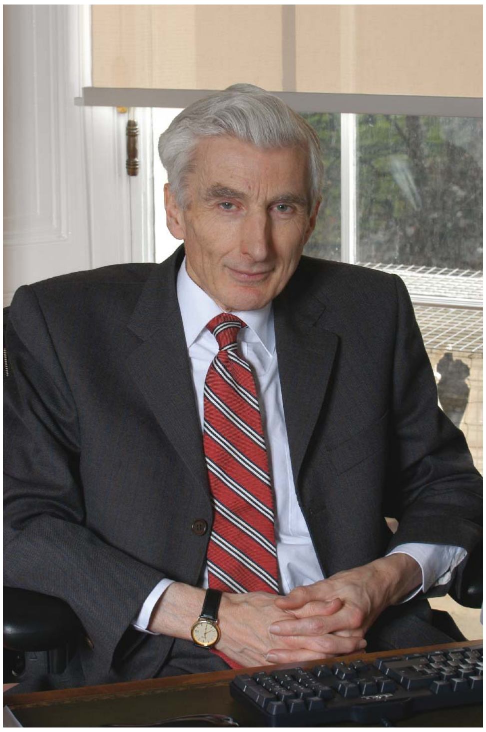

The continuing rise in the atmospheric concentration of greenhouse gases, mainly caused by the burning of fossil fuels, is driving changes in the Earth's climate. The long-term consequences will be exceedingly threatening, especially if nations continue 'business as usual' in the coming decades. Most nations now recognise the need to shift to a low-carbon economy, and nothing should divert us from the main priority of reducing global greenhouse gas emissions. But if such reductions achieve too little, too late, there will surely be pressure to consider a 'plan B'—to seek ways to counteract the climatic effects of greenhouse gas emissions by 'geoengineering'.

Many proposals for geoengineering have already been made—but the subject is bedevilled by much doubt and confusion. Some schemes are manifestly far-fetched; others are more credible, and are being investigated by reputable scientists; some are being promoted over-optimistically. In this report, the Royal Society aims to provide an authoritative and balanced assessment of the main geoengineering options. Far more detailed study would be needed before any method could even be seriously considered for deployment on the requisite international scale. Moreover, it is already clear than none offers a 'silver bullet', and that some options are far more problematic than others.

This report is therefore offered as a clarification of the scientific and technical aspects of geoengineering, and as a contribution to debates on climate policy. The Society is grateful to all the members of the Working Group, and especially to John Shepherd, its chairman. We also acknowledge the valuable inputs from the Council's review group, and the expert support, throughout the exercise, of the Society's Science Policy team.

Membership of working group

The members of the working group involved in producing this report were as follows:

Chair	
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Richard Heap	Senior Policy Adviser.
Andy Parker	Policy Adviser.
James Wilsdon	Director, Science Policy Centre.

This report has been reviewed by an independent panel of experts and also approved by the Council of the Royal Society.

Review Panel

The Royal Society gratefully acknowledges the contribution of the reviewers. The review group were not asked to endorse the conclusions or recommendations of this report, nor did they see the final draft of the report before its release.

Dame Jean Thomas DBE, CBE, FRS, FMedSci (Chair)	Professor of Macromolecular Biochemistry, University of Cambridge, UK.
Professor David Fowler CBE FRS	Centre for Ecology and Hydrology, Edinburgh UK.
Sir John Lawton CBE FRS	Chairman, Royal Commission on Environmental Pollution, UK.
Professor John Mitchell OBE FRS	Director of Climate Science, UK Met Office.
Professor Michael Oppenheimer	Albert G. Milbank Professor of Geosciences and International Affairs, Princeton University, USA.
Professor Susan Owens OBE	Professor of Environment and Policy, University of Cambridge, UK.
Sir David Read FRS	Emeritus Professor of Plant Sciences, University of Sheffield, UK.

Carbon Dioxide Removal methods reviewed in this study include:

- Land use management to protect or enhance land carbon sinks;
- The use of biomass for carbon sequestration as well as a carbon neutral energy source;
- Enhancement of natural weathering processes to remove CO_2 from the atmosphere;
- Direct engineered capture of CO_2 from ambient air;
- The enhancement of oceanic uptake of CO_2, for example by fertilisation of the oceans with naturally scarce nutrients, or by increasing upwelling processes.

Solar Radiation Management techniques directly modify the Earth's radiation balance, and would take only a few years to have an effect on climate once they had been deployed. They do not treat the root cause of climate change (increased levels of greenhouse gases in the atmosphere) but because they act quickly, they could be useful in an emergency, for example to avoid reaching a climate 'tipping point'. Methods considered in this study include:

- Increasing the surface reflectivity of the planet, by brightening human structures (eg by painting them white), planting of crops with a high reflectivity, or covering deserts with reflective material;
- Enhancement of marine cloud reflectivity;
- Mimicking the effects of volcanic eruptions by injecting sulphate aerosols into the lower stratosphere;
- Placing shields or deflectors in space to reduce the amount of solar energy reaching the Earth.

Key recommendation:

- Evaluations of geoengineering methods should take account of the major differences between the main two classes of methods; ie Carbon Dioxide Removal methods which remove CO_2 from the atmosphere and Solar Radiation Management methods which modify the albedo (reflectivity) of the planet.

Evaluation of geoengineering methods

None of the geoengineering methods evaluated offers an immediate solution to the problem of climate change, or reduces the need for continued emissions reductions.

In most respects Carbon Dioxide Removal methods would be preferable to Solar Radiation Management methods because they effectively return the climate system to closer to its natural state, and so involve fewer uncertainties and risks. Of the Carbon Dioxide Removal methods assessed, none has yet been demonstrated to be effective at an affordable cost, with acceptable side effects. In addition, removal of CO_2 from the atmosphere only works very slowly to reduce global temperatures (over many decades). If safe and low cost methods can be deployed at an appropriate scale they could make an important contribution to reducing CO_2 concentrations and could provide a useful complement to conventional emissions reductions. It is possible that they could even allow future reductions of atmospheric CO_2 concentrations (negative emissions) and so address the ocean acidification problem.

Carbon Dioxide Removal methods that remove CO_2 from the atmosphere without perturbing natural systems, and without large-scale land-use change requirements, such as CO_2 capture from air and possibly also enhanced weathering, are likely to have fewer side effects. Techniques that sequester carbon but have land-use implications (such as biochar and soil based enhanced weathering) may be useful contributors on a small-scale although the circumstances under which they are economically viable and socially and ecologically sustainable remain to be determined. The extent to which methods involving large-scale manipulation of Earth systems (such as ocean fertilisation), can sequester carbon affordably and reliably without unacceptable environmental side-effects, is not yet clear.

Compared to Carbon Dioxide Removal methods, Solar Radiation Management techniques are expected to be relatively cheap and would take only a few years to have an effect on the climate once deployed. However there are considerable uncertainties about their consequences and additional risks. It is possible that in time, assuming that these uncertainties and risks can be reduced, that Solar Radiation Management methods could be used to augment conventional mitigation. However, the large-scale adoption of Solar Radiation Management methods would create an artificial, approximate, and potentially delicate balance between increased greenhouse gas concentrations and reduced solar radiation, which would have to be maintained, potentially for many centuries. It is doubtful that such a balance would really be sustainable for such long periods of time, particularly if emissions of greenhouse gases were allowed to continue or even increase. The implementation of any large-scale Solar Radiation Management method would introduce additional risks and so should only be undertaken for a limited period and in parallel with conventional mitigation and/or Carbon Dioxide Removal methods.

The climate achieved by Solar Radiation Management methods, especially those which have with regionally variable impacts, will only approximate that with less greenhouse warming, particularly for critical variables other than temperature (such as precipitation), which are very sensitive to regional differences such as weather systems, wind speeds and ocean currents. Such unintended environmental effects should be carefully assessed using improved climate models as well as the best now available. However, because Solar Radiation Management techniques offer the only option for limiting or reducing global temperatures rapidly they should also be the subject of further scientific investigation to improve knowledge in the event that such interventions become urgent and necessary. Much more needs to be known about their climate and environmental effects and social consequences (both intended and unintended) before they should be considered for large-scale experiments or deployment.

Of the Solar Radiation Management methods considered, stratospheric aerosols are currently the most promising because their effects would be more uniformly distributed than for localised Solar Radiation Management methods, they could be much more readily implemented than space-based methods, and would take effect rapidly (within a year or two of deployment). However, potentially significant uncertainties and risks are associated with this approach and research into methods of delivery and deployment, effectiveness, impacts on stratospheric ozone and high-altitude tropospheric clouds, and detailed modelling of their impacts on all aspects of climate (including precipitation patterns and monsoons) is needed.

It would be risky to embark on the implementation of any large-scale Solar Radiation Management methods, which may not be sustainable in the long term, and which would do nothing for the ocean acidification problem, without a clear and credible exit strategy.

Key recommendations:

- Geoengineering methods of both types should only be considered as part of a wider package of options for addressing climate change. Carbon Dioxide Removal methods should be regarded as preferable to Solar Radiation Management methods as a way to augment continuing mitigation action in the long term. However Solar Radiation Management methods may provide a potentially useful short-term backup to mitigation in case rapid reductions in global temperatures are needed;
- Carbon Dioxide Removal methods that have been demonstrated to be safe, effective, sustainable and affordable should be deployed alongside conventional mitigation methods as soon as they can be made available;
- Solar Radiation Management methods should not be applied unless there is a need to rapidly limit or reduce global average temperatures. Because of the uncertainties over side-effects and sustainability they should only be applied for a limited time period, and if accompanied by aggressive programmes of conventional mitigation and/or Carbon Dioxide Removal so that their use may be discontinued in due course.

Future needs for geoengineering

If geoengineering is to have a future role, and is to be applied responsibly and effectively, then coordinated and collaborative work is needed to enhance knowledge, develop governance mechanisms and agree decision-making processes.

Key recommendation:

- To ensure that geoengineering methods can be adequately evaluated, and applied responsibly and effectively should the need arise, three priority programmes of work are recommended:

  a. Internationally coordinated research and technological development on the more promising methods identified in this report;

  b. International collaborative activities to further explore and evaluate the feasibility, benefits, environmental impacts, risks and opportunities presented by geoengineering, and the associated governance issues;

  c. The development and implementation of governance frameworks to guide both research and development in the short term, and possible deployment in the longer term, including the initiation of stakeholder engagement and a public dialogue process.

Governance

The international mechanisms most applicable to geoengineering methods and their impacts have not been developed for the purpose of regulating geoengineering, and for some methods there are as yet no regulatory mechanisms in place.

The greatest challenges to the successful deployment of geoengineering may be the social, ethical, legal and political issues associated with governance, rather than scientific and technical issues. For some methods, like ambient air capture, pre-existing national mechanisms are likely to be sufficient, for others, such as ocean iron-fertilisation, existing international mechanisms may be relevant but require some modification. There will however be some methods, particularly those that require transboundary activity or which have transboundary effects, for example stratospheric aerosols or space-based mirrors, which may require new international mechanisms. Appropriate governance mechanisms for deployment should be established before Carbon Dioxide Removal or Solar Radiation Management methods are actually needed in practice. This will require an analysis of whether existing international, regional and national mechanisms are appropriate for managing geoengineering, and the initiation of an international dialogue involving the scientific, policy, commercial and non-governmental communities.

It would be highly undesirable for geoengineering methods that involve activities or effects (other than simply the removal of greenhouse gases from the atmosphere) that extend beyond national boundaries to be subject to large-scale research or deployment before appropriate governance mechanisms are in place. It is essential that the governance challenges posed by geoengineering are explored, and policy processes established as a priority.

Key recommendation:

- The governance challenges posed by geoengineering should be explored in more detail by an international body such as the UN Commission for Sustainable Development, and processes established for the development of policy mechanisms to resolve them.

Research and development

A research governance framework is required to guide the sustainable and responsible development of research activity so as to ensure that the technology can be applied if it becomes necessary. Codes of practice for the scientific community should be developed, and a process for designing and implementing a formal governance framework initiated. Research activity should be as open, coherent, and as internationally coordinated as possible and trans-boundary experiments should be subject to some form of international governance, preferably based on existing international structures.

Little research has yet been done on most of the geoengineering methods considered, and there have been no major directed programmes of research on the subject. The principal research and development requirements in the short term are for much improved modelling studies and small/medium scale experiments (eg laboratory experiments and field trials). Investment in the development of improved Earth system and climate models is needed to enable better assessment of the impacts of geoengineering methods on climate and weather patterns (including precipitation and storminess) as well as broader impacts on environmental processes. Much more research on the feasibility, effectiveness, cost, social and environmental impacts and possible unintended consequences is required to understand the potential benefits and drawbacks, before these methods can be properly evaluated. The social and environmental impacts of most geoengineering methods have not yet been adequately evaluated, and all methods are likely to have unintended consequences. These need to be strenuously explored and carefully assessed.

Key recommendations:

- The Royal Society in collaboration with international science partners should develop a code of practice for geoengineering research and provide recommendations to the international scientific community for a voluntary research governance framework. This should provide guidance and transparency for geoengineering research, and apply to researchers working in the public, private and commercial sectors. It should include:
    a. Consideration of what types and scales of research require regulation including validation and monitoring;
    b. The establishment of a *de minimis* standard for regulation of research;
    c. Guidance on the evaluation of methods including relevant criteria, and life cycle analysis and carbon/climate accounting.
- Relevant international scientific organisations should coordinate an international programme of research on geoengineering methods with the aim of providing an adequate evidence base with which to assess their technical feasibility and risks, and reducing uncertainties within ten years.
- Relevant UK government departments (DECC[1] and DEFRA[2]) in association with the UK Research Councils (BBSRC[3], ESRC[4], EPSRC[5], and NERC[6]) should together fund a 10 year geoengineering research programme at a level of the order of £10M per annum. This should actively contribute to the international programme referred to above and be closely linked to climate research programmes.

The public acceptability of geoengineering

Public attitudes towards geoengineering, and public engagement in the development of individual methods proposed, will have a critical bearing on its future. Perception of the risks involved, levels of trust in those undertaking research or implementation, and the transparency of actions, purposes and vested interests, will determine the political feasibility of geoengineering. If geoengineering is to play a role in reducing climate change an active and international programme of public and civil society dialogue will be required to identify and address concerns about potential environmental, social and economic impacts and unintended consequences.

Key recommendation:

The Royal Society, in collaboration with other appropriate bodies, should initiate a process of dialogue and engagement to explore public and civil society attitudes, concerns and uncertainties about geoengineering as a response to climate change.

1 Department of Energy and Climate Change.
2 Department for Environment, Food, and Rural Affairs.
3 Biotechnology and Biological Sciences Research Council.
4 Economic and Social Research Council.
5 Engineering and Physical Sciences Research Council.
6 Natural Environment Research Council.

1 Introduction

1.1 Background

Geoengineering, or the *deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change*, has been suggested as a new potential tool for addressing climate change. Efforts to address climate change have primarily focused on mitigation, the reduction of greenhouse gas emissions, and more recently on addressing the impacts of climate change—adaptation. However, international political consensus on the need to reduce emissions has been very slow in coming, and there is as yet no agreement on the emissions reductions needed beyond 2012. As a result global emissions have continued to increase by about 3% per year (Raupach *et al*. 2007), a faster rate than that projected by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2001)[7] even under its most fossil fuel intensive scenario (A1FI[8]) in which an increase in global mean temperature of about 4°C (2.4 to 6.4°C) by 2100 is projected (Rahmstorf *et al*. 2007).

The scientific community is now becoming increasingly concerned that emissions will not be reduced at the rate and magnitude required to keep the increase in global average temperature below 2°C (above pre-industrial levels) by 2100. Concerns with the lack of progress of the political processes have led to increasing interest in geoengineering approaches. This Royal Society report presents an independent scientific review of the range of methods proposed with the aim of providing an objective view on whether geoengineering could, and should, play a role in addressing climate change, and under what conditions.

1.2 Geoengineering

Geoengineering proposals aim to intervene in the climate system by deliberately modifying the Earth's energy balance to reduce increases of temperature and eventually stabilise temperature at a lower level than would otherwise be attained (see Figure 1.1). The methods proposed are diverse and vary greatly in terms of their technological characteristics and possible consequences. In this report they have been classified into two main groups:

i. Carbon dioxide removal (CDR) methods: which reduce the levels of carbon dioxide (CO_2) in the atmosphere, allowing outgoing long-wave (thermal infra-red) heat radiation to escape more easily;

or:

ii. Solar radiation management (SRM) methods: which reduce the net incoming short-wave (ultra-violet and visible) solar radiation received, by deflecting sunlight, or by increasing the reflectivity (albedo) of the atmosphere, clouds or the Earth's surface.

Note that while it would theoretically also be possible for geoengineering methods to remove greenhouse gases other than CO_2 from the atmosphere (eg, methane (CH_4), nitrous oxide (N_2O)), most if not all of the methods proposed so far focus on CO_2 which is long-lived, and present at a relatively high concentration, and so these are the focus in this report. Mitigation efforts to reduce emissions of such non-CO_2 greenhouse gases are of course still extremely important, but are not regarded as geoengineering and so are not considered.

The objective of CDR methods is to remove CO_2 from the atmosphere by:

- Enhancing uptake and storage by terrestrial biological systems;
- Enhancing uptake and storage by oceanic biological systems; or
- Using engineered systems (physical, chemical, biochemical).

SRM methods may be:

- Surface-based (land or ocean albedo modification);
- Troposphere-based (cloud modification methods, etc.);
- Upper atmosphere-based (tropopause and above, ie, stratosphere, mesosphere);
- Space-based.

1.3 The climate system

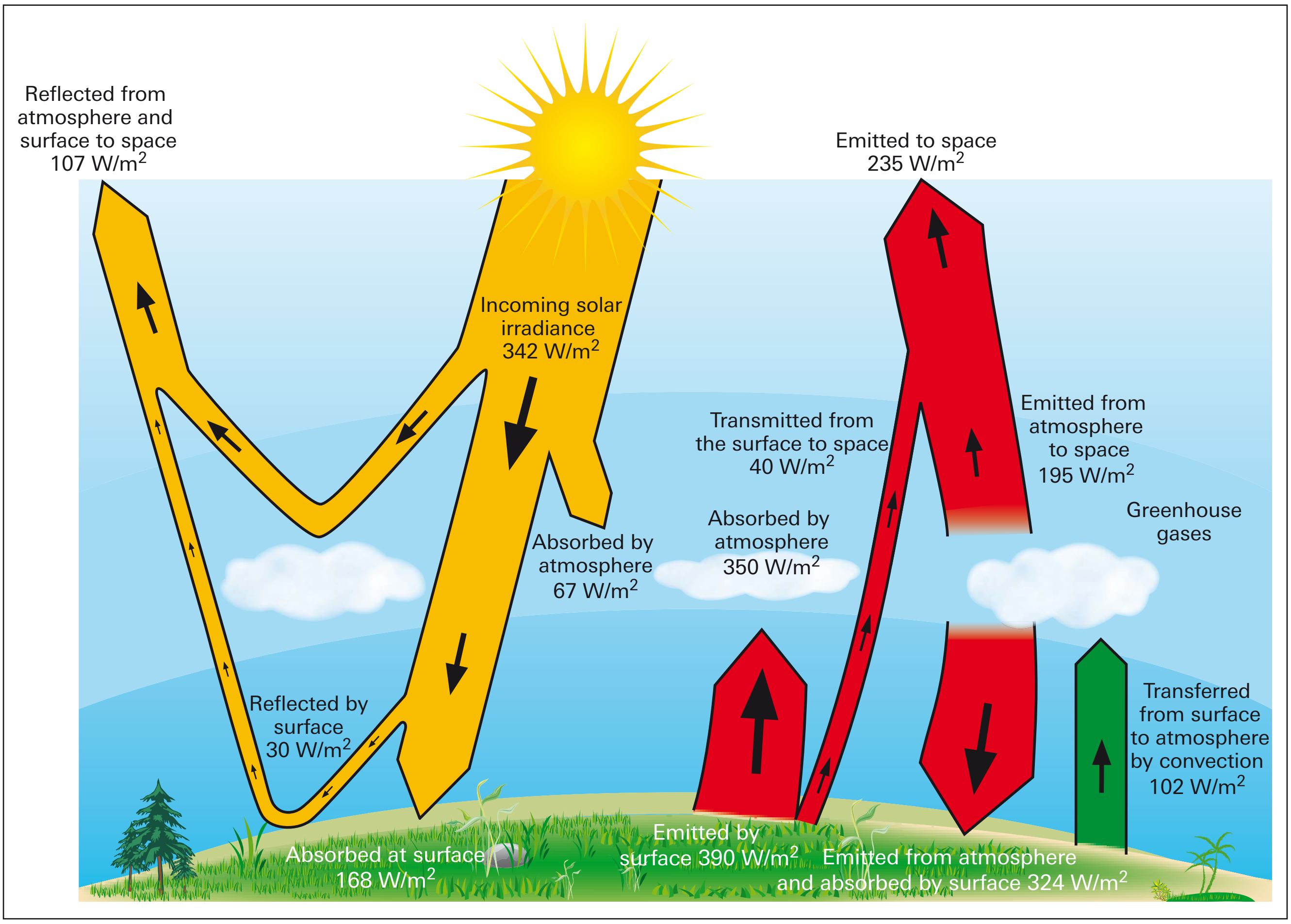
To understand the principles of geoengineering and the methods by which the range of interventions have effect it is necessary to understand the climate system. A detailed review of the science of climate change is provided in the IPCC Fourth Assessment working group 1 report (AR4) (IPCC 2007a). Here brief descriptions of the climate system and the drivers that lead to climate change are provided.

Most geoengineering proposals aim either to reduce the concentration of CO_2 in the atmosphere (CDR techniques, Chapter 2), or to prevent the Earth from absorbing some solar radiation, either by deflecting it in space before it reaches the planet, or by increasing the reflectivity of the Earth's surface or atmosphere (SRM techniques, Chapter 3). These geoengineering techniques would work by manipulating the energy balance of the Earth: the balance between incoming radiation from the sun (mainly short-wave ultraviolet and visible light) that acts to heat the Earth, and

7 Because of the economic crisis, 2008 and 2009 emissions will be lower than the most pessimistic of the IPCC Special Report on Emissions Scenarios (SRES). However, this emission reduction is due only to the downturn in GDP growth. Underlying factors, such as rates of deployment of carbon-neutral energy sources and improvement in efficiency continue to be worse than even the most pessimistic of the IPCC emission scenarios.

8 The A1FI scenario is based on a future world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient (but fossil fuel intensive) technologies (IPCC 2000a).

Figure 1.1. Schematic showing the global average energy budget of the Earth's atmosphere. Yellow indicates solar radiation; red indicates heat radiation and green indicates transfer of heat by evaporation/condensation of water vapour and other surface processes. The width of the arrow indicates the magnitude of the flux of radiation and the numbers indicate annual average values. At the top of the atmosphere the net absorbed solar radiation is balanced by the heat emitted to space. Adapted from Kiehl & Trenberth (1997).



out-going (long-wave) thermal infrared radiation which acts to cool it. It is this balance which fundamentally controls the Earth's temperature, and which drives and maintains the climate system (Figure 1.1).

These radiation streams do not reach or leave the Earth's surface unimpeded. About one third of the incoming solar radiation on average is reflected by clouds, and by ice caps and bright surfaces. This reflectivity of the Earth is referred to as its albedo (see Section 3.2). Most of the incoming radiation passes through the atmosphere to reach the Earth's surface, where some is reflected and most is absorbed, so warming the surface. Some of the outgoing thermal radiation emitted by the Earth's surface is absorbed by the greenhouse gases in the atmosphere (mainly natural water vapour and CO_2) and also by clouds, reducing the amount of heat radiation escaping to space, and so also warming the atmosphere and the Earth's surface. Only about 60% of the thermal radiation emitted by the surface eventually leaves the atmosphere, on average, after repeated absorption and re-emission within the atmosphere.

The outgoing thermal radiation increases strongly as surface temperature increases while the incoming solar radiation does not. This creates a strong negative feedback, because the temperatures of the surface and atmosphere increase until the outgoing and incoming radiation are in balance, and then stabilises. The flux of solar energy at the Earth's distance from the Sun, the 'solar constant', is approximately 1,368 W/m^2 which gives a value of 342 W/m^2 when averaged over the whole globe (refer to Box 1.1).

Box 1.1 Units used in this report

Radiative forcing is normally measured in W/m^2 and these units are used throughout this report. For masses of carbon and CO_2, quantities are often expressed in GtC, ie gigatonnes (10^9 T, or billions of tonnes) of carbon. 1 GtC is exactly the same as 1 PgC (1 petagram or 10^{15} g) of carbon, an alternative commonly used unit. The CO_2 molecule has a mass that is 3.67 times that of a carbon atom, so to convert masses of carbon to masses of CO_2 they must be multiplied by 3.67. In this report masses of carbon are used, because the quantity of carbon remains the same irrespective of its chemical form (carbon, CO_2, CH_4, etc).

Of this, more than 30% is reflected back to space leaving 235 W/m^2 entering the atmosphere and absorbed by the climate system. In equilibrium an equal flux of 235 W/m^2 of infrared radiation leaves the Earth. This is a delicate balance. If either radiation stream is perturbed by 1% (ie, 2.35 W/m^2) the surface temperature will change by about 1.8°C (range 1.2 to 2.7°C, IPCC 2007a).

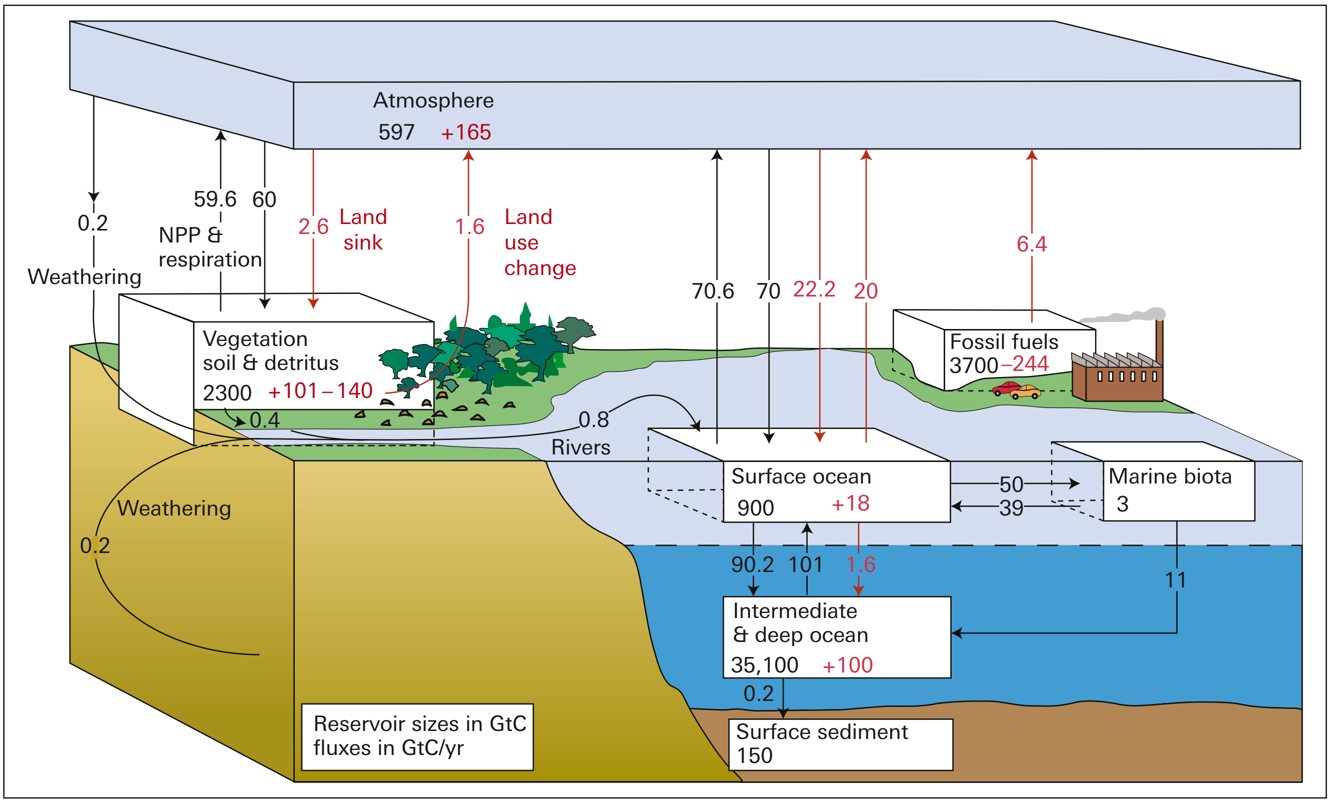
Increases in atmospheric greenhouse gas concentrations (eg, CO_2, CH_4, N_2O, ground level ozone (O_3) and chlorofluorocarbons (CFCs)) due to human activities such as fossil fuel burning, deforestation and conversion of land for agriculture, have upset this delicate balance as the gases restrict the emission of heat radiation to space a little more than usual. To restore this imbalance the lower atmosphere has warmed, and is emitting more heat (long-wave) radiation, and this warming will continue as the system evolves to approach a new equilibrium.

The global carbon cycle plays an important role in mediating the concentrations of greenhouse gas concentrations in the atmosphere (Figure 1.2) and so influences the rate at which equilibrium can be restored.

Carbon is exchanged naturally between the land, oceans, and atmosphere, and large quantities are stored in natural 'sinks' on land and in the oceans. Every year 60 to 90 Gt of carbon are absorbed from the atmosphere by the vegetation of both the land surface and the surface ocean and an equal amount is released to the atmosphere. By far the largest store of carbon in this system is in the deep ocean, where it exists predominantly as bicarbonate ions. The next largest store is the carbon locked up in vegetation and soils. Only a tiny amount is stored in marine biota. Marine biology nevertheless has a substantial influence on atmospheric CO_2 concentrations because it mediates a flux of carbon into the deep ocean which is responsible for the enrichment of the carbon content of the deep sea, at the expense of the surface ocean and the atmosphere—the 'biological pump' (see Chapter 2). Prior to the industrial revolution, these fluxes balanced closely, with a small net flux of a fraction of a GtC/yr from atmosphere to land and from oceans to atmosphere. Today there is a flux of approximately 2 GtC/yr from the atmosphere into each of the land and ocean and these partially offset the fossil fuel and land-use change fluxes releasing CO_2 into the atmosphere. In the oceans, the absorption of this increase in atmospheric CO_2 (see Figure 1.2) has led to a decline in the average pH of the oceanic surface waters by 0.1 units since the industrial revolution. This ocean acidification will continue to increase in future along with increasing CO_2 levels (Royal Society 2005) as discussed in Section 2.4.

The temperature of the planet is determined by the balance at the top of the atmosphere between the solar radiation absorbed and the long-wave radiation emitted to space. Any imbalance in these energy fluxes constitutes a 'radiative forcing' that ultimately causes an adjustment of the global mean temperature until balance is restored.

Figure 1.2. Representation of the global carbon cycle, where the numbers and arrows in black represent reservoir and flux sizes in the pre-industrial steady state, while those in red represent additions due to human activity (in units of GtC and GtC/yr respectively, appropriate to the period 1990–1999). Reprinted with permission from Sarmiento JL & Gruber N (2002). Sinks for anthropogenic carbon. Physics Today **55***(8): 30–36. Copyright 2002. American Institute of Physics.*



For example, human activities since pre-industrial times are estimated to have produced a net radiative forcing of about +1.6 W/m^2. About half of this radiative forcing has been balanced by the global warming of 0.8°C to date, but a similar amount of additional warming would occur even if CO_2 and other greenhouse gases were immediately stabilised at current levels (which is not possible). This lag in the response of the global mean temperature is primarily due to the large heat capacity of the oceans, which only warm up slowly. A doubling of the CO_2 concentration from its pre-industrial value to 550 ppm would give a radiative forcing of about 4 W/m^2 and an estimated equilibrium global warming of about 3°C (range 2.0 to 4.5°C) (IPCC 2007a).

1.4 Climate change and geoengineering—the policy context

Geoengineering is not a new idea. It has been recognised as a possibility since the earliest studies of climate change. Weather modification dates at least back to the 1830s when the proposals of American meteorologist James Pollard Espy to stimulate rain by controlled forest burning led to him becoming feted as the 'Storm King'. More recently the US 'Project Stormfury' sought for two decades to modify the path of hurricanes through seeding them with silver iodide. Geoengineering proposals for climate modification, specifically designed to counteract the greenhouse effect, date at least from 1965 when a report of the US President's Science Advisory Council was issued. Preliminary studies were conducted throughout the 1970s to 1990s (Budyko 1977, 1982; Marchetti 1977; US National Academy of Sciences 1992), and geoengineering was more recently discussed during a workshop convened by the Tyndall Centre and the Cambridge–MIT Institute in 2004. For a detailed review of the history of geoengineering see Keith (2000). However, in the 1980s and 1990s the emphasis of climate change policy discussions shifted to mitigation, primarily due to the efforts at the UN level to build a global consensus on the need for emissions controls.

The UN Framework Convention on Climate Change (UNFCCC) commits contracting states to stabilising greenhouse gas concentrations at levels short of those that would cause 'dangerous anthropogenic interference' in the climate system (Mann 2009). The UNFCCC Kyoto Protocol (1997) establishes a framework for control and reduction of greenhouse gas emissions through emissions targets and flexible mechanisms such as emissions trading.

Whilst the amount of global warming that corresponds to 'dangerous anthropogenic interference' has not been formally decided, there is a widespread consensus that a rise of about 2°C above the pre-industrial level is a reasonable working figure, and this has been formally adopted by the European Union as an upper limit and more recently by the G8 group of nations (G8 2009). According to recent studies (Allen *et al.* 2009; Meinshausen *et al.* 2009; Vaughan *et al.* 2009) even scenarios in which global emissions of CO_2 and other greenhouse gases are reduced by about 50% by 2050 give only a 50:50 chance that warming will remain less than 2°C by 2100. Moreover, there is no realistic scenario under which it would be possible for greenhouse gas emissions to be reduced sufficiently to lead to a peak and subsequent decline in global temperatures this century (because of lags in the climate system).

Climate models generally indicate that stabilisation of atmospheric CO_2 at about 450 ppm would be necessary to avoid warming exceeding 2°C (Allen *et al*. 2009).[9] However, this would require a revolutionary transformation of global energy production and consumption systems, and whilst it is still physically possible to deliver emissions reductions of the magnitude required by mid-century (Anderson *et al.* 2006; Ekins & Skea 2009; Royal Society 2009) there is little evidence to suggest such a transformation is occurring. Atmospheric concentrations are already more than 380 ppm CO_2 and are still rising steadily, and it seems increasingly likely that concentrations will exceed 500 ppm by mid-century and may approach 1000 ppm by 2100.

In addition, there is continuing uncertainty about crucial parameters such as climate sensitivity (IPCC 2007a; Allen *et al.* 2009) and the existence, and likely location of, possible thresholds or 'tipping points' in the climate system (Lenton *et al.* 2008). Some climate impacts may be happening sooner than predicted (eg, the low Arctic summer sea-ice minima in 2007 and 2008), of which the causes are unknown, and the consequences very uncertain. There is potential for positive feedbacks (due to CH_4 release and/or the reduction in albedo resulting from less sea-ice), which are credible but not yet fully quantified. According to Hansen *et al.* (2008), the effect of additional long-term positive feedbacks (due to the carbon cycle and ice-sheet extent/albedo effects) would lead to a higher level of climate sensitivity on millennial time-scales. This means that CO_2 levels may need to be reduced again in the future, to around 350 ppm, rather than stabilising at 450 ppm.

Concerns regarding the slow progress on achieving emissions reductions, and uncertainties about climate sensitivity and climate tipping points have led some members of the scientific and political communities to suggest that geoengineering may offer an alternative solution to climate change mitigation. In response, concerns have been expressed that geoengineering proposals could reduce the fragile political and public support for mitigation and divert resources from adaptation (this is sometimes referred to as 'the moral hazard argument', see Chapter 4), pose significant potential environmental risks, and have large uncertainties in terms of effectiveness and feasibility. Furthermore, the wide range of proposals present a variety

9 These figures are for CO_2 only. The effects of both non-CO_2 greenhouse gases and tropospheric aerosols also need to be considered. At present and in the recent past these additional effects have roughly cancelled, but they may not do so in future.

Box 1.2 Assessment of geoengineering proposals using numerical models of the climate system

A range of climate models is now used to assess the climate system and its perturbation by anthropogenic greenhouse gas emissions. If the impact of a particular geoengineering technique on climate is to be adequately assessed then the same or similar climate models must be employed. It is therefore essential to understand the current strengths and weaknesses of such models and the roles to which particular types are best suited.

Atmosphere-ocean general circulation models (AOGCMs) have been widely used in the IPCC assessments to make projections of future climate change given greenhouse gas emission scenarios. AOGCMs are based on fundamental physical laws (Newton's laws of motion, conservation of energy, etc.). Based on these laws, a computer model of the atmosphere can then be used to calculate the state of the climate system (temperature, winds, water vapour, etc.) for the whole atmosphere and ocean as a function of time. Typically the atmosphere and ocean are represented by a large number of boxes; their spatial resolution will depend on computer power available. Typical horizontal atmospheric resolutions are 2° x 2°; important atmospheric processes with typical scales less than this must be represented ('parameterised') empirically, introducing a degree of approximation and uncertainty.

Considerable advances have been made in climate modelling over the last 20 years, including the progression from simple atmospheric general circulation models (GCMs) to AOGCMs and the progressive addition of a wider range of processes (eg, aerosol feedback, atmospheric chemistry, cryospheric processes, etc.) as well as the ability to model at higher spatial resolution as computer power has increased. In the IPCC AR4 it is concluded that there is 'considerable confidence' that AOGCMs 'provide credible quantitative estimates of future climate change, particularly at continental and large scales' (Randall *et al.* 2007). Confidence in these estimates is greater for some climate variables (eg, temperature) than for others (eg, precipitation). This confidence is based on a large international effort to compare and evaluate climate models, including detailed study of recent climate change. The models capture well the observed global temperature record when anthropogenic and natural forcings are included. They also reproduce some important climate variability over the past century, as well as the impact of perturbations, for example, the eruption of Mt Pinatubo. There is less confidence in the ability of the current generation of AOGCMs to address regional scale changes, and bridging the spatial gap from global/continental to regional scales is a major research challenge.

It is important to recognise that there are model limitations that may limit confidence in their use to assess some geoengineering techniques (Submission: Palmer), and it will be necessary to use models which are well suited to evaluate the processes affected by the technique being considered. For example, the treatment of cloud processes and feedbacks is a longstanding problem in climate modelling and is highlighted in the IPCC AR4 (IPCC 2007a) as an important deficiency. This is of general concern for the evaluation of any geoengineering technique but would be a particularly relevant uncertainty for those methods which, for example, attempt to modify the occurrence and opacity of clouds, such as marine low-level clouds.

The terrestrial and marine carbon cycles play an important role in climate processes for decadal and longer timescales. Detailed treatments of carbon cycle dynamics (including soils, vegetation, and the marine biosphere) were not routinely incorporated into all the AOGCM simulations used in the AR4, although these processes are now represented in many GCMs and in Earth System models. These include a wider range of processes than standard AOGCMs and are generally adapted to simulate the longer timescales over which carbon cycle processes become very important. However, given present computer power, to include these additional processes and feedbacks these models usually have to compromise model representation in some area, such as by a reduction in spatial resolution or by increased use of parametrizations. Such Earth System Models of intermediate complexity (EMICs) are excellent tools for long-term simulations and for exploring model sensitivity and feedback processes, but are currently less well suited for spatially detailed quantitative projections of the next century or so.

of social, ethical and legal issues, which are only now beginning to be identified.

As geoengineering is a relatively new policy area there are no regulatory frameworks in place aimed specifically at controlling geoengineering activities and consequently the risk exists that some methods could be deployed by individual nation states, corporations or even one or more wealthy individuals without appropriate regulation or international agreement. While it is likely that some existing national, regional and international mechanisms may apply to either the activities themselves, or the impacts of geoengineering, they have yet to be analysed or tested with this purpose in mind. Recently, this has become an issue as organisations have shown interest in the potential of interventions such as ocean fertilisation to capture carbon and qualify for carbon credits through certification under the Clean Development Mechanism of the Kyoto Protocol. Commercial involvement in ocean fertilisation experiments has provoked a rapid and vocal response from the international political and scientific communities and environmental non-governmental organisations (NGOs).

Given the current poor state of understanding about geoengineering science, potentially useful techniques could be prematurely dismissed out of hand, and dangerous proposals may be promoted with enthusiasm. Policymakers need well-informed and authoritative advice based on sound science. With growing concern that geoengineering proposals were being promoted by some as a possible 'solution' to the problem of climate change, that experiments were being undertaken, in some cases potentially in contravention of national or international laws, and that active investment in the development and testing of new technologies is occurring, the Royal Society decided to undertake an independent scientific review of the subject.

1.5 Conduct of the study

The Royal Society established a working group of international experts in 2008 chaired by Professor John Shepherd FRS. The aim of the project was to provide a balanced assessment of a range of different climate geoengineering proposals, to help policymakers decide whether, and if so, when and which methods should be researched and deployed. The Terms of Reference can be found in Annex 8.2. The content of this report has been subjected to external peer review and endorsed by the Council of the Royal Society.

A call for submissions from academics, policy makers, industrialists and other interested parties was issued in March 2008 (see Annex 8.4 the list of submissions). The written evidence received is available (except where confidentiality was requested) from the Royal Society. The report is based so far as possible on peer-reviewed literature, using additional sources where necessary and appropriate. The contents of the submissions received were considered and have been used in the preparation of this report as appropriate. Four public focus groups were held along with a small opinion poll in May 2009, and selected experts were also invited to participate in a small workshop on the ethics of geoengineering in May 2009 (see Chapter 4 and Annex 8.3).

The scope of the study includes, in principle, any methods for geoengineering climate, defined as proposals which are intended to moderate climate change by deliberate large-scale intervention in the working of the Earth's natural climate system. Any methods, which the working group considered to be feasible and reasonably effective, were included in the study (see note to Annex 8.2).

Proposals for large-scale engineering activities, which do not involve deliberate intervention in the climate system and are therefore not normally regarded as geoengineering, were not considered in detail. Some of these have however already been well covered in the peer reviewed literature. They include:

- the development (and large-scale deployment) of low-carbon sources of energy (Royal Society (2008); Ekins & Skea (2009); German Advisory Council on Climate Change (WGBU 2009); Royal Society (2009));
- methods for reducing emissions of greenhouse gases, such as Carbon Capture & Storage (CCS) deployed at the point of emission (IPCC (2005));
- conventional afforestation and avoided deforestation (IPCC (2000b); Royal Society (2001)).

The focus of this report is to consider what is known, and what is not known about the expected effects, advantages and disadvantages of proposed geoengineering methods. All of the proposals considered are in the early outline/concept stage and estimates of cost and environmental impacts are very tentative. However, an initial evaluation is possible using criteria developed for the purposes of the report but based on the work of Lenton & Vaughan (2009) (Submission: Lenton & Vaughan).

As explained above, for the purposes of this evaluation the methods assessed have been classified according to whether their objective is to remove CO_2 from the atmosphere (CDR), or to modify planetary albedo or decrease short-wave solar radiation received (SRM).

There is a range of criteria by which geoengineering proposals should be evaluated; these can be broadly grouped into technical criteria and social criteria. In Chapters 2 and 3 the characteristics of the two classes are introduced and discussed, and their feasibility and efficacy assessed as far as possible against four technical criteria. These are composites of several related criteria, and (except for cost) are defined so that a positive evaluation implies desirable features.

1. Effectiveness: including confidence in the scientific and technological basis, technological feasibility, and the magnitude, spatial scale and uniformity of the effect achievable.
2. Timeliness: including the state of readiness for implementation (and the extent to which any necessary experiments and/or modelling has been completed), and the speed with which the intended effect (on climate change) would occur.
3. Safety: including the predictability and verifiability of the intended effects, the absence of predictable or unintended adverse side-effects and environmental impacts (especially effects on inherently unpredictable biological systems), and low potential for things to go wrong on a large scale.
4. Cost: of both deployment and operation, for a given desired effect (ie for CDR methods, cost per GtC, and for SRM methods, cost per W/m^2) evaluated over century timescales (later also expressed as its inverse, ie affordability). In practice the information available on costs is extremely tentative and incomplete, and only order-of-magnitude estimates are possible.

On the basis of these criteria the likely costs, environmental impacts and possible unintended consequences are identified and evaluated so far as possible, so as to inform research and policy priorities. Summary evaluation tables are provided for each method in Chapters 2 and 3. The ratings assigned are explained in Section 5.3.

A further very important criterion is the technical and political reversibility of each proposal; ie the ability to cease a method and have its effects (including any undesired negative impacts) terminate within a short time, should it be necessary to do so. All the methods considered here are likely to be technically reversible within a decade or two, and so this criterion does not help to discriminate between them. There may however also be non-technical reasons (such as vested interests in income streams) which may reduce reversibility in practice (see Section 4.2), and which should also be considered.

There are also non-technological criteria by which such proposals should be evaluated. These include issues such as public attitudes, social acceptability, political feasibility and legality, which may change over time. A preliminary exploration of these issues, and their importance for determining the acceptability of geoengineering research and deployment activities, is provided in Chapters 4 and 5.

In Chapter 5, the relative advantages and disadvantages of the most feasible technologies are identified. No attempt is made to identify a single overall preferred geoengineering method. However, a semi-quantitative rating system is applied based on the criteria defined to enable easy identification of methods that deserve further attention. The conclusions and recommendations arising from this analysis are presented in Chapter 6.

2 Carbon dioxide removal techniques

2.1 Introduction

Increasing atmospheric concentrations of greenhouse gases (chiefly CO_2, with small contributions from N_2O, CH_4, ground level O_3 and CFCs), are the main human causes of warming of the physical climate system. By removing greenhouse gases from the atmosphere it would, in principle, be possible to reduce the speed at which the planet is warming, and in theory, to remove greenhouses gases to the point where global warming would stop and the climate would start to cool. In addition, by reducing the increase in CO_2 concentrations these methods mitigate other direct and deleterious consequences, such as ocean acidification.

A number of methods aimed at the direct removal of CO_2 from the atmosphere have been proposed, including large scale engineering approaches which use either chemical or physical processes to remove the greenhouse gas, and biologically based methods which aim to simulate or enhance natural carbon storage processes (see Figure 1.2). Reducing the emissions of other greenhouse gases such as CH_4, N_2O or ground level O_3 is also of great importance for addressing climate change (eg, Richardson *et al.* 2009). Geoengineering methods for removing these gases from the atmosphere for this purpose are in principle possible but have not yet been developed, and so are not considered in this report.

In this chapter, methods for the removal of CO_2 by both traditional and novel means are discussed. Traditional methods of enhancing carbon sequestration through land-use practices such as afforestation and avoided deforestation are considered only briefly as they have already been subjected to detailed review (see IPCC 2000b, 2007c; Royal Society 2001; UNEP 2009). Similarly, conventional carbon capture and storage (CCS) is not considered in detail as this issue was recently extensively discussed by the IPCC (2005). Most of this chapter is concerned with novel technologies that may potentially offer greater benefits in terms of greenhouse gas reductions.

Table 2.1 categorises the carbon dioxide removal (CDR) methods considered in this report according to whether they are land or ocean based, and whether they are predominantly biological, chemical or physical interventions.

When considering the potential effectiveness of methods that aim to directly remove CO_2 from the atmosphere or the oceans, it is necessary to consider the spatial and temporal scales at which the proposals can potentially operate.

The spatial scale over which direct removal methods using chemical or physical engineering technologies operate will be an important consideration. If these methods are to manage a significant fraction of global emissions, they will require the creation of an industry that moves material on a scale as large as (if not larger than) that of current fossil fuel extraction, with the risk of substantial local environmental degradation and significant energy requirements. Enhanced weathering might require mining on a scale larger than the largest current mineral extraction industry, and biologically based methods might require land at a scale similar to that used by current agriculture worldwide.

The time scale of CO_2 removal is also an important consideration. Some methods remove CO_2 from the atmosphere for decades to centuries (eg, most biomass and ocean fertilisation options). Methods that involve enhanced carbonate weathering remove CO_2 from the atmosphere for thousands of years. Methods that involve geological storage or weathering of silicate minerals remove CO_2 from the atmosphere effectively permanently. All of these options could therefore potentially play important roles in diminishing rates of warming this century; however, only the longer-lived options assure reduced commitment to long-term global warming that could persist over many thousands of years (Archer *et al.* 2009).

The current CO_2 release rate from fossil fuel burning alone is 8.5 GtC/yr, so to have an impact CDR interventions

Table 2.1. Carbon dioxide removal methods.

	Land	Ocean
Biological	Afforestation and land use Biomass/fuels with carbon sequestration	Iron fertilisation Phosphorus/nitrogen Fertilisation Enhanced upwelling
Physical	Atmospheric CO_2 scrubbers ('air capture')	Changing overturning circulation
Chemical ('enhanced weathering' techniques)	*In-situ* carbonation of silicates Basic minerals (incl. olivine) on soil	Alkalinity enhancement (grinding, dispersing and dissolving limestone, silicates, or calcium hydroxide)

would need to involve large-scale activities (several GtC/yr) maintained over decades and more probably centuries. It is very unlikely that such approaches could be deployed on a large enough scale to alter the climate quickly, and so they would help little if there was a need for 'emergency action' to cool the planet on that time scale. The time over which such approaches are effective is also related to the residence time of the gas in the atmosphere (and the lifetime of a perturbation to atmospheric CO_2 concentration is much longer than the residence time of any individual molecule, of the order of hundreds of years (Archer *et al.* 2009)).

2.2 Land-based CDR methods

2.2.1 Land use management, afforestation, reforestation and avoidance of deforestation

Terrestrial ecosystems remove about 3 GtC/yr from the atmosphere through net growth, absorbing about 30% of CO_2 emissions from fossil fuel burning and net deforestation, while the world's forest ecosystems store more than twice the carbon in the atmosphere (Canadell *et al.* 2007; Canadell & Raupach 2008). Hence simple strategies based around the protection and management of key ecosystems could do much to enhance the natural drawdown of CO_2 from the atmosphere. Yet currently emissions from land use change, primarily deforestation, account for about 20% of all anthropogenic greenhouse emissions and the amount has been continuing to rise during the early years of the 21st century. Tropical deforestation alone now accounts for 1.5 GtC/yr (about 16% of global emissions) and is the fastest rising source of emissions (Canadell *et al.* 2007).

Interventions to moderate atmospheric CO_2 through ecosystem management have potential for carbon sequestration and can take a range of forms including avoided deforestation, afforestation, reforestation, and planting of crops or other vegetation types (Royal Society 2001, 2008b; Submission: Reay). Such interventions are not normally considered to be geoengineering, and have limited long-term potential (Royal Society 2001). They are however immediately available, often have significant co-benefits, may be particularly useful in the immediate future, and are considered briefly here, since they are familiar and provide a useful yardstick for comparison of other methods.

Terrestrial ecosystems store about 2,100 GtC in living organisms, leaf litter and soil organic matter, which is almost three times that currently present in the atmosphere. Among the world's seven major biomes, tropical and subtropical forests store the largest amount of carbon, almost 550 GtC, and tropical deforestation is therefore contributing substantially to global carbon emissions. Temperate forests, especially those with the oldest age classes intact, also have high carbon storage potential (over 500 tC/ha) and can also show very high positive annual rates of carbon sequestration (Naidoo *et al.* 2008). The boreal forest biome holds the second largest stock of carbon, most of it stored in the soil and litter. Draining of boreal forest peatlands, certain forestry practices and inappropriate fire management may all cause significant losses of the carbon stored in this ecosystem (UNEP 2009). About one quarter of the world's terrestrial land surface is now classified as agricultural land of some sort and agricultural systems, at least in temperate areas, tend to occupy fertile soils that would have formerly supported temperate grassland or forest. Land clearance for croplands and pasture has therefore greatly reduced above-ground carbon stocks and soil carbon stocks are also often depleted as tillage disrupts the soil, opening it to decomposer organisms and generating aerobic conditions that stimulate respiration and release of CO_2. Land-use changes over the past 100 years have therefore played a significant role in altering soil carbon stores and fluxes.

Simply reversing this trend is clearly not an option as there are continuing demands for land, especially for agriculture. However, the potential for land-use management should not be underestimated and may play a small but significant role in reducing the growth of atmospheric CO_2 concentrations. Reducing emissions from deforestation and forest degradation is a vital component but afforestation or replanting can play a significant role too, especially in the case of degraded agricultural land. The establishment of new forested areas may however conflict with other environmental and social priorities, especially food production and biodiversity conservation. Afforestation and reforestation should therefore be approached in an integrated manner considering competing demands for land.

There are two scales of management that might use improved ecosystem and land-use management to reduce atmospheric greenhouse gas concentrations. At local to regional scales, increased adoption of land use management that incorporates multiple ecosystem services, including carbon storage, could deliver significant benefits. In one spatially explicit watershed scale study in Oregon, USA, carbon storage could be doubled through changed land use policies that were beneficial over a wide range of economic and ecosystem services (Nelson *et al.* 2009). Realistic policy changes in this area could potentially increase carbon sequestration by 5 million tons in an area of around 30,000 km^2. At the global level, mechanisms aimed at both reforestation and reduced deforestation, underpinned by effective financial mechanisms and policies, could achieve 0.4 to 0.8 GtC/yr by 2030 assuming carbon prices of \$20 to \$100) per ton of CO_2 (IPCC 2007c; Canadell & Raupach 2008) offsetting 2 to 4% of projected emissions increases over that period.

These mechanisms can be encouraged by well-founded carbon markets, by effective land-use planning and, in the case of avoided deforestation, by the new proposals for 'reducing emissions from deforestation and degradation' (REDD) under the UNFCCC. Effective implementation will depend on reliable baseline estimates, monitoring and enforcement. Critically, to achieve worthwhile benefits and to establish effective incentives, land-use-planning based solutions will necessitate larger scale planning and

Table 2.2. Land-use and afforestation summary evaluation table. The ratings given (refer Table 5.1) are according to the criteria explained in Chapter 1.

Land use and afforestation		
Effectiveness	Limited potential for carbon removal	Low
Affordability	Cheap to deploy	Very high
Timeliness	Ready for immediate deployment and starts CO_2 reductions immediately Slow to reduce global temperatures (CDR method)	Medium
Safety	Few undesirable side effects except for potential land use conflicts and biodiversity implications	High

management regimes, often exceeding national jurisdictions in order to gain the benefits of scale.

As summarised in Table 2.2 these methods are feasible and are low risk, but are long-term and can achieve only small to medium effects on atmospheric CO_2 concentrations (see also Table 5.1). Several regional scale studies have demonstrated that overall benefits to the economy and to other ecosystem services such as water regulation, amenities, biodiversity conservation and agriculture can result from integrated land-use planning that would deliver enhanced CO_2 draw-down and storage. However, carbon stored in vegetation is not securely sequestered in the long-term, as it can easily be released by fire, drought or deliberate deforestation (Royal Society 2001).

2.2.2 Biochar and biomass-related methods

As terrestrial vegetation grows it removes large quantities of carbon from the atmosphere during photosynthesis. When the organisms die and decompose, most of the carbon they stored is returned to the atmosphere. There are four ways in which the growth of biomass may be harnessed to slow the increase in atmospheric CO_2 (Keith 2001).

1. *Land Carbon Sinks.* Carbon may be sequestered *in-situ* in soil or as standing biomass, as discussed above in Section 2.2.1.
2. *Bioenergy & Biofuels.* Biomass may be harvested and used as fuel so that CO_2 emissions from the fuel's use are (roughly) balanced by CO_2 captured in growing the energy crops. The use of bioenergy and biofuels (Royal Society 2008a) is considered to be a means of reducing emissions, rather than geoengineering and is not considered further here.
3. *Bioenergy with CO_2 capture and sequestration (BECS).* Biomass may be harvested and used as fuel, with capture and sequestration of the resulting CO_2; for example, one may use biomass to make hydrogen or electricity and sequester the resulting CO_2 in geological formations.
4. *Biomass for sequestration.* Biomass may be harvested and sequestered as organic material, for example, by burying trees or crop wastes, or as charcoal (biochar).

Bioenergy with CO_2 sequestration (BECS) builds directly on existing technology for bioenergy/biofuels and for CCS, and inherits the advantages and disadvantages of both of these technologies. There is no doubt that it is technically feasible, and there are already some small real-world examples (Keith 2001; Obersteiner *et al.* 2001; IPCC 2005). It is again not necessarily or normally regarded as geoengineering, and has been reviewed in some detail by the IPCC (2005). However, BECS has much in common with some other methods considered here, and has therefore been included for comparison purposes, but is not reviewed in detail (see Table 2.3).

Sequestration of biomass and biochar have been proposed as a method for intervening in the natural cycle so that some or all of the carbon fixed by organic matter can be stored in soils or elsewhere for hundreds or thousands of years. For example, it has been proposed to bury wood and agricultural waste both on land and in the deep ocean to store the carbon rather than allow decomposition to return it to the atmosphere (Submission: Mark Capron; Submission: Newcastle University; Submission: Ning Zeng; Strand & Benford 2009). In contrast to bioenergy with CO_2 sequestration, there is relatively little peer-reviewed literature about biomass for sequestration, though there appears to be growing interest in the biochar process (discussed later in this section).

Methods involving burying biomass in the land or deep ocean will require additional energy consumption for transport, burying and processing. Most seriously, the processes involved may disrupt growth, nutrient cycling and viability of the ecosystems involved. In the deep ocean, for example, organic material would be decomposed and the carbon and nutrients returned to shallow waters, since oxygen is generally present (unless sufficient material were deposited to create anoxic conditions, which would constitute a major ecosystem perturbation). Full assessments are not yet available to assess the costs and benefits involved but it seems unlikely that this will be a viable technique at any scale that could usefully reduce atmospheric carbon.

Biochar (charcoal) is created when organic matter decomposes, usually through heating, in a low- or zero

Table 2.3. BECS-bioenergy with carbon sequestration summary evaluation table.

BECS—bio-energy with carbon sequestration		
Effectiveness	Limited by plant productivity and conflicts over land use with agriculture and biofuels for transport More effective than biochar as sequesters more carbon	Low to Medium
Affordability	Similar to biofuels (NB costs of fertilisers and transportation) More expensive than fossil fuel CCS (as fuel is more expensive) Cheaper than biochar as more bio-energy is generated	Low to Medium
Timeliness	Slow to reduce global temperatures (CDR method) Sustainability of feedstocks must be established before widespread use	Medium
Safety	Potential land-use conflicts (food versus growth of biomass for fuel)	High

oxygen environment (Lehmann *et al.* 2006; Submission: Peter Read; Submission: UK Biochar Research Centre). Known as pyrolysis, the decomposition process produces both biochar and biofuels (syngas and bio-oil). As the carbon atoms in charcoal are bound together much more strongly than in plant matter, biochar is resistant to decomposition by micro-organisms and locks in the carbon for much longer time periods. The range of potential raw materials ('feedstocks') for creating biochar is wide, including, for example, wood, leaves, food wastes, straw, and manure, and it is also claimed that addition of biochar to soils can improve agricultural productivity. Biochar is therefore sometimes proposed as an answer to a number of different problems, since it draws down and locks up atmospheric carbon, it can improve crop yields, and it creates biofuels, a renewable energy source. How effectively it achieves each of these goals, at what costs, and with what wider impacts, will determine the influence biochar can have as a geoengineering technology.

One of the key questions regarding biochar is whether it is better to 'bury or burn?'. It remains questionable whether pyrolysing the biomass and burying the char has a greater impact on atmospheric greenhouse gas levels than simply burning the biomass in a power plant and displacing carbon-intensive coal plants (Keith & Rhodes 2002; Metzger *et al.* 2002; Strand & Benford 2009). Submissions to this study (UK Biochar Research Centre) suggest that biochar production may in some circumstances be competitive with use of the biomass as fuel.

The residence time of carbon converted to biochar in soils, and the effect on soil productivity of adding large loadings of char is uncertain (Submission: Biofuelwatch). It is known, for example from archaeological sites that charcoal can have a residence time of hundreds or thousands of years in soils. However, the conditions of pyrolysis may affect both the yield of char and its long-term stability in the soil (Submission: UK Biochar Research Centre) and further research is required.

Proponents of biomass for sequestration argue that very large rates of sequestration are in principle achievable. For example, Lehmann *et al.* (2006), quote a potential carbon sink of 5.5 to 9.5 GtC/yr by 2100, larger than the present day fossil fuel source (and approaching 10% of global primary production by plants). Such fluxes suppose that there will be enormous growth in the resources devoted to the production of biofuels, and that some large fraction of this carbon would be converted to biochar. The use of crops for renewable fuels on such a scale would very likely conflict with the use of agricultural land for the production of food and/or biofuels.

As summarised in Table 2.4 biomass for sequestration could be a significant small-scale contributor to a geoengineering approach to enhancing the global terrestrial carbon sink, and it could, under the right circumstances, also be a benign agricultural practice. However, unless the sustainable sequestration rate exceeds around 1 GtC/yr, it is unlikely that it could make a large contribution. As is the case with biofuels, there is also the significant risk that inappropriately applied incentives to encourage biochar might increase the cost and reduce the availability of food crops, if growing biomass feedstocks becomes more profitable than growing food.

Biochar and other forms of sequestered biomass have not yet been adequately researched and characterised, and so should not be eligible for carbon credits under the UNFCCC flexible mechanisms until there is a reliable system in place for verifying how much carbon is stored, and the wider social and environmental effects have been determined. Substantial research will be required to achieve these conditions for methods other than BECS.

2.2.3 Enhanced weathering (land and ocean-based methods)

Carbon dioxide is naturally removed from the atmosphere over many thousands of years by processes involving the weathering (dissolution) of carbonate and silicate rocks. Silicate minerals form the most common rocks on Earth, and they react with CO_2 to form carbonates (thereby

Table 2.4. Biochar summary evaluation table.

Biochar		
Effectiveness	Limited by plant productivity and conflicts over land use with agriculture and biofuels Burning biochar (in place of fossil fuels) may be preferable to burying it	Low
Affordability	Similar to biofuels (NB costs of fertilisers and transportation)	Low
Timeliness	Slow to reduce global temperatures (CDR method) Substantial prior research required to investigate efficacy and impacts	Low
Safety	Potential land-use conflicts (food versus growth of biomass for fuel) Long-term effects on soils not yet known	Medium

consuming CO_2). The reactions (which may involve either calcium (Ca) or magnesium (Mg) cations, or both) can be written schematically as:

$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$$

These weathering processes have a major influence on the CO_2 concentrations in both the atmosphere and the oceans, and would slowly decrease the atmospheric CO_2 concentration if given enough time. However, the rate at which these reactions take place is very slow by comparison to the rate at which fossil fuel is being burned. Carbon dioxide from the atmosphere is absorbed at less than 0.1 GtC/yr, around one hundredth of the rate at which it is currently being emitted (IPCC 2005).

Carbon dioxide could be removed from the atmosphere by accelerating the natural weathering process; reacting silicate rocks with CO_2 and forming solid carbonate and silicate minerals. This reaction consumes one CO_2 molecule for each silicate molecule weathering and stores the carbon as a solid mineral.

A variant on this process would be to weather silicate rocks, but instead of forming solid minerals, to release the dissolved materials into the oceans. This could potentially remove CO_2 from the atmosphere through the following schematic reaction:

$$CaSiO_3 + 2CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2$$

This reaction has the advantage that two CO_2 molecules are stored in the ocean for each silicate molecule weathering. It is not possible to place the dissolved material anywhere except the ocean, as no other reservoir is large enough for deployments at large scale. It must be noted that this is a discussion of basic concepts. In practice the chemistry is somewhat more complicated, with the result that slightly less CO_2 would be stored in practice than on paper.

A similar approach is to react carbonate rocks (instead of silicates) with CO_2, with the resulting materials also placed in the ocean.

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

This reaction has the advantage that carbonate minerals are more easily dissolved than silicate minerals, but carbonate minerals contain oxidized carbon, so only about one additional CO_2 molecule is stored in the ocean for each silicate molecule weathering.

Alternatively, CO_2 can be stored in the ocean through the production and addition of strong bases (alkalis) such as lime. For example:

$$Ca(OH)_2 + 2CO_2 \rightarrow Ca^{2+} + 2HCO_3^-$$

However, strong bases are relatively rare on Earth and manufacturing them from salts can be energy intensive, and the reaction produces acidity (eg, $CaCl_2 + 2H_2O \rightarrow Ca(OH)_2 + 2HCl$). This raises disposal issues, because if the acid is placed back in the ocean, it will tend to drive additional CO_2 back into the atmosphere.

Proposed methods of enhanced weathering

A number of geoengineering proposals aimed at artificially increasing by large factors the rates of these reactions have been suggested. There is no question about the basic chemical ability of the enhanced weathering of carbonate or silicate minerals to decrease CO_2 emissions and atmospheric concentrations. Primary barriers to deployment are related to scale, cost, and possible environmental consequences.

All chemical approaches require a molecule-for-molecule response to the amount of CO_2 emitted. Representative molecules of silicate and carbonate rocks typically weigh more than twice as much as molecules of CO_2, so it would take roughly two tonnes of rock to remove and store each tonne of CO_2. The industrial scale of the CO_2 mitigation effort would thus be the same order-of-magnitude as the scale of the energy system that produces that CO_2. These methods are likely to be relatively expensive, although some proposed methods may be able to compete on a cost basis with other carbon capture and storage methods.

One proposal is to add abundant silicate minerals such as olivine to soil used for agriculture (Schuiling & Krijgsman 2006; Submission: Schuiling). Large quantities of rocks would have to be mined and ground up, transported, and then spread over fields. It is estimated that a volume of about 7 km^3 per year (approximately twice the current rate of coal mining) of such ground silicate minerals, reacting each year with CO_2, would remove as much CO_2 as we are currently emitting. It is conjectured that the CO_2 could be immobilised partly as carbonate minerals and partly as bicarbonate ion in solution, but the consequences for soil processes are currently not known.

Alternatively, it has been suggested that carbonate rock could be processed and ground, and reacted with CO_2 in chemical engineering plants (most likely with concentrated CO_2 captured from power plants, for example). The resulting bicarbonate solutions would be released into the sea (Rau & Caldeira 1999; Rau 2008). An alternative approach would be to release the carbonate minerals to the sea directly (Harvey 2008). They would however not dissolve until they reached under-saturated deep water, so making the process very slow to have any effect. In a variant ('liming the ocean'), which would operate faster, limestone carbonate rocks would be heated to drive off pure CO_2, (which must be captured and sequestered) to form lime $Ca(OH)_2$. This would be added to the oceans to increase their alkalinity, resulting in additional uptake of CO_2 from the atmosphere (Kheshgi 1995; see also Submission: CQuestrate). While this process is energy and therefore cost intensive it would sequester roughly twice the amount of CO_2 per unit of carbonate mined.

Alternatively, the rate of the reaction of CO_2 with basic minerals such as basalts and olivine could be enhanced *in-situ* in the Earth's crust (Kelemen & Matter 2008; Submission: Sigurðardóttir & Gislason). This idea would also require elevated CO_2 concentrations in the reactant gas, and might be better thought of as a CO_2 sequestration technique rather than remedial geoengineering, as the end result of the method would be the creation of carbonates *in-situ*. Kelemen and Matter suggest there is the potential to sequester more than 1 GtC/yr of carbon in Oman alone by this method. Again, much further research is required to know if it is in fact feasible at these scales.

It has also been proposed (House *et al.* 2007) to accelerate silicate weathering using electrolysis to divide sea salt into strong bases and strong acids. When strong bases are dissolved in seawater they cause CO_2 to be stored in the ocean as HCO_3^- as noted above. House *et al.* (2007) propose to use the strong acid to weather silicate rocks. The weathering of silicate rocks can neutralise the acid and form a relatively benign salt that could also be added to the ocean. This approach is energy intensive and requires a large amount of mass handling, and thus is likely to be more expensive than conventional CCS approaches.

Environmental impact of enhanced weathering methods

Enhanced weathering methods clearly have the capacity to reduce climate risk, by reducing CO_2 emissions or removing CO_2 from the atmosphere. However, before they are deployed their side effects, lifecycle costs and environmental effects must be better understood and taken into consideration. For example, the final result of nearly all of these methods would be to increase the bicarbonate (anion) and calcium or magnesium (cation) concentration (and hence the alkalinity) of sea water. Even if the weathering reaction initially took place distributed in soils (as with olivine above, for example), the resultant chemicals would eventually be washed to the oceans. Sea water contains substantial concentrations of these ions already, and it would be possible to take up all the excess CO_2 in the atmosphere without greatly increasing those concentrations. Such an increase in bicarbonate concentrations and alkalinity would reduce rather than increase the acidity of sea water, helping to slow the progress of ocean acidification (see Section 2.4), and might therefore be beneficial to those organisms and ecosystems otherwise threatened by rising atmospheric CO_2. It is not yet known, however, whether all the combined effects on ocean chemistry or biology would be negligible or benign.

Furthermore, to be quantitatively important, most of these proposals require large mining and transportation activities. These activities would likely damage the environment locally (and 'local' here would mean over large areas, comparable to or greater than those of present-day cement production and coal mining). Some options require large amounts of water. Others require additional energy (for electrolysis or lime production), which would need to come from carbon-free sources. In the case of solid mineral production, there are also issues of disposal (or use) of large amounts of solid material.

In summary, all enhanced weathering methods utilise naturally occurring minerals and reactions, and produce stable natural products, which are already present in large quantities in soils and the oceans, and they may therefore be regarded as benign in principle. They operate by making soils or the ocean somewhat more alkaline, which on a global scale reduces CO_2 induced acidification of the terrestrial and marine environments. However, the products are generated in large quantities in a more-or-less localised way, and may therefore have substantial impacts that would need to be managed. There are substantial questions concerning desirable particle sizes and the rates of dispersion, dilution and dissolution required. The pH of soils and ocean surface waters would be increased locally, with possible effects (not necessarily adverse) on vegetation and marine biota, and potential for increased precipitation of carbonate minerals that would reduce their effectiveness. Moreover, because these chemical approaches require that each CO_2 molecule react with dissolved minerals, mass requirements for mineral inputs and outputs will greatly exceed the mass of CO_2 sequestered. These approaches require major mining and processing operations and are likely to be more expensive to operate than conventional CCS (IPCC 2005), for example, unless they are able to utilise cheap ('stranded') sources of energy, or are undertaken where labour and other costs are low (see Tables 2.5 and 2.6).

Table 2.5. Summary evaluation table for terrestrial enhanced weathering methods.

Enhanced weathering—terrestrial		
Effectiveness	Very large potential for carbon storage in soils CDR method so addresses cause of climate change and ocean acidification	High
Affordability	Requires mining, processing and transportation of large quantities of minerals Some methods may require large energy inputs	Low
Timeliness	Slow to reduce global temperatures (CDR method) Would require substantial infrastructure construction Research required to investigate environmental impacts, efficacy and verifiability	Low
Safety	May have few serious side effects, but effects on soil pH, vegetation etc need to be established (at levels of application which are effective)	Medium or High

Table 2.6. Summary evaluation table for ocean based enhanced weathering methods.

Enhanced weathering—ocean		
Effectiveness	Very large potential for carbon storage in oceans CDR method so addresses cause of climate change Ocean methods act directly to reduce or reverse ocean acidification	High
Affordability	Requires mining, processing and transportation of large quantities of minerals Faster methods require large energy inputs (eg. for electrolysis, calcination)	Low
Timeliness	Slow to reduce global temperatures (CDR method) Would require substantial infrastructure construction Research required to investigate environmental impacts, efficacy & verifiability	Low
Safety	Reverses undesirable effects of ocean acidification, but may nevertheless have adverse side-effects on some marine biota	Medium or High

2.2.4 Carbon dioxide capture from ambient air

Air capture is an industrial process that captures CO_2 from ambient air producing a pure CO_2 stream for use or disposal. There is no doubt that air capture technologies could be developed (Keith *et al.* in press (a)). The technical feasibility of this is demonstrated, for example, by commercial systems that remove CO_2 from air for use in subsequent industrial processes. Several methods for air capture have been demonstrated at laboratory scale, although as yet no large-scale prototypes have been tested, and it remains to be seen whether any of these processes can be made sufficiently cost effective (Keith *et al.* in press (a)).

Capturing CO_2 from the air where its concentration is 0.04% might well seem unpromising given that there is still no power plant in which CO_2 is captured from the full exhaust stream. Two factors make air capture more difficult than capturing CO_2 from exhaust streams; firstly, the thermodynamic barrier due to the lower concentration of CO_2 in air; and secondly, the energy and materials cost of moving air through an absorbing structure. However, neither of these is necessarily a dominant factor in determining costs (Keith *et al.* in press (a)) and as the method can be implemented anywhere it may be possible to make use of stranded energy resources.

At present, there are three main technological routes being pursued to develop large-scale commercial capture of CO_2 from air.

- Adsorption on solids. One proposal (Lackner 2009) involves a humidity swing absorption cycle using surfaces derived from commercial ion-exchange resins. An alternative system uses solid amines on a mesoporous silica substrate, similar to those that are being developed for CO_2 capture from power plants (Gray *et al.* 2008).
- Absorption into highly alkaline solutions. The rate of CO_2 uptake into aqueous solutions is inherently slow, but if concentrated solutions (high pH, with molarity >1 M OH^-) are used, then sufficiently fast reaction kinetics can be obtained. One proposal involves use of sodium hydroxide solutions with regeneration of the sodium carbonate achieved using the titanate or calcium caustic recovery processes (Stolaroff *et al.* 2008; Mahmoudkhani & Keith 2009).

Table 2.7. Summary evaluation table for CO_2 capture from ambient air.

Carbon dioxide capture from ambient air		
Effectiveness	Feasible, with no inherent limit on size of effect achievable CDR method so addresses cause of climate change and ocean acidification Very large potential but requires additional carbon storage (CCS)	High
Affordability	Potential high costs (energy & materials) *cf.* CCS at source	Low
Timeliness	Slow to reduce global temperatures (CDR method) Much R&D still required to find cost effective methods Would require substantial infrastructure construction	Low
Safety	Minimal undesirable side effects (except those for process materials and CCS)	Very high

- Absorption into moderately alkaline solutions with a catalyst. The naturally occurring enzyme carbonic anhydrase can accelerate the $CO_2 + H_2O$ reaction by a factor of ~109, and facilitates respiration in living cells by catalysing the reverse reaction. Using an enzyme as a catalyst is challenging because they only operate in a narrow pH and temperature range, and as organic compounds they may be decomposed by micro-organisms (Bao & Trachtenberg 2006). Development of synthetic catalysts that would be somewhat less effective, but which could be tailored for the air capture application is however being undertaken (Aines & Friedman 2008).

Air capture may compete with bio-energy with CCS (BECS). Unlike BECS which provides energy, all air capture technologies will require energy inputs which could come from a range of sources ranging from solar (Nikulshina *et al.* 2009) to nuclear, and these energy costs will generally be larger than that required for post-combustion capture. On the other hand air capture systems have a land-use footprint that is hundreds or thousands of times smaller than BECS per unit of carbon removed.

As with conventional CCS from power stations, the removed CO_2 would be transported for storage at suitably secure locations, such as oil or gas fields, although air capture plants may more readily be located adjacent to the disposal sites.

An alternative disposal or re-use strategy is to convert the CO_2 into a transport fuel by combining it with hydrogen (Zeman & Keith 2008). In that event, the plants might be located in a desert location where solar power is used to produce hydrogen through the electrolysis of water.

Potential economic significance of air capture

Air capture will be more expensive than conventional post-combustion capture at a power plant if both are built at the same time and in the same location; but air capture may still be competitive because there is surprising value in the economic freedom to build a capture plant where it is cheapest to do so and near the best sequestration sites. Moreover, air capture enables the application of industrial economies of scale to deal with small and hard-to-control sources of CO_2 emissions (especially transport-related sources) for which CCS cannot be used. In such contexts it may prove to have a sufficiently low cost to play an important role in managing emissions, especially if 'stranded' energy sources can be utilised.

As summarised in Table 2.7 air capture methods could be useful and important even if the costs are substantially higher than other means of cutting emissions in formulating a long-term climate policy (Keith *et al.* 2005; Parson 2006). Proposals for new methods are still appearing (confidential submissions received) and it is very likely that substantial cost reductions are possible in future.

2.3 Ocean ecosystem methods

2.3.1 Ocean fertilisation methods

Carbon dioxide released either naturally or by the activities of humanity, undergoes a regular cycle between the atmosphere, land, ocean, and biological organisms. Of the carbon that readily exchanges between oceans and atmosphere and land vegetation, the great majority is in the deep ocean (about 35,000 GtC compared with about 750 GtC in the atmosphere, see Figure 1.2).

Carbon dioxide in the surface ocean rapidly exchanges with the atmosphere, while the transfer of CO_2 into the deep sea is much slower. Most of the CO_2 being released today will eventually be transferred into the deep sea given an elapsed time of order 1,000 years. Some climate engineering options aim to increase this rate of transfer by manipulating the ocean carbon cycle (Submission: Climos).

Carbon dioxide is fixed from surface waters by photosynthesisers—mostly, microscopic plants (algae). Some of the carbon they take up sinks below the surface waters in the form of organic matter composed of the remains of planktonic algal blooms, faecal material and other detritus from the food web. As this material settles into the deep ocean by gravity, it is used as food by bacteria and other organisms. They progressively consume it, and as they respire they reverse the reaction that fixed the carbon, converting it back into CO_2, that is re-released into the water. The combined effect of photosynthesis in the surface followed by respiration deeper in the water column is to remove CO_2 from the surface and re-release it at depth. This 'biological pump' exerts an important control on the CO_2 concentration of surface water, which in turn strongly influences the concentration in the atmosphere. If this mechanism were suddenly to stop operating for example, atmospheric CO_2 would increase by more than 100 ppm in a few decades (eg, Sarmiento & Gruber 2006).

The ability of the biological pump to draw carbon down into deeper waters is limited by the supply of nutrients available that allow net algal growth in the surface layer. Methods have been proposed to add otherwise limiting nutrients to the surface waters, and so promote algal growth, and enhance the biological pump. This would remove CO_2 faster from the surface layer of the ocean, and thereby, it is assumed (sometimes incorrectly) from the atmosphere.

Over the majority of the open oceans the 'limiting nutrient' is thought to be nitrogen. One suggestion therefore has been to add a source of fixed nitrogen (N) such as urea as an ocean fertiliser (Submission: Ocean Nourishment Corporation). Phosphate (P) is also close to limiting over much of the ocean. Finally some important regions, such as the Equatorial Pacific and Southern Ocean, have abundant N and P, but have been shown to be limited by the lack of iron (Fe) (these are the 'High Nutrient Low Chlorophyll', or HNLC regions). Addition of these nutrients have been suggested as a possible means of enhancing the biological pump in deep waters (Martin 1990, see Lampitt *et al.* 2008 and Smetacek & Naqvi 2008 for recent reviews).

The quantity of nutrients needed to have an effect on the carbon cycle depends on the relative amounts of elements which algae use in building their organic tissue—the characteristic Redfield ratios of the nutrient elements to carbon, in algal tissues. These ratios for C:N:P:Fe are typically quoted as 106:16:1:0.001 (eg, Sarmiento & Gruber 2006). Fertilisation with N, if fully effective, might therefore lock up in the order of 6 carbon atoms for each atom of N added. One atom of P might sequester about 100 atoms of carbon whereas one atom of Fe could theoretically stimulate production of 100,000 organic carbon atoms. Hence most attention has been paid to Fe fertilisation, since the quantity of material required (as soluble iron minerals, not 'iron filings') is relatively very small.

However, it is incorrect to assume, as some proponents have in the past that local stimulation of algal carbon production by Fe or other nutrients equates to the removal of the same amount of carbon from the atmosphere. Estimation of the effectiveness (of Fe fertilisation in particular, but other nutrients too) is complex, as account must be taken not just of any carbon that is fixed, but also of its fate (Submission: Robert Anderson). Most of it is in fact rapidly returned to its inorganic mineral form (remineralised) as a result of respiration in surface water and elsewhere, and only a small fraction is finally transported and sequestered deep in the water column or in the sediments (see for example Lampitt *et al.* 2008). Moreover, there may also be a decrease in production 'downstream' of the fertilised region. This effect, called 'nutrient robbing', can occur because essential nutrients besides the one being added (for instance N and P when Fe is being added) are removed by the intervention, and are unavailable downstream. As a consequence, it is insufficient to measure export of carbon from a fertilised area as a means of determining the net increase in sequestration (Gnanadesikan & Marinov 2008; Watson *et al.* 2008). Proper assessment of the effectiveness of fertilisation instead requires a consideration of the entire ocean carbon system, and the use of ocean carbon models. However, frequently the results for sequestration efficiency are uncertain and model-dependent, since they are sensitive to the biogeochemical cycling of the nutrients in question and to the circulation of the ocean in the region of the fertilisation, details which may not be well characterised. An important limitation of all proposed mechanisms therefore, is that their efficiency (at removing atmospheric CO_2) is not easily verifiable, either by direct measurements or by modelling—it is hard to tell whether they are working or not.

Generic limitations on fertilisation strategies

The biological pump is responsible for sinking ~10 GtC/yr out of the surface layer, of which only a fraction sinks deep enough to be sequestered for centuries, as required (see Figure 1.2). If a geoengineering strategy were able to generate a sustained increase in this figure by 10% (which would require a massive, global-scale fertilisation programme) we could expect that at maximum, some fraction of 1 GtC/yr extra could be extracted from the atmosphere. Given that carbon is currently being released due to human activities at the rate of 8.5 GtC/yr, it is apparent that ocean fertilisation can play at best only a modest role in carbon sequestration (see Table 2.8). Its effect is on a similar scale to what might be gained by re-forestation of the land surface (Section 2.2.1), as might be expected given that the productivity of global terrestrial biota is similar to that of the oceans (Figure 1.2).

Undesirable side effects

All ocean fertilisation proposals involve intentionally changing the marine ecosystem, but because of its complexity the possible consequences are uncertain. In particular, the complex trophic structures typical of ocean food webs make the ecological impacts and their consequences for nutrient cycling and flow hard to predict. A few of these have been suggested as potentially advantageous (eg, the increased productivity might support a larger population of fish and/or invertebrates). However there is no reason to believe that the increased populations would be of species considered desirable by humans: experience with eutrophication in estuarine and freshwater systems suggests otherwise. In particular, there is the potential that the anoxic (oxygen-starved) regions of

Table 2.8. Summary evaluation table for ocean fertilisation methods.

	Ocean fertilisation	
Effectiveness	Likely to be feasible but not very effective CDR method so addresses cause of climate change (and would reduce ocean acidification in surface waters but not deep ocean) May reduce biological carbon uptake elsewhere in the oceans Likely low long-term carbon storage potential	Low
Affordability	Not expected to be very cost-effective (especially for methods other than iron fertilisation)	Medium
Timeliness	Slow to reduce global temperatures (CDR method) Substantial prior research required to investigate environmental impacts, efficacy and verifiability	Low/ Very low
Safety	High potential for unintended and undesirable ecological side effects Would increase oxygen used for respiration and so may increase anoxic regions of ocean ('dead zones') Slightly increased acidification of deep ocean	Very low

the ocean may increase in area because respiration of the increased biological material uses additional dissolved oxygen. This process is already occurring in some places because of nitrogen inputs from land-based sources (Diaz & Rosenberg 2008). In parallel with this is the possibility that the removal of CO_2 from the atmosphere may be offset by the production of some biogenic greenhouse gases such as CH_4 and N_2O (Submission: Greenpeace). Thus, avoidance of negative environmental consequences could limit the scale at which ocean fertilisation could be deployed.

Iron fertilisation

Iron fertilisation is by far the best studied artificial ocean fertilisation technique. This is because until comparatively recently the degree to which Fe is a limiting nutrient in the oceans was controversial, and the best way of testing the 'iron hypothesis' was by conducting small-scale (~10 km^2) releases of Fe (Martin *et al.* 1994). As a consequence more than a dozen such limited release experiments have been performed in the last 15 years (Boyd *et al.* 2007) under circumstances that might mimic a geoengineering application on a very small scale. These experiments have demonstrated only limited transient effects as increased iron led to the predicted phytoplankton bloom, but the effect is moderated either by other limiting elements, respiration or by grazing by zooplankton (Submission: ACE Research Cooperative; UK Met Office).

Iron stimulates biological production chiefly in the HNLC regions of the world ocean—the Southern Ocean, equatorial Pacific and Northern Pacific. Because the nutrient-robbing effect is especially important for Fe and limits the efficiency with which carbon is removed from the atmosphere from warm water regions in particular, most studies suggest the Southern Ocean as the most efficient region to fertilise. The effects and efficacy of Fe fertilisation remain subjects for research because comparatively little is known about the biogeochemistry of iron in the oceans.

Nitrogen and phosphorus fertilisation

In the subtropical gyres, which form 70% of the ocean area, biological production is limited by lack of N, with P also at close-to-limiting concentrations. It is debatable whether addition of N alone would lead to long-term fixation of more carbon. Nitrogen fixation occurs naturally at substantial rates in these regions, and it is thought likely that the rate of this natural process is set by the N deficit experienced by plankton (Tyrrell 1999; Lenton & Watson 2000). This appears to be an effective negative feedback, which acts to keep oceanic P and nitrate closely in balance. If this is the case, addition of extra N by itself would cause natural fixation of N to decrease, and there would be little net increase in carbon uptake.

Current understanding suggests that P addition would be more effective at the long-term fertilisation of the oceans than N, and that P addition to the oceans would promote N fixation in the subtropical gyres. Global enhancement of the P flux to the oceans from rivers by human activity is already substantial and may be contributing to the net fixation of several tenths of a GtC/yr (Lenton & Vaughan 2009). Phosphate fertilisation may be compared to Fe fertilisation: in favour of P, its basic geochemistry is better understood and it has a long residence time (10,000 years or more). It is possible to calculate its long-term sequestration potential, and nutrient-robbing effects are likely to be less important. However, much larger quantities of P need to be mobilised than is the case for Fe. Also, because P is a valuable commodity needed for fertilisation of crops, large-scale use of it for deliberate ocean fertilisation would be relatively costly and would likely conflict with agricultural needs and food security. The issues of possible undesirable side effects are similar for Fe and P.

It might be argued that one easy way to implement P fertilisation of the oceans is to allow and even encourage agricultural fertiliser runoff, which eventually reaches rivers and the oceans. Such runoff is however one of the principal causes of the substantial damage to freshwater, estuary and coastal ecosystems by eutrophication that has already occurred over recent decades. Increasing still further this pathway for addition of P to the oceans is not an option that society is likely to find acceptable.

2.3.2 Oceanic upwelling or downwelling modification methods

A second group of ocean-based methods is based on the principle that the rate at which atmospheric carbon is transferred to the deep sea may be enhanced by increasing the supply of nutrients by the upwelling or overturning circulation of the ocean (Submission: Duke). It has been proposed both to enhance upwelling rates locally using vertical pipes to pump water from several hundred metres depth to the surface (eg, Lovelock & Rapley 2007; Submission: Atmocean Inc.) and to promote downwelling of dense water in the subpolar oceans (Zhou & Flynn 2005). Most of the CO_2 in the deep sea is transported there by the overturning circulation (the 'solubility pump') and not by biologically-driven sedimentation (Sarmiento & Gruber 2006), so there is some expectation that increasing this circulation will lead to more rapid sequestration. However, once again the calculation of the efficiency of sequestration must take account of non-local effects: increasing ocean downwelling (or upwelling) must be compensated by increased upwelling (or downwelling) at another location, which may in general be on the other side of the world and which also will affect the carbon balance.

Zhou and Flynn estimate that increasing downwelling water by 1 million m^3/s, which would be a very substantial engineering challenge, would increase ocean uptake of carbon by only ~0.01 GtC/yr. The amount of carbon sequestered by the ocean pipes proposal will depend critically on location and may well be negative, for example leading to release, rather than uptake, of carbon from the ocean (Yool *et al.* 2009). Making optimistic assumptions, it is estimated that enhancing upwelling by 1 million m^3/s would lead to sequestration of only ~0.02 GtC/yr (Lenton & Vaughan 2009).

2.4 Discussion

On the basis of the available literature, indications are provided in Table 2.9 of maximum effects of the respective technologies on CO_2 concentrations in the next century. Figures are informed by the literature cited, and by Lenton & Vaughan's (2009) strong mitigation scenario table II, in which atmospheric CO_2 concentrations rise to 450 ppm in 2050 and stabilise at 500 ppm in 2100. Deliberately wide ranges are given, intended only to show the approximate potential of these technologies if deployed to the maximum, regardless of cost or possible side effects.

Costs are assessed as 'low' if generally less than \$20 per tonne of carbon sequestered, medium if between \$20 and \$80, otherwise 'high'. Risk is assessed as high for those technologies that involve manipulating the ocean or relatively undisturbed natural land ecosystems at a large scale, and medium for agricultural and biomass technologies, on the rationale that agricultural impacts are relatively well understood and would not directly affect undisturbed terrestrial ecosystems.

It is clearly technically possible to remove CO_2 from the atmosphere using many different technologies, ranging from ecosystem manipulation to 'hard' engineering. Plans to begin removal using some methodologies are in place now, and if societies put a realistic value on carbon removed (for example, more than \$30 per tonne of carbon), it would start to happen with existing technologies.

All other points being equal, methods that are (not in any order of preference): (1) cheaper, (2) have fewer possibly unintended side effects, (3) have large potential to remove CO_2, and (4) do not involve manipulation or interference with natural or near-natural ecosystems are likely to be preferred. Methods which: (5) are likely to be easily accepted by society and (6) do not raise difficult issues of governance are also likely to be favoured. Since none of the proposed methods meets all of these criteria it is necessary to balance these different properties against one another, and this is bound to raise differences of opinion.

The ocean fertilisation proposals are virtually the only ones that have had anything amounting to sustained research activity by the scientific community. This is an historical accident, because relevant experiments were undertaken to address fundamental research questions in marine science, and not because of their possible geoengineering applications. In the geoengineering context, the sole attraction of these methodologies is that iron (and possibly phosphate) fertilisation are potentially relatively inexpensive. They do however have only a relatively small capacity to sequester carbon, and verification of their carbon sequestration benefit is difficult. Furthermore, there are likely to be unintended and probably deleterious ecological consequences. With these drawbacks societal and political acceptance is likely to be low. Ocean circulation methodologies have the same issues, but also appear to have effects on atmospheric CO_2 that are too small to be worthwhile.

Methods such as BECS, biomass burial and biochar, which use biomass to sequester carbon, appear to have relatively low cost, with moderate and predictable environmental impacts and low-to-medium risk of unanticipated effects. However, unless deployed on a very large scale, the carbon sequestration potential is moderate, and there would be competition with biofuels and agriculture for use of available land. However the carbon sequestered by biomass burial and biochar has value as fuel, and it could be preferable to use this and displace fossil fuels such as coal, at least until abundant low-carbon energy becomes available. Land use management (afforestation and

Table 2.9. *Comparison of maximum effectiveness of the different CDR methods.*

Technique	Cost (Deployed to remove 1 GtC/Yr)	Impact of anticipated environmental effects (Deployed to remove 1 GtC/Yr)	Risk of unanticipated environmental effects (Deployed to remove 1 GtC/Yr)	Ultimate constraint	Max reduction in CO_2 (ppm)	Reference
Land use and afforestation	Low	Low	Low	Competition with other land uses, especially agriculture	n/a	Canadell & Raupach (2008); Naidoo *et al.* (2008)
Biomass with carbon sequestration (BECS)	Medium	Medium	Medium	Competition with other land uses, especially agriculture. Availability of sequestration sites	50 to 150	Read & Parshotam (2007); Korobeinikov *et al.* (2006)
Biomass and biochar	Medium	Medium	Medium	Supply of agricultural / forestry waste	10 to 50	Gaunt & Lehmann (2008)
Enhanced weathering on land	Medium	Medium	Low	Extraction and energy costs	n/a	Schuiling & Krijgsman (2006)
Enhanced weathering—increasing ocean alkalinity	Medium	Medium	Medium	Extraction and energy costs, ocean carbonate precipitation	n/a	Kheshgi (1995); Rau (2008)
Chemical air capture and carbon sequestration	High	Low	Low	Cost availability of sequestration sites	no obvious limit	Keith *et al.* (2005)
Ocean Fe fertilisation	Low	Medium	High	Dynamics of ocean carbon system	10 to 30	Aumont & Bopp (2006)
Ocean N and P fertilisation	Medium	Medium	High	Cost and availability of nutrients	5 to 20	Lenton & Vaughan (2009)
Ocean upwelling, downwelling	Not possible				1 to 5	Zhou & Flynn (2005)

reforestation) for carbon sequestration purposes is a low risk approach that in addition to having climate benefits could also provide economic, social and other environmental benefits. The carbon sequestration potential is however small to moderate.

Air capture is expected to be effective but costly, with relatively low environmental impacts and low risk of unanticipated consequences, except for those associated with the sequestration of the CO_2 captured (which would be similar to those for conventional CCS, which are low in the present context). The visual impact of a potentially large number of capture installations may be an issue, however this cannot be estimated in the absence of detailed designs and location could be chosen to avoid such conflicts.

Enhanced weathering is expected to be reasonably effective, with costs and environmental impacts broadly comparable to those of conventional mineral mining activities. The risk of unanticipated consequences should be low, since the processes envisaged are similar to those occurring naturally, but the minerals used would need to be distributed effectively to avoid local effects at the point of release.

All CDR methods have the potential benefit that in addition to addressing climate change, they also address the direct effects of elevated atmospheric CO_2, especially ocean acidification. As explained in Section 1.3, the increasing concentration of CO_2 in the atmosphere causes a decrease in the pH of the surface ocean when it dissolves in surface waters (Submission: UK Met Office). This will be deleterious for some marine species and may have a negative impact on marine ecosystems globally, with some important regions particularly affected (coral reef systems and the Southern Ocean for example) (Royal Society 2005; IAP 2009). It is estimated that on average the ocean is about 0.1 pH units more acidic now than it was pre-industrially, and this would increase to 0.3 pH units by 2100 under 'business as usual' emissions scenarios (Caldeira & Wickett 2003). While all of the methods discussed in this chapter will help to counteract ocean acidification in surface waters, ocean fertilisation and alkalinity increase strategies reduce surface water CO_2 concentrations more than atmospheric concentrations, and so should counteract surface ocean acidification more effectively. Ocean fertilisation does however increase dissolved inorganic carbon concentrations in the deep sea, so would conversely also tend to increase acidity there (Submission: Ocean Nourishment Corporation). The alkalinity increase strategies would increase pH at all depths and therefore reduce the effects of acidification throughout the water column.

2.5 Conclusion

The removal of CO_2 from the atmosphere to slow global warming is technically possible. However, the methods proposed differ in terms of the scale of the reductions possible, their environmental impacts and risks of unintended consequences, and costs. The most promising methods are those that remove CO_2 from the atmosphere without perturbing other natural systems and that do not have large-scale land use requirements. Land use management that incorporates carbon sequestration, afforestation and reduced deforestation are all useful techniques that should be encouraged, though their effectiveness is lower than for some other methods described here.

All of the CDR methods have the dual benefit that they address the direct cause of climate change and also reduce direct consequences of high CO_2 levels including surface ocean acidification (but note that the effect of ocean fertilisation is more complex). However, they have a slow effect on the climate system due to the long residence time of CO_2 in the atmosphere and so do not present an option for rapid reduction of global temperatures. If applied at a large enough scale and for long enough, CDR methods could enable reductions of atmospheric CO_2 concentrations (or negative emissions) and so provide a useful contribution to climate change mitigation efforts. Significant research is however required before any of these methods could be deployed at a commercial scale. In principle similar methods could also be developed for the removal of non-CO_2 gases from the atmosphere.

3 Solar radiation management techniques

3.1 Introduction

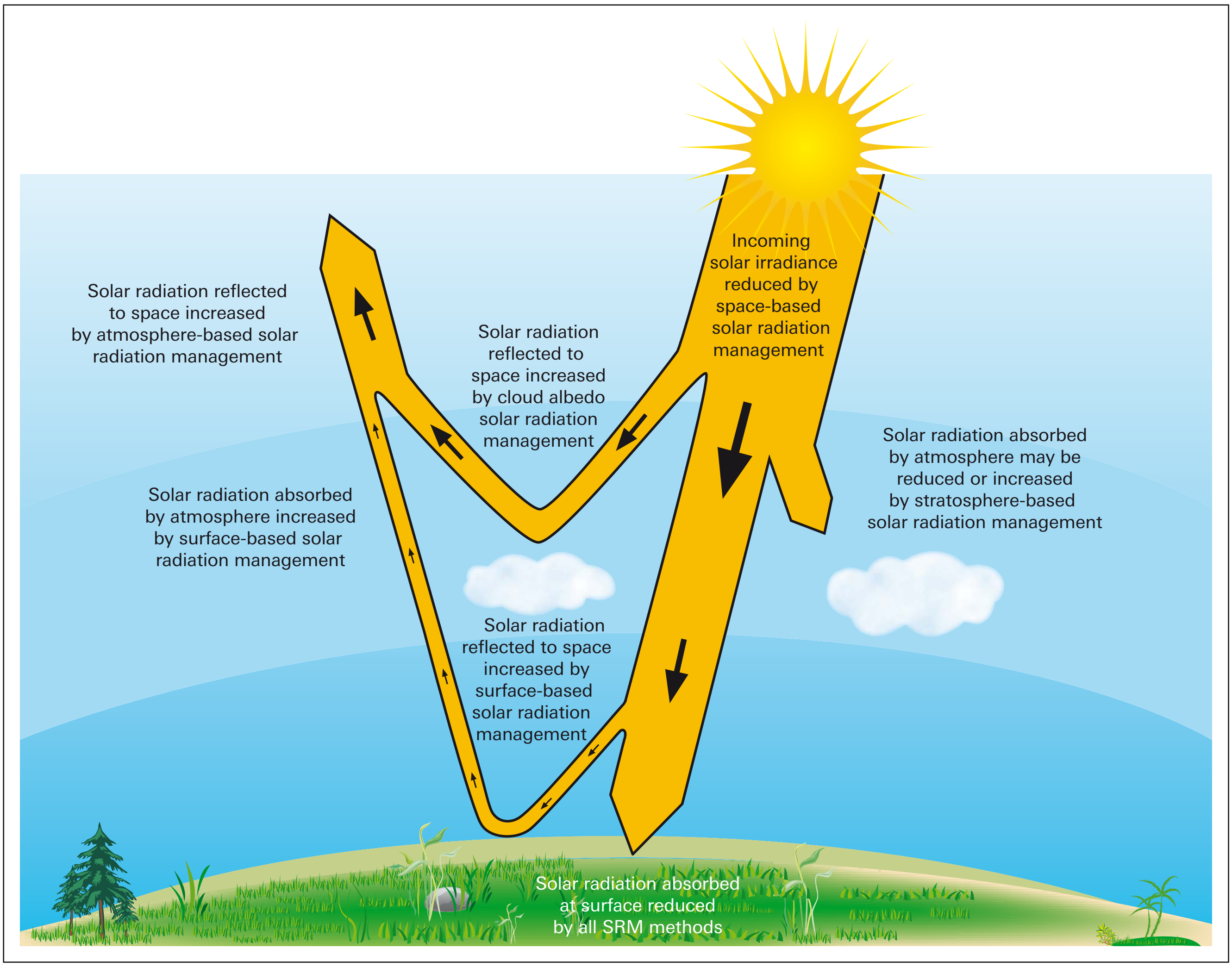
The second major class of climate geoengineering methods aims to offset greenhouse warming by reducing the incidence and absorption of incoming solar (short-wave) radiation (often referred to as insolation). Solar radiation management (SRM) methods propose to do this by making the Earth more reflective, that is by increasing the planetary albedo, or by otherwise diverting incoming solar radiation. This provides a cooling effect to counteract the warming influence of increasing greenhouse gases. Various techniques have been proposed to produce this effect; these involve brightening the Earth's surface, or introducing reflective matter into the atmosphere, or inserting light-scattering material in space between the Sun and the Earth. The concept is illustrated in Figure 3.1, which indicates how the solar radiation streams would respond.

3.2 General characteristics of SRM methods

The aim of SRM methods is to produce a reduced (possibly near zero) net radiative forcing by balancing the positive forcing of greenhouse gases with a negative forcing introduced by reducing absorbed solar radiation. To balance the global mean radiative forcing of about +4 W/m^2 that would arise from a doubling of CO_2 concentration (IPCC 2007a), the method would therefore need to provide a similar reduction in absorbed solar radiation. As can be seen from Figure 1.1, a method that resulted in an extra 1% of solar irradiance being reflected away from Earth would produce a radiative forcing of –2.35 W/m^2. To balance a positive forcing of 4 W/m^2 therefore requires a reduction of about 1.8%. However, the impact on radiative forcing of a given SRM method is dependent on altitude, that is whether the method is applied at the surface, in the atmosphere, or in space, and on the radiative properties of the atmosphere and surface, as well as on its geographical location.

Space-based SRM methods would require a diversion of about 1.8% of the incoming solar radiation. To have an equivalent radiative forcing effect, atmosphere or surface-based methods would need to increase the planetary

Figure 3.1. Schematic showing the impact of different SRM methods on solar radiation fluxes.



albedo[10] from about 0.31 to about 0.32, so that 111 W/m^2 rather than 107 W/m^2 of solar radiation are reflected by the planet (Figure 1.1). To achieve this the local reflectivity of the atmosphere, clouds or the surface may, however, need to be increased by considerably more than this amount, because some of the radiation may already have been reflected away (eg by clouds), and because only a small area may be available for modification, as discussed by Lenton & Vaughan (2009). Planetary surfaces are in any case non-uniform; the very large area of the oceans has a low albedo of about 0.1, while that of land surfaces varies considerably, typically in the range 0.2 to 0.4, with much higher values of around 0.6 to 0.8 for snow and ice-covered surfaces.

The amount of solar radiation reduction which would actually be needed to offset a doubling of atmospheric CO_2 content is not yet known precisely, as this is affected both by uncertainties in CO_2 radiative forcing and climate system feedbacks, but it is around 2%, as estimated by the simple calculation above. For example, Govindasamy & Caldeira (2000) estimated that in the NCAR CAM 3.1 model, a solar reduction of 1.7% would compensate for the global mean warming effect of a doubling of atmospheric CO_2, whereas the results of Lunt *et al.* (2008) using the Hadley Centre model indicate that 2.1% of incoming sunlight would need to be deflected away from the Earth.

It should therefore be feasible to balance the ***global*** radiative forcing from greenhouse gases as precisely as required, using SRM methods. However, it is important to note that the cancellation will not be exact at any given location, with likely residual net impacts on ***regional*** climates. Therefore if a method results in zero net global average radiative forcing it cannot be assumed to imply no climate response on regional scales. Furthermore, some methods may affect factors other than the radiation budget, such as the chemical composition of the stratosphere (especially O_3), and the local and regional balance between evaporation and precipitation. For a specified amount of global mean temperature change, changes in the solar flux affect the hydrological cycle more strongly than do equivalent changes in greenhouse gas concentration (Bala *et al*. 2008). Therefore if the goal were to compensate mean changes in precipitation, rather than mean changes in temperature, somewhat less solar reduction would be required. The potential impacts of the different methods therefore need to be investigated at a level of complexity well beyond that which is offered by the assessment of average radiative forcing alone.

The timescale on which an SRM method becomes effective depends on how quickly it can be deployed and the speed at which the climate responds. Similarly the timescale for 'switching it off' would be influenced both by how quickly it can be decommissioned and the longevity of its climate impact. The different SRM approaches have different timescales for deployment, as discussed below. The climate system would however respond quite quickly, with surface temperatures returning towards their pre-industrial conditions within a few years of deployment, depending on the amount and rate of reduction deployed (since a very rapid reduction might be undesirable). By the same token, however, should such a method, having been implemented for a significant period, subsequently fail or be abruptly stopped, then there would also be a very swift and sustained rise in temperature (an upward 'step', rather than a 'spike') and a rapid transition to the much warmer climate associated with the higher CO_2 levels then pertaining. This is referred to as the 'termination problem', although it cannot be foreseen whether or not such a rapid cessation might ever occur, or under what circumstances.

While SRM methods might therefore help to mitigate against a rise in global mean surface temperature, they do nothing directly to reduce atmospheric concentrations of CO_2, or the rate at which they are increasing. There would be some indirect effects due to carbon cycle feedbacks in the Earth system, but the solar radiation and greenhouse gas forcing agents operate in different ways, and have very different impacts on ecosystems, as discussed further below.

The different SRM methods proposed are considered in more detail below.

3.3 Specific techniques

3.3.1 Surface albedo approaches

The aim of surface albedo approaches is to make the planet as a whole reflect more solar radiation by making the surface brighter.

The starting point for analysis is the energy balance of the climate system, which is shown schematically in Figure 1.1. The surface albedo measures the reflectivity (brightness) of the surface, and is defined as the proportion of the solar radiation incident on the surface that is reflected. Mean surface albedo is therefore currently about 30/198[11] or 0.15 (see Figure 1.1). To cool the planet by engineering a radiative forcing of –4 W/m^2, albedo modification approaches would need to increase the total solar radiation reflected by the planet from ~107 to ~111 W/m^2. In the case of surface albedo approaches this would be achieved by increasing the solar radiation reflected by the Earth's surface from 30 to 34 W/m^2, which involves a relatively modest increase in the mean surface albedo of the planet from 0.15 to about 0.17. This increase of 0.02 appears at first sight to be rather modest. However, most of the planetary surface is covered by oceans, which have a low albedo (about 0.1), and which would be difficult to change. So the increase that would be required over the land is on average about four times greater (0.08). Moreover, not all of the land surface would be available for

10 Albedo is a defined as a fraction (the proportion of radiation reflected) and is therefore a dimensionless quantity measured on a scale from 0 to 1 (0 = low reflectivity and 1 = high reflectivity).

11 198 W/m^2 is the amount of solar radiation that reaches the Earth's surface.

brightening, and the required change could in fact only be achieved by (in round numbers) increasing the albedo of about 10% of the total land surface to a high level approaching the maximum value of 1.0.

Individual surface albedo approaches focus on brightening a particular surface type (eg urban area, croplands, deserts) and therefore tend to be localised in space. As a result, the effectiveness of surface albedo approaches also depends on the amount of sunlight reaching the surface (which varies strongly with cloud cover and latitude), as well as on the fractional area of the Earth's surface over which albedo can be increased. Surface albedo modifications that cover small fractions of the Earth's surface, such as 'white roof' methods in urban areas, need to produce large local albedo changes to produce a significant cooling of the local climate. However, methods that involve smaller changes over larger land areas may potentially be in conflict with other human land-use such as agriculture and forestry.

The patchy nature of the radiative forcings arising from most surface albedo modifications has the potential to change atmospheric circulation, and in some locations brightening the surface could even lead to a counterproductive reduction in cloud cover and rainfall (Charney 1975). These potential side effects of deliberate surface albedo modification have not yet been fully assessed in climate models, but the associated risks will be higher for larger scale and more regionally patchy forcing patterns.

White roof methods and brightening of human settlements

One idea is to increase the reflectivity of the built environment by painting roofs, roads and pavements bright reflective 'white' (Akbari *et al.* 2009, Submission: Mark Sheldrick). This would be most effective in sunny regions and during summertime where there might also be co-benefits through savings in air-conditioning. Akbari *et al.* (2009) estimate that the albedo of urban roofs and pavements could be increased by 0.25 and 0.15 respectively, resulting in a net increase in the albedo of urban areas of about 0.1. The resulting global radiative forcing depends on how much urban area can be brightened in this way, and here the estimates differ from 1% of the land surface (Alkbari *et al.* 2009) to 0.05% of the land-surface (Lenton & Vaughan 2009). Using the smaller urban area, Lenton & Vaughan (2009) estimate a potential radiative forcing of only –0.01 W/m^2, which is too small to have any significant global effect. However, based on a broader definition of human-settlements in terms of population density Lenton & Vaughan (2009) also consider albedo modification on a much higher fraction of the land surface (2.3%), which would yield a radiative cooling of about –0.2 W/m^2.

A rough estimate of the costs of painting urban surfaces and structures white can be made using standard costs for domestic and industrial painting (see also Submission: Mark Sheldrick). Assuming a re-painting period of once every ten years, combined paint and manpower costs would be of the order of \$0.3/m^2/yr, although this would likely vary greatly from country to country. On this basis the overall cost of a 'white roof method' covering an area of 1% of the land surface (about 10^{12} m^2) would be about \$300 billion/yr, making this one of the least effective and most expensive methods considered (see Table 3.1).

More reflective crop varieties and grasslands

Land plants tend to absorb strongly in the visible photosynthetically active part of the solar spectrum, but are highly reflective in the near infrared frequencies. However, the albedo of plant canopies can vary significantly between different plant types and varieties, due to differences in basic leaf spectral properties, morphology and canopy structure (Ridgwell *et al*. 2009). It may therefore be possible to significantly increase the albedo of vegetated surfaces through careful choice of crop and grassland species and varieties. Ridgwell *et al*. (2009) considered a 0.04 increase in the albedo of crops to be feasible and modelled its impact using a coupled climate model. They found a summertime cooling of up to 1°C in much of North America and Central Europe. Hamwey (2007) estimated the radiative cooling that would arise from increasing the mean albedo of grassland, open shrubland and savannah from 0.17 to 0.21, coming up with a figure of –0.56 W/m^2. In their synthesis paper

Table 3.1. Summary evaluation table for surface albedo (human habitation) methods. The ratings given (refer Table 5.1) are according to the criteria explained in Chapter 1.

	Surface albedo (human settlement)	
Effectiveness	Not enough settlement area in the world to be adequately effective	Very low
Affordability	High materials, labour and maintenance costs for painting of surfaces	Very low
Timeliness	Could take several decades to change colour of road surfaces and other built structures throughout the world, but rapidly effective once implemented: no R&D required	Medium to High
Safety	Known technology, minimal environmental side-effects from materials etc Localised and non-uniform effect but on very small spatial scales, so unlikely to modify weather patterns etc even if deployed at maximum level	Very high

Lenton & Vaughan (2009) combine these proposals to produce an overall cooling of about –1 W/m^2, assuming a maximum 0.08 increase in crop albedo and a 0.04 increase in the albedo of grassland and savannah.

There are no published estimates of the costs of such a large-scale change in land management. Reducing the photosynthetically active radiation absorbed by plants has the potential to reduce overall primary productivity and crop yields. However, this is judged here to be a relatively low risk since canopy photosynthesis tends to be light-saturated during most of the growing season. The potential side-effects on factors such as market price, disease resistance, growth rates and drought tolerance also remain to be determined.

Desert reflectors

Hot desert areas make up about 2% of the Earth's total surface area and experience very high levels of incident solar radiation. Large increases in the albedo of deserts therefore have the potential to produce fairly large negative radiative forcings. Gaskill (2004) proposed covering deserts with a reflective polyethylene-aluminium surface to increase the mean albedo from 0.36 to 0.8, and provide a very significant global radiative forcing of –2.75 W/m^2. This approach would however probably conflict with other land uses. The ecological consequences of covering deserts with long-lived man-made materials are also likely to be a major concern. In common with other very localised radiative forcings, this approach has the potential to change large-scale patterns of atmospheric circulation, such as the East African monsoon that brings rain to sub-Saharan Africa. The ecological impacts of any such associated local climate change, and of covering the land, would clearly be very great in the areas affected, and constitute very serious disadvantages of this method if it were implemented on any scale large enough to be effective. In addition, if the costs of reflective sheeting, with an allowance for routine replacement of damage, were somewhat similar to those of painting at ~\$0.3/m^2/yr, the cost of covering 10^{13} m^2 (~10% of the Earth's land surface) could thus amount to several \$ trillion per year (see Table 3.2).

Reforestation

Large-scale reforestation is normally considered as a carbon mitigation strategy (see Chapter 2), but has also been proposed as a method to encourage 'global cooling' through biophysical effects. The overall impact of forests on climate depends very much on where they are planted (Bala *et al.* 2007). Forests in the tropics and sub-tropics tend to cool the surface by increasing evaporation and transpiration, while forests in the mid and high latitudes tend to warm because they are much darker than the underlying snow and therefore absorb more solar radiation (Betts 2000). The overall biophysical impact of forests on global mean temperature is believed to be small, but they can have very significant impacts on regional climates (Pielke *et al.* 2002). This is especially true in some semi-arid regions, such as the Sahel or parts of Australia, which may support multiple climate-vegetation equilibria. In these locations it may be possible to flip the system into a green-wet state by replanting forests, although the effect of this could be overall warming rather than cooling. Such approaches are unlikely to have a major impact on the overall energy balance of the planet (and so are not considered further in this report), although they do offer promise as a means to proactively adapt to climate change.

Ocean Albedo

Two submissions were received for increasing ocean albedo (both requested confidentiality). This was in fact the first geoengineering method proposed in 'Restoring the quality of our environment', the report to US President Johnson that was the first high-level report on the CO_2 climate problem (Keith 2000). In view of the large proportion of the Earth's surface occupied by the oceans and the low albedo associated with such surfaces, any technique that significantly increased that albedo could have a major effect. The engineering challenges and environmental impacts of such methods are considerable. However no proposals appear to have been published in the peer-reviewed literature at present, and without more detailed information on the feasibility, costs and ecological impacts of such methods it is not yet possible to provide an assessment.

Table 3.2. Summary evaluation table for surface albedo (desert) methods.

	Surface albedo (desert)	
Effectiveness	Complete and highly reflective coverage of all major desert areas (~10% of all land) would be needed to achieve adequate effect (4 W/m^2)	Low to Medium
Affordability	Cost of materials, deployment and maintenance potentially very large	Very low
Timeliness	Fairly quick to implement if desired and rapidly effective No R&D required except for environmental side-effects	High
Safety	Major environmental and ecological effects on desert ecosystems Localised and non-uniform effect on large scale: probable effects on weather patterns, rainfall etc	Very Low

3.3.2 Cloud-albedo enhancement

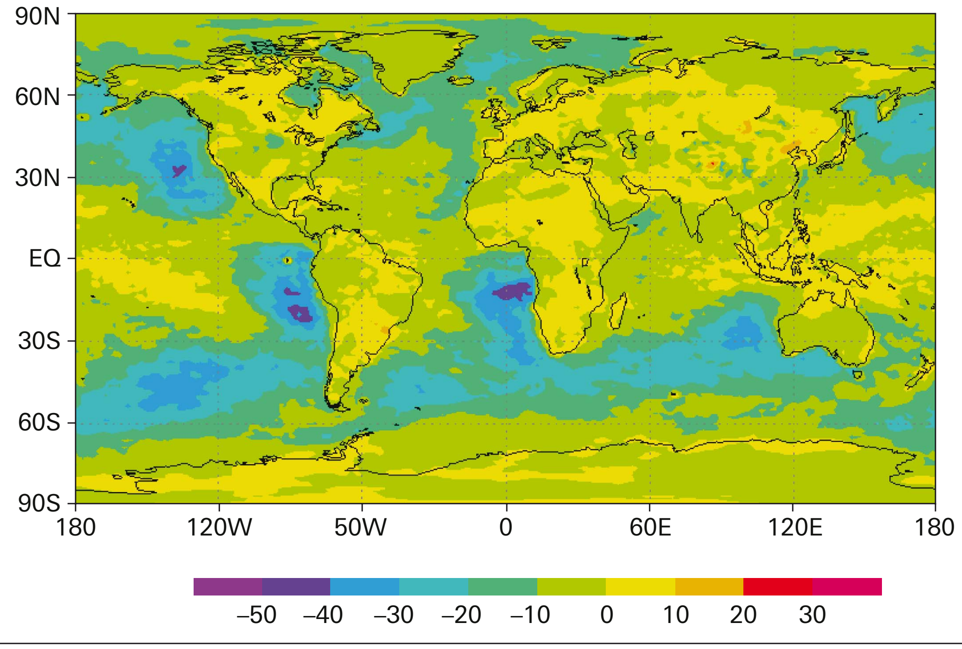
It has been proposed that the Earth could be cooled by whitening clouds over parts of the ocean. This proposal springs from the observation (Twomey 1977) that, in relatively dust-free parts of the marine atmosphere, increasing the number of cloud-condensation nuclei (CCN)[12] per unit volume in low-level marine clouds (which cover approximately one-quarter of the ocean surface) raises cloud albedo significantly and possibly also increases the cloud lifetime (Albrecht 1989). It is readily demonstrated that many small cloud micro-droplets scatter and so reflect more of the incident light than a smaller quantity of larger droplets of the same total mass since the surface area of the small droplets is greater. The longevity of the cloud may also be increased because the coalescence of the droplets to form larger droplets (leading, when a critical size is reached, to drizzle) is delayed.

Numerical studies using atmospheric models (Figure 3.2) have identified the extensive areas of marine stratus clouds off the west coasts of North and South America and the west coast of Africa as being areas where cloud albedo might be effectively enhanced in this way (Latham *et al.* 2008). Latham *et al*. report that a doubling of the natural cloud-droplet concentration in all such clouds would increase the cloud-top albedo sufficiently to compensate, roughly, for a doubling of atmospheric CO_2. (Very recent repeats of some of the simulations using a more elaborate, coupled atmosphere-ocean GCM show the same type of behaviour (Submission: Latham *et al*.).)

Vital issues for the successful implementation of this strategy are, firstly, the creation of a supply of particles of an appropriate diameter and quantity to serve as CCN, and secondly, a means of distributing them. The release of a suitable hydrophilic powder from aircraft has been suggested and may offer a technically uncomplicated route to delivering CCN to precisely the location needed, but no detailed design proposals or costings have been made yet. Most attention has so far focused on the generation of fine particles of sea-salt derived from ocean water, delivered by either conventional ocean-going vessels, aircraft, or specially designed un-manned, radio-controlled sea craft (Salter *et al.* 2008). If this could be achieved it could be a useful option, but other methods to enhance CCN may also emerge.

For the vessel delivery method to be successful at producing a global cooling roughly equivalent to the increase in insolation since the start of the industrial period (~3.7 W/m^2), it has been estimated (Latham *et al.* 2008; Salter *et al*. 2008) that the number of CCN should be doubled and that to achieve that a global fleet of up to 1500 vessels would be required. As a proportion of these micro-droplets diffuse upwards by turbulent mixing, the water evaporates leaving the hydrophilic salt micro-grains available to serve as sites for droplet condensation when they reach super-saturated strata near the cloud base. The above estimate of the required spray discharge rate takes account of the fact that only a few per cent of spray droplets released at sea-level would actually reach the cloud base to act as CCN.

Figure 3.2. Five-year mean difference (W/m^2) in radiative forcing at the top of the atmosphere between a control simulation (with CCN of 100/cm^3) and a test run with CCN of 375/cm^3 in regions of low-level maritime cloud (an extension of results from Latham et al. 2008).



12 Cloud condensation nuclei are tiny particles around which droplets of water coalesce to form clouds.

Spray generators capable of delivering the desired quantity and size of droplets are not available commercially and numerous technical design challenges remain. Further research is needed into methods for sea water filtration, and mechanical, electro-static and electro-mechanical strategies for spray generation and operation. Experimental trials at sea would be needed prior to deployment (Submission: Stephen Salter; Submission: Latham *et al*.).

The proposal to whiten marine clouds has a number of advantages over most alternative approaches to reducing absorbed insolation. Firstly, should unforeseen problems arise, spraying could be stopped and within ten days nearly all of the salt particles would rain or settle out of the atmosphere; secondly, sea spray occurs naturally in large quantities. Moreover, at different times of the year different regions of the oceans can be covered offering scope for targeted cooling in particularly sensitive areas. The submission received from Latham *et al* suggests that raising the CCN in the north-eastern Atlantic could reduce the warming of the northbound surface sea current helping to reduce the summer retreat of the Arctic ice. The production of CCN in the marine atmosphere could also potentially be deployed separately or in conjunction with other approaches to intentionally modify climate. A combined system may be able to produce a climate state with qualities that no individual approach could achieve on its own. On the other hand, localised cooling is likely to modify regional weather patterns as discussed further below.

However, numerous questions remain to be answered and problems to be addressed (see Table 3.3). On the engineering side further research and development on the spray generator is needed. In case no secure solution to these design problems can be devised, the more direct seeding of the clouds from ships or low-flying aircraft could also be considered. Whichever technique for augmenting CCN is adopted, the potential impact on ocean-circulation patterns of strong cooling applied to a 'patch' some hundreds of thousands of km^2 in extent should be considered. The local radiative forcing required over a small area would be much greater than the global average forcing so attained, and would likely be sufficient to modify regional weather systems (Submission: Met Office). Effects on near-surface winds, ocean currents and precipitation, would need to be examined. Coupled AOGCM (atmosphere-ocean general circulation model) computations of the impacts of augmented CCN (Jones *et al.* 2009; Latham, personal communication) give varying results, although the adequacy of current physical models for such simulations is questionable (Submission: Shine *et al*.). With regard to the cloud physics, Latham *et al.* (2008) also draw attention to possible complex couplings between the salt droplets and the clouds, which led to the conclusion that *'it is unjustifiably optimistic to assume that adding CCN to clouds will always brighten them'*. On the climate side, too, there are questions about how changes in marine clouds will affect climate (precipitation and temperature) over land. There may be potential for this approach to either increase or decrease precipitation over land depending on particular characteristics of specific deployments (eg, area, season, amount). In this connection, it is noted that the observational phase of a large international research project, VOCALS, involving five aircraft and two ships, has recently been completed examining the cloud properties of low-level marine stratus clouds off the Chilean coast (Submission: Gadian *et al*.). When the data have been processed they should provide important new information on the radiative and microphysical properties of these clouds.

Only very preliminary estimates of costs and timescales have so far been attempted for this method. Salter *et al.* (2008) suggest that a further £30 M for hardware research and development would be needed and a similar sum for tooling costs. Thus, with a prudent safety factor, the total development costs should be of the order of £100 M to produce a prototype deployment system. Time scales are even less precise though, provided the spray/filtration problems can be resolved, a period of one decade to complete research, finalise a design and complete tooling would appear achievable. For production-line deployment, Salter estimates a cost of £1 M to £2 M per fully-equipped craft. An annual outlay of £1 B should permit the construction and deployment of 300 to 400 additional or

Table 3.3. Summary evaluation table for cloud albedo enhancement methods.

Cloud albedo enhancement		
Effectiveness	Feasibility (production of sufficient CCN) and effectiveness still uncertain Limited maximum effect and limited regional distribution SRM method so does nothing to counter ocean acidification	Low to Medium
Affordability	Very uncertain: short aerosol lifetime at low altitude so requires continual replenishment of CCN material, but at lower cost per unit mass	Medium
Timeliness	Once deployed would start to reduce temperatures within one year Could be deployed within years/decades (but basic science and engineering issues need to be resolved first)	Medium
Safety	Non-uniformity of effects—may affect weather patterns and ocean currents Possible pollution by CCN material (if not sea-salt)	Low

replacement vessels per year along with the necessary infrastructure to support their operation. If more conventional, diesel-powered vessels were employed, the capital costs should be significantly less but this would be offset at least in part by increased operating cost. If aerosol spraying from aircraft were chosen, development times would be shorter, since modified cargo transport aircraft could be used for both developmental tests and operational deployment.

3.3.3 Stratospheric aerosols

A wide range of types of particles could be released into the stratosphere with the objective of scattering sunlight back to space. Important factors that differentiate the effects of different types of particles include their size, and whether or not they conduct electricity (Teller *et al.* 1997, 2002). For non-conducting particles, the optimal size for scattering sunlight is a few tenths of a micron. Particles much larger than this become effective at scattering outgoing longwave (heat) radiation and thus have potential to cause a warming influence. Conducting particles or resonant scatterers may have potential to deflect sunlight with much less mass, but these approaches have been subjected to much less analysis (Teller *et al.* 1997). It could also be possible to construct reflective micro-balloons, which would reflect sunlight back to space (Teller *et al*. 2002). Various other types of stratospheric aerosol particles have also been suggested (Teller *et al*. 1997; Blackstock *et al*. 2009; Keith in press (b); Submission: Katz). Engineered aerosols might enable scattering that did not produce so much diffuse illumination, potentially circumventing a significant side-effect of sulphate aerosols. Alternative materials might also avoid the coagulation and vaporisation problems that will be significant for sulphate aerosols. Finally, it is possible that advanced engineered particles could be designed that had longer lifetimes, or that were lofted out of the lower stratosphere, so reducing the impact of the aerosol on ozone chemistry, or enabling radiative forcing to be concentrated in special locations such as the polar regions.

Most of the focus on the potential for stratospheric aerosol methods has however recently been on sulphate aerosols, for several reasons. Hydrogen sulphide (H_2S) or sulphur dioxide (SO_2) can be introduced into the stratosphere as gases, where they are expected to oxidise into sulphate particles with characteristic sizes of several tenths of a micron. With the introduction of solids, there are significant technical problems associated with distributing and avoiding clumping of particles, which is obviated by the introduction of a gas. Furthermore, global cooling has been produced in the past by volcanogenic sulphate aerosols, providing direct evidence that these particles would have a cooling influence. Because much of the published research with respect to stratospheric options has focused on sulphate particles, this is the focus of this report. This does not mean that some other type of particle may not ultimately prove to be preferable to sulphate particles.

The low stratosphere contains a naturally occurring layer of sulphate aerosol (sulphuric acid particles) which contribute to the global albedo. The source of the layer is *in-situ* oxidation of various natural sulphur-containing gases, mainly carbonyl sulphide (OCS), which are transported upward from the troposphere. Because of the stability of the stratosphere the lifetime of the aerosol is long (~ years) and, hence, the aerosol tends to be spread throughout the lower stratosphere. In contrast, aerosols in the troposphere can be rapidly washed out and so have a much shorter lifetime. Major volcanic eruptions can dramatically increase the sulphur aerosols in the stratosphere increasing the amount of sunlight reflected back into space, with a potential impact on surface climate lasting several years. For example, the eruption of Mt Pinatubo was followed by a peak global cooling of about 0.5 K; regional impacts varied and included a strengthening of the North Atlantic Oscillation, one of the important modes of climate variability (see for example Groisman 1992; Robock & Mao 1992; Graf *et al.* 1993; Robock & Mao 1995; Kirchner *et al.* 1999).

Simulating the effect of large volcanic eruptions on global climate has been the subject of proposals for climate geoengineering for some time (see Keith 2000). These proposals aim to artificially increase sulphate aerosols in the stratosphere above natural levels, causing an increase in planetary albedo and thereby reducing the incoming solar radiation. A simple calculation (see above) shows that a reduction of solar input by about 2% can balance the effect on global mean temperature of a doubling of CO_2 (see also Govindasamy & Caldeira 2000; Govindasamy *et al*. 2002, 2003; Crutzen 2006; Wigley 2006).

Of course, the climate system involves (and is in part driven by) gradients in heating and cooling, so that a simple global balance model may seriously misrepresent any actual spatially varying response. Furthermore, major volcanic eruptions are sporadic and their impacts might only last a few years. In contrast, geoengineering of the stratospheric sulphate layer would require a constant injection of sulphur for decades or centuries to balance the increased radiative forcing by greenhouse gases. The analogy with volcanic eruptions is therefore imperfect; it is unknown whether slow processes in the climate system operating on longer time scales (see below) would be more important in this quasi-steady state, compared to their role following a transient event such as an eruption.

Several climate model studies have explored the impact of an engineered stratospheric sulphate layer (see Caldeira & Wood, 2008; Rasch *et al.* 2008a,b; Robock *et al.* 2008). Some of these studies have specified the distribution of sulphate aerosol (so that the aerosol in the model has not been fully interactive); in addition, other simplifications to modelling the Earth system are still necessary even in state-of-the-art models. Nevertheless, a first-order conclusion is that the model climate, with both increased greenhouse gases and enhanced sulphate aerosol, is much closer to the present day climate than is the case with just increased greenhouse gases. For example, Figures 3.3 and 3.4 are

Figure 3.3. Annual mean temperature changes calculated in GCM studies by Caldeira & Wood (2008). a & b refer to a model experiment with 2 × CO_2 and c & d are from an idealised climate engineering experiment with 2 × CO_2 and a reduction in global mean insolation of 1.84%. Panels a & c show temperature changes from the 1 × CO_2 cases; panels b & d show areas where the temperature change is statistically significant at the 0.05 level. Caldeira & Wood argue that the idealised climate engineering simulation indicates that relatively simple climate engineering may be able to diminish temperature changes in most of the world. Reproduced with permission from the authors, Phil. Trans. Roy. Soc. A 2008; 366, 4039–4056.

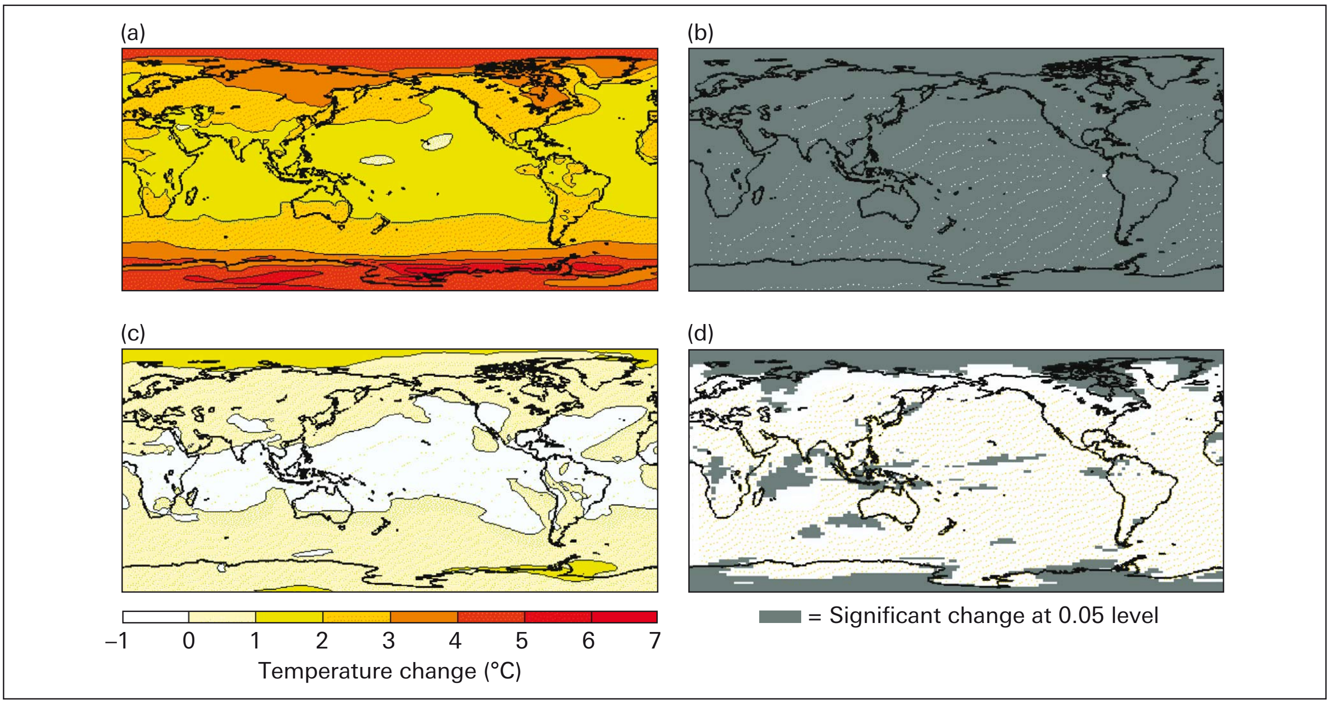
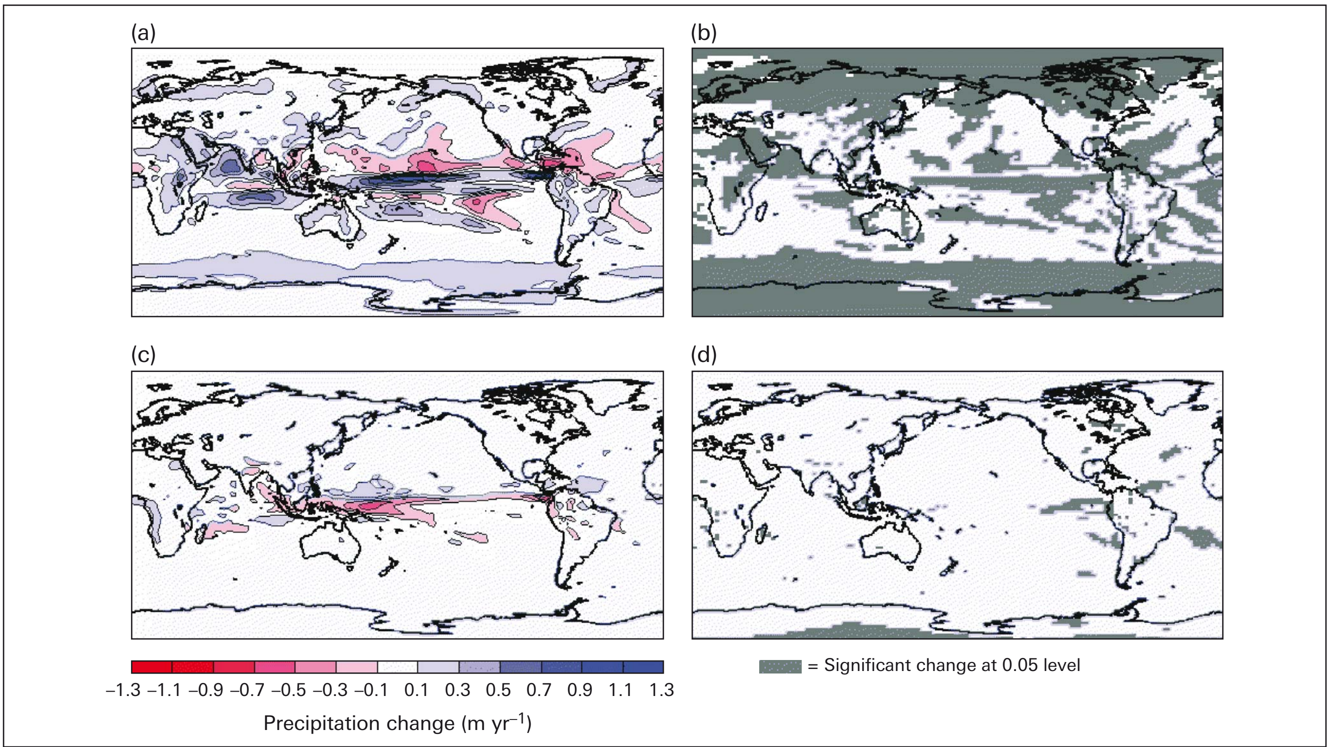


Figure 3.4. Annual mean precipitation changes calculated in GCM studies by Caldeira & Wood (2008). a & b refer to a model experiment with 2 × CO_2 and c & d are from an idealised climate engineering experiment with 2 × CO_2 and a reduction in global mean insolation of 1.84%. Panels a & c show precipitation changes from the 1 × CO_2 cases; panels b & d show areas where the precipitation change is statistically significant at the 0.05 level. As in figure 3.3, the idealised geoengineering simulation indicates that relatively simple climate engineering may be able to diminish precipitation changes in most of the world. Reproduced with permission from the authors, Phil. Trans. Roy. Soc. A 2008; 366, 4039–4056.



from Caldeira & Wood (2008) who have considered the impact of a reduction in incoming solar radiation of 1.84%, which could be produced by enhanced sulphate aerosol or other SRM approaches (they do not attempt to model the aerosol layer). The figures show changes in surface temperature and precipitation under certain idealised scenarios. A general conclusion from these studies is that geoengineering with stratospheric aerosols could, in principle, be used as a means to counteract the first-order, global effects of increased greenhouse gas concentrations.

For more reliable assessments, it is essential that these initial model studies, some of which are rather idealised, are developed further. Increased complexity is needed in the models and the importance of regional and seasonal, as well as global and annual average, impacts must be resolved. For example, the microphysics of the aerosol layer need to be modelled in detail. Rasch *et al.* (2008a) estimate that between 1.5 and 5 Tg S/yr would need to be injected into the stratosphere. The climate impact depends crucially on the size distribution of the aerosol, with droplet radius of order 0.1 μm being the optimum for interaction with incoming solar radiation. Maintaining the appropriate size distribution against, for example, sink processes (coagulation, etc.) would be difficult; the relationship between sulphur injection, particle size and optical depth is non-linear (see Pinto *et al*. 1998). Note that the size distribution of the natural, 'background' sulphate layer (small particles) is different from the volcanically enhanced layer (larger particles). Available estimates of the quantity (source strength) needed are therefore rather uncertain. Engineering and maintaining the optimal aerosol size distribution could be very challenging.

Impacts also need to be assessed in much more detail. For example, Trenberth & Dai (2007) have examined the observed effect of the Mt Pinatubo eruption on the hydrological cycle. They found that following the eruption there was a substantial decrease in precipitation over land with corresponding record reductions in runoff and river discharge. Using a quite detailed ocean-atmosphere GCM, Robock *et al.* (2008) found that injections of SO_2 to enhance stratospheric aerosol would modify the Asian and African summer monsoons, reducing precipitation and thus (like climate change) potentially impacting the food supply to billions of people. Both studies suggest that major regional effects could result from sulphate geoengineering, which could counteract or reinforce those associated with climate change itself.

The enhanced stratospheric sulphate layer which followed the eruption of Mt Pinatubo led to a significant reduction in stratospheric ozone, with global ozone about 2% below the expected values (Harris *et al.* 1997). Tilmes *et al.* (2008) suggest that Arctic ozone depletion following geoengineering of the sulphate layer could be substantially increased and cause a delay in 'recovery' of the Antarctic ozone layer by perhaps up to 70 years (see also Submission: Tilmes). Also important could be more subtle changes in ozone in the middle latitude lower stratosphere; the connection between decadal scale climate variability and stratospheric ozone is increasingly being discussed (see for example, Baldwin *et al.* 2003; Shaw & Shepherd 2008). Indeed there is a range of so far unexplored feedback processes, which could become important with a permanently engineered sulphate layer. These could include increased stratosphere-troposphere exchange (STE), driven by aerosol heating in the tropical lower stratosphere. This could have a long-term impact on stratospheric water vapour, and radiative forcing (see Joshi & Shine, 2003); increased STE would also lower the lifetime of the aerosol layer, calling for increased injections to maintain a particular value of the optical depth.

Changes in surface water and soil moisture as well as in solar radiation intensity at the surface would both be expected to have an impact on the biosphere and there are indications that the carbon cycle did change after the eruption of Mt Pinatubo since changes in the rates of increase of atmospheric CO_2 and CH_4 were observed (IPCC 2007a). No assessment of this in the geoengineering

Table 3.4. Summary evaluation table for stratospheric aerosol methods.

Stratospheric aerosols		
Effectiveness	Feasible and potentially very effective (*cf*. volcanoes) No inherent limit to effect on global temperatures SRM method so does nothing to counter ocean acidification	High
Affordability	Small quantities of materials need to be used and moved: likely to be low cost *cf.* most other methods	High
Timeliness	Could be deployed within years/decades (but engineering issues and possible side-effects need to be resolved first) Once deployed would start to reduce temperatures within one year	High
Safety	Residual regional effects, particularly on hydrological cycle Possible adverse effect on stratospheric ozone Possible effects on high-altitude tropospheric clouds Potential effects on biological productivity	Low

context has yet been carried out. An increase in acid rain appears to be unlikely to be a problem, as the perturbation to the global sulphur cycle by these stratospheric emissions is quite small (natural volcanic emissions are ~50 MtS/yr, and industrial emissions are much larger).

Delivering between 1 and 5 MtS/yr to the stratosphere is feasible. The mass involved is less than a tenth of the current annual payload of the global air transportation, and commercial transport aircraft already reach the lower stratosphere. Methods of delivering the required mass to the stratosphere depend on the required delivery altitude, assuming that the highest required altitude would be that needed to access the lower tropical stratosphere, about 20 km, then the most cost-effective delivery method would probably be a custom built fleet of aircraft, although rockets, aircraft/rocket combinations, artillery and balloons have all been suggested. Very rough cost estimates based on existing aircraft and artillery technology suggest that costs would be of the order of 3 to 30 $/kg putting the total annual cost at 10s of billion dollars (US National Academy of Science 1992; Keith 2000; Blackstock *et al.* 2009). The environmental impacts of the delivery system itself would of course also need to be carefully considered.

3.3.4 Space-based techniques for reducing solar radiation

Space-based methods propose to reduce the amount of solar energy reaching Earth by positioning sun-shields in space to reflect or deflect the solar radiation. For each approach the technical issues that need to be addressed include the design of the shields, where they should be located, how many are needed and by what method they are to be placed at, and maintained at, the chosen location.

A number of proposals have suggested placing sunlight deflectors in near-Earth orbits (Submission: McInnes). One method (US National Academy of Sciences 1992) proposed 55,000 mirrors, each with an area of 100 m^2 in random orbits. An alternative suggestion (Mautner 1991) is to create a Saturn-like ring of dust particles with shepherding satellites, in the equatorial plane between altitudes of about 2000 and 4500 km. This would shade the tropics of the winter hemisphere but also tend to illuminate the summer hemisphere during night-time. To achieve a reduction in solar insolation of about 2%, that is approximately the amount of radiative forcing to compensate for a doubling of CO_2, it is estimated that a total mass of dust particles of over 2 billion tonnes would be required. This would be injected into space from Earth, or possibly derived from the Moon or asteroids. A development of this idea (Pearson *et al.* 2006) is a ring of lightweight satellites, electrodynamically tethered into a ring in low Earth orbit so that no other shepherding is required.

All of these near Earth orbit systems must trade-off mass against lifetime. If the reflecting systems are made with a very low mass per unit of solar scattering then launch costs could be correspondingly smaller; however, as the mass is reduced the solar scatterers will be rapidly blown out of orbit by the light-pressure force exerted by the sunlight they are designed to scatter. Orbital decay therefore limits the extent to which mass can be reduced (Keith & Dowlatabadi 1992; Teller *et al.* 1997). For near earth orbits, the only proposed solution is to add mass but this adds to the total cost of launch and deployment

An alternative to placing reflectors in low Earth orbit is to place them near the L1 point: the position about 1.5 million km from Earth towards the Sun where the gravitational attractions of the two bodies are equal. The potential advantages of this location are that it is possible to choose orbits near L1 that balance the light-pressure force so eliminating the trade-off mentioned above, and enabling much lighter weight scattering structures. In addition, the sunlight need be deviated by only a small angle in order to avoid the Earth, further reducing the minimum required mass by a factor of approximately 100. Finally, the sunshades would presumably pose less of a threat to earth-orbiting satellites. To provide a ~2% reduction in solar irradiance reaching the Earth the effective area of the sunshades would need to be about 3 million km^2. Various proposals have been made for the composition of an L1-point shield. These include, among others:

- a refractor made on the Moon of a hundred million tonnes of lunar glass (Early 1989);
- a superfine mesh of aluminium threads, about one millionth of a millimetre thick (Teller *et al*.1997);
- a swarm of trillions of thin metallic reflecting disks each about 50 cm in diameter, fabricated in space from near-Earth asteroids (McInnes 2002);
- a swarm of around ten trillion extremely thin high-specification refracting disks each about 60 cm in diameter, fabricated on Earth and launched into space in stacks of a million, one stack every minute for about 30 years (Angel 2006).

Because of the huge logistical demands associated with all of the proposals, it would take several decades before any of them could be fully implemented. Atmospheric temperatures, however, would respond quite quickly (within a few years) once they were in place (Matthews & Caldeira 2007). For the same reasons, should such a system, having been successfully implemented for some time, fail or be 'switched off' then there would be a very rapid transition to the much warmer world associated with the higher CO_2 concentrations which might have built up in the interim.

Just as with stratospheric aerosols (as discussed in the previous section), computer models have been used to investigate the climate of a world in which the total solar irradiance is reduced to offset increasing CO_2 concentrations (eg, Govindasamy *et al.* 2003; Caldeira & Wood 2008; Lunt *et al.* 2008) although none of these include a full representation of all components of the climate system (see Box 1.2).

These model experiments (also discussed above) are designed such that the reduction in absorbed solar radiation exactly balances the radiative forcing due to the increased concentration of greenhouse gases. The resulting climate is compared with that of a world of pre-industrial CO_2 concentrations and no reduction in sunlight. It is found that the temperature of the air near the surface is substantially less affected in the geoengineered world than in the non-geoengineered case but, nevertheless, is slightly cooler in tropical regions, where the solar effect dominates, and warmer at high latitudes, where the greenhouse trapping is greater. The weaker latitudinal temperature gradient affects other climate parameters. For example the amplitude of the seasonal cycle is reduced, giving warmer winters and cooler summers. The cooler tropics result in less evaporation and a generally drier atmosphere with less precipitation. One model study (Lunt *et al.* 2008), which included fully coupled ocean circulations, also shows a decreased intensity of El Niño events, with concomitant impacts on tropical climate, in particular tending to enhance overall precipitation over south-east Asia and India.

Even though the global radiation balance is the same for both, the pre-industrial and geoengineered simulations show significant regional and temporal differences. Nevertheless, these differences are small compared to those associated with a non-geoengineered future.

There are numerous and considerable uncertainties involved in most aspects of the proposed space-based SRM methods and all these would need to be addressed by detailed research before any method might be deemed potentially fit for purpose. Apart from the development of necessary technology, and the solution of problems concerning its implementation and maintenance in space, the research would need to investigate carefully the potential impacts on the climate system. All the space-based SRM methods propose to reduce the total amount of solar energy entering the atmosphere but each affects the incoming solar beam differently. Reflectors at the L1 point would essentially have the effect of reducing the solar constant and initial studies of the impact of this, within in a high CO_2 atmosphere, have already been carried out, as outlined above. More detailed assessments would investigate the impact on regional meteorology, temperature and precipitation patterns, including any changes in seasonality and variability, and also impacts on polar ice cover and ocean circulations. Reflectors in low Earth orbit would redistribute solar radiation in far more complex ways which would each need to be carefully determined, even before any model assessment could be made of their climate impact. While such studies would be able to give some indication of the potential impacts of the space-based SRM methods all would be subject to the caveats expressed in Box 1.2 concerning the limitations of climate models.

All of the space-based techniques summarised in this section (see Table 3.5) contain such great uncertainties in costs, effectiveness (including risks) and timescales of implementation that they are not realistic potential contributors to short-term, temporary measures for avoiding dangerous climate change. This is not to dismiss them from future consideration, however. If, in the future it became probable that some form of geoengineering would be needed for a period approaching a century or longer, on such a timescale (and with the continual advance of technical capabilities) it is quite possible that the best examples of this type may offer a cheaper and less risky approach to SRM than any of the stratospheric or near-Earth techniques. With launch costs to near-Earth orbit approaching a few $ M per tonne (http://www.thespacereview.com/article/233/1), it may eventually be possible to place a one Megatonne system into high orbit at a price of a few $ trillion, of the same order as that for some of the other proposals considered, and potentially with a much longer lifetime. Some designs proposed for the L1-based systems have masses considerably lower than a Megaton, so even at current launch costs the cost of launch could conceivably be smaller than the cost of other SRM techniques (Keith 2000). However at these rates, the costs of placing billions of tonnes of material (eg dust) into orbit would be prohibitive. Desk-based engineering design studies could advance understanding of the likely feasibility and costs of such proposals

Table 3.5. Summary evaluation table for space-based methods.

Space-based methods		
Effectiveness	No inherent limit to effect on global temperatures SRM method so does nothing to counter ocean acidification	High
Affordability	High cost of initial deployment (depends on mass required): plus additional operational costs (eg maintaining positions): but long lifetime once deployed	Very low to Low
Timeliness	Would take several decades (at least) to put reflectors into space Once in place, reflectors would reduce global temperatures within a few years	Very low
Safety	Residual regional climate effects, particularly on hydrological cycle No known direct biochemical effects on environment beyond possible effects of reduced insolation	Medium

considerably. A further review following such studies, in about a decade, would be appropriate to reconsider the prospects for such approaches at that time, in the light of advances in relevant technologies, and the likelihood of some more permanent geoengineering contribution possibly being needed.

3.4 Discussion

SRM methods do nothing to reduce concentrations of CO_2 but have the advantage over CDR methods that they reduce mean global temperatures rapidly after deployment. Full implementation could take from a year to several decades depending on the method: surface and atmospheric-based techniques would be much easier and quicker to implement than space-based methods, which would involve a space programme many times larger than anything yet attempted.

It is likely that once a SRM method is implemented the climate system would respond quite quickly with surface temperatures, although not necessarily precipitation patterns to the same extent, returning towards their pre-industrial conditions within a few years of deployment (Matthews & Caldeira 2007), depending on the amount and rate at which the reduction of solar radiation was deployed. Deployment could therefore be delayed until the need for emergency climate intervention became apparent. The rapid effect on climate does however also carry with it the 'termination problem' an issue that would need to be considered before implementation of any SRM method.

SRM methods may have regional climate effects even if they result in zero net global average radiative forcing. Even with a simple reduction in incoming solar radiation, such as might be introduced using space-based reflectors, the geographical distributions of the solar and greenhouse gas forcings are different. A uniform percentage reduction in insolation primarily affects latitudes closer to the equator while the greatest rises in temperatures (and, arguably, the location of some of the most probable 'tipping points' arising from global warming) are found in the polar regions. The impacts that SRM approaches have on global and regional temperatures, and on other aspects of the climate system, also differ from proposal to proposal. Surface-based techniques and cloud-albedo approaches both have the potential to cool the Earth significantly. However, they are both local in their primary effects, and would produce large temperature gradients between the areas in which they were deployed and areas where they were not. Space-based technologies would reduce fairly uniformly the proportion of solar radiation incident on Earth, meaning that in principle, temperature reductions would be more uniform around the planet. They are however unlikely to be completely uniform and it is possible that such techniques could also produce significant and undesirable changes to regional weather patterns. Stratospheric aerosols may, depending on the location and height of releases, provide a cooling effect that is predominantly global or local. As with space-based proposals, even predominantly global cooling effects would not be without varied local impacts. A method to achieve a reduction, which varies somewhat with latitude through some mixed approach may therefore be preferable, but the effects of this would need to be modelled in detail.

Furthermore, climatic parameters other than the radiation budget, such as the chemical composition of the stratosphere may also be affected. Preliminary studies with climate models (eg, Govindasamy *et al.* 2003; Lunt *et al.* 2008) show much reduced but still significant changes in tropical precipitation and Arctic sea ice depth under a scenario in which the solar constant is reduced by the same proportion everywhere to mitigate against warming due to increase CO_2 concentrations.

SRM methods may also have direct ecosystem effects. By reducing temperatures, SRM methods tend to decrease plant respiration rates and therefore increase net CO_2 uptake by the land biosphere (Matthews & Caldeira 2007). However, this effect is not strong enough to markedly diminish global warming or ocean acidification (Matthews *et al.* 2009). Furthermore, by not reducing CO_2 concentrations, SRM methods would lead to entirely new environmental conditions with impacts on biological systems that are hard to predict. Available evidence from models and field experiments suggests that CO_2 fertilisation will be a common short term consequence but that it will vary with vegetation age and type, as well as with the availability and responses of other potentially limiting factors including water and other nutrients (Norby *et al.* 2005; IPCC 2007b). Many potential effects will be be non-linear and have complex effects throughout the ecosystem (Rial *et al*. 2004). Elevated CO_2 increases both land primary productivity and river runoff (Gedney *et al.* 2006) but has negative impacts on marine ecosystems through ocean acidification (Caldeira & Wickett 2003). Atmospheric aerosols may on the other hand have a positive impact on land photosynthesis through their enhancement of diffuse solar irradiation, despite reducing total sunlight at the surface (Mercado *et al.* 2009).

None of the principal proposals are yet ready to be put into operation. Further research and development of the individual approaches (including, in some cases, pilot-scale trials) would be needed to assess uncertainties about effectiveness and undesired side effects and to identify any preferred approach.

Effectiveness and impacts of specific methods

The relative effectiveness and impacts of the SRM methods considered are compared in Table 3.6. Regarding surface-based methods, increasing the albedo of urban areas would make only a very small overall contribution. Outline proposals and ideas for much larger scale surface changes, such as raising the reflectivity of desert areas, while, on paper offer a prospective radiative forcing in excess of -2 W/m^2, have not addressed implementation, maintenance and ecological issues which could render them impracticable. Proposals to increase the albedo of

Table 3.6. Comparison of SRM techniques.

SRM technique	Maximum radiative forcing (W/m^2)	Cost per year per unit of radiative forcing ($\$10^9/yr/W/m^2$)	Possible side-effects	Risk (at max likely level)
Human Settlement Albedo[a]	–0.2	2000	Regional Climate Change	L
Grassland and Crop Albedo[b]	–1	n/a	Regional Climate Change Reduction in Crop Yields	M L
Desert Surface Albedo[c]	–3	1000	Regional Climate Change Ecosystem impacts	H H
Cloud Albedo[d]	–4	0.2	Termination effect[h] Regional Climate Change	H H
Stratospheric Aerosols[e]	Unlimited	0.2	Termination effect Regional Climate Change Changes in Strat. Chem.	H M M
Space-based Reflectors[f]	Unlimited	5	Termination effect Regional Climate Change Reduction in Crop Yields	H M L
Conventional Mitigation[g] (for comparison only)	–2 to –5[g]	200[g]	Reduction in Crop Yields	L

(a) Radiative forcing estimate from Lenton & Vaughan (2009). Mark Sheldrick (private communication) has estimated the costs of painting urban surfaces white, assuming a re-painting period of once every 10 years, and combined paint and manpower costs of £15,000/ha. On this basis the overall cost of a 'white roof method' covering a human settlement area of 3.25×10^{12} m^2 would be £488 billion/yr, or £2.4 trillion per W/m^2 per year.

(b) Radiative forcing estimate from Lenton & Vaughan (2009).

(c) Radiative forcing estimate from Gaskill (2004).

(d) Radiative forcing estimate from Latham *et al*. (2008). Cost estimate from Brian Launder assuming 300 to 400 craft per year plus operating costs, giving a total cost of £1 billion per year.

(e) Costs here are the lowest estimated by Robock *et al*. (in press) for the injection of 1 TgC H_2S per year using nine KC-10 Extender aircraft. It is assumed that 1 TgS per year would produce a –1 W/m^2 radiative forcing (*cf*. Lenton & Vaughan (2009) quote 1.5 to 5 TgS yr^{-1} to offset a doubling of CO_2).

(f) For a radiative forcing sufficient to offset a doubling of CO_2 (–3.7 W/m^2), a launch mass of 100,000 tons is assumed. Cost assessment is predominantly dependent on expectations about the future launch costs and the lifetime of the solar reflectors. Launch costs of $5000/kg are assumed, and that the reflectors will need to be replaced every 30 years. This produces a total cost of $17 billion per year for –3.7 W/m^2, or about $5 billion per year per W/m^2 (Keith 2000; Keith, private communication).

(g) Conventional Mitigation: 0.5 to1% of Global World Product (GWP) required to stabilise CO_2 at 450 to 550 ppmv (Held 2007). Current GWP is about $40 trillion per year, so this represents about $400 billion per year. Assuming that unmitigated emissions would lead to about 750 ppmv by 2100, then the unmitgated RF = 3.7/ln(2)*ln(750/280) = 5.25 W/m^2, and the conventional mitigation instead leads to a RF = 3.7/ln(2)*ln(500/280) = 3.1 W/m^2. So the net change in radiative forcing due to this mitigation effort is about 2.15 W/m^2. On this basis the cost of conventional mitigation is about $200 billion per year per W/m^2. Stern estimates 1% of global GDP per year, which is currently about $35 trillion (amounting to an annual cost of $350 billion per year), to stablise at 500 to 550 ppmv of CO_2 equivalent (http://www.occ.gov.uk/activities/stern_papers/faq.pdf). This gives a similar conventional mitigation cost of $150 to 200 billion per year per W/m^2.

(h) 'Termination effect' refers here to the consequences of a sudden halt or failure of the geoengineering system. For SRM approaches, which aim to offset increases in greenhouse gases by reductions in absorbed solar radiation, failure could lead to a relatively rapid warming which would be more difficult to adapt to than the climate change that would have occurred in the absence of geoengineering. SRM methods that produce the largest negative forcings, and which rely on advanced technology, are considered higher risks in this respect.

vegetated surfaces, which are variously estimated as offering reductions in radiative forcing of between 0.5 and 1.0 W/m^2, could make a useful contribution if sufficiently widespread take-up were stimulated. However, incentives for growing high-albedo plant varieties instead of those currently grown would have to be designed and implemented, and the unintended effects, including land use conflicts, of such incentives would have to be carefully researched before they could be considered for deployment.

Increasing the albedo of maritime cloud by increasing the number density of cloud-condensation nuclei would appear to be capable of achieving a radiative forcing of ~ -4 W/m^2. The principal implementation strategy being considered at present is seeding clouds with micro salt grains from seawater droplets dispersed from unmanned sea-going vessels. This approach should be compared with the costs and timescales of more conventional approaches using crewed ships or the direct release from aircraft of a suitable hydrophilic powder. Principal concerns are the potential impact on rainfall patterns over down-wind land areas and the possible adverse effects of local cooling on winds and ocean currents. These issues are currently being explored via computational simulations although current AOGCM codes may not be adequate for such relatively fine-scale effects. However, the approach may be useful in offering extra protection to particularly vulnerable regions like the Arctic. Conversely, applying a reduction in insolation in one hemisphere but not the other would be expected to shift the seasonal range of the inter-tropical convergence zone (ITCZ) and so modify monsoons, the potential consequences of which would need to be examined with extreme care.

Injection of sulphate aerosols into the stratosphere is the one area of SRM where experimental evidence (provided by volcanic eruptions) has shown the magnitude of the reduction in global temperatures that can be expected. There is not yet agreement on the best delivery mechanism, but the approach could, if necessary, be started on a timescale of a few years. However, even a preliminary exploration of the potential environmental impacts might take several years. The issues mainly concern undesirable side effects of which one is the impact on the ozone layer, while possible adverse impacts on precipitation patterns are also of considerable concern. To this should be added a range of feedback processes that may become important with a continually renewed stratospheric sulphate layer (as opposed to the transient effects from a volcanic eruption). Concerns have been expressed that deployment of stratospheric sulphates could lead to increased 'acid rain' and exacerbate ocean acidification. The quantities of sulphates added to the stratosphere would however be extremely small compared to both those of natural volcanic releases and the acidifying effect of CO_2 emissions and would therefore not directly cause any significant increase in the ocean acidification process.

While an interesting variety of spaced-based strategies has been proposed, methods advocating placement of a 'cloud' of deflectors (or reflectors) at the L1 point seem the most plausible (with deflectors carrying some type of position-control mechanism, both to stop them drifting away and, in an emergency, to disperse some or all of the cluster). However, the costs of setting in place such a space-based armada for the relatively short period that SRM geoengineering may be considered applicable (decades rather than centuries) would likely make it uncompetitive with other SRM approaches. As noted in Section 3.3.4, however, if the duration of application were to change to centuries, it seems possible that this may then offer an approach as cheap as any of the geoengineering alternatives. Moreover, unlike stratospheric aerosols and cloud brightening techniques, space-based approaches avoid releasing artificial materials into the atmosphere and the Earth's ecosystems (other than those generated by the launch and manufacturing activity involved).

3.5 Conclusion

The SRM methods may provide a useful tool for reducing global temperatures rapidly should the need arise. However, as greenhouse gas concentrations are not reduced by these methods, the application of any SRM method would carry with it the termination problem, and would not address ocean acidification or other CO_2 effects. The impact of SRM methods on climate is dependent on where in the atmosphere they are targeted, and their geographical location, and it should therefore not be assumed that a zero net global average radiative forcing means that there are no regional climate effects.

None of the methods assessed are yet ready for deployment, and all require significant research including in some cases, pilot scale trials, to establish their potential effectiveness and effects on climatic parameters including temperature and precipitation at both the global and regional scales.

Of the methods assessed the global techniques appear to be the safest methods for reducing global average temperature. The early stage of development of the various space based methods proposed, and their high R&D costs relative to the other global SRM methods mean that they are unlikely to be feasible in the medium term. Stratospheric aerosols therefore appear to be the most promising as they could be more rapidly developed and implemented than the space based methods. However, significant R&D would be required to identify and evaluate potential impacts on the hydrological cycle, stratospheric ozone and on the biosphere prior to deployment.

4 Governance

4.1 Introduction

Climate change is a field in which policy disagreements continually find their expression in surrogate disputes about science (Hulme 2009). Already, the politics of geoengineering are complex and contested, and the positions taken by scientists and other analysts may interweave policy preferences with technical judgements. Social evaluation of the technologies is further complicated by the wide variation in technical characteristics of the various options. Different options may therefore be favoured to achieve different policy objectives on different time scales.

Even where there is apparent agreement on scientific or cost issues, the judgements of experts often diverge. For example, air capture technology was recently dismissed on the basis that it would be unacceptably expensive at \$20 trillion per 50 ppm of carbon removed from the atmosphere (Hansen 2008). This translates into a carbon price of \$190 per tonne or \$52 per tonne of CO_2, which by 2030 would amount to about 1.5% cumulative global GDP (Pielke Jr 2008). However, this is not much greater than the 1% of GDP that the Stern Report (2007) regards as a necessary cost for society to pay for conventional mitigation in order to avoid costs of 5% or more of GDP associated with climate impacts. Even though the analogy between the air capture cost (itself highly uncertain) and the Stern calculation is not exact, this example nevertheless illustrates the risk of making premature judgments about comparative costs. Differences in professional and personal values may therefore play a significant role in the evaluation of geoengineering options relative to conventional mitigation and adaptation.

The very discussion of geoengineering is controversial in some quarters because of a concern that it may weaken conventional mitigation efforts, or be seen as a 'get out of jail free' card by policy makers (Submission: Greenpeace; Submission: IOP; Submission: Lewis-Brown). This is referred to as the 'moral hazard' argument, a term derived from insurance, and arises where a newly-insured party is more inclined to undertake risky behaviour than previously because compensation is available. In the context of geoengineering, the risk is that major efforts in geoengineering may lead to a reduction of effort in mitigation and/or adaptation because of a premature conviction that geoengineering has provided 'insurance' against climate change

These disagreements highlight possible barriers to researching geoengineering options, and to any moves towards deployment. Technical, legal, ethical, economic and other concerns need to be balanced carefully in a policy and governance framework which is international in scope and remains flexible in light of fresh evidence. This chapter introduces the key policy questions surrounding geoengineering that the international community needs to confront, and outlines initial steps toward addressing them.

4.2 Governance, risk and uncertainty

The central problem for the governance of geoengineering is that while potential problems can be identified with all geoengineering technologies, these can only be resolved through research, development and demonstration. This is the classic 'technology control dilemma' (Collingridge 1980). Ideally, appropriate safeguards would be put in place during the early stages of the development of any new technology. But anticipating in the early stages how a technology will evolve is difficult. By the time it is widely deployed, it is often too late to build in desirable characteristics without major disruptions. The control dilemma has led to calls for a moratorium on certain emerging technologies and, in some cases, on field experiments with geoengineering (Submission: ETC Group).

Recent moves under the Convention on Biological Diversity (CBD) to ban field trials with iron fertilisation, except in coastal waters, provide an example of this. An obvious drawback of a moratorium is that it inhibits research, in this case, research that has been ongoing for decades to inform marine ecology and other oceanographic studies. In the context of geoengineering, it would make it almost impossible to accumulate the information necessary to make informed judgements about the feasibility or acceptability of the proposed technology. Furthermore, it is likely to deter only those countries, firms and individuals who would be most likely to develop the technology in a responsible fashion, while failing to discourage potentially dangerous experimentation by less responsible parties. To overcome this problem, some commentators have suggested forming an international consortium to explore the safest and most effective options, while also building a community of responsible geoengineering researchers, along the lines of other international scientific collaborations, such as the European Organisation for Nuclear Research (CERN) and the Human Genome Project (Broecker & Kunzig 2009; Victor *et al.* 2009).

Other factors for consideration include the reversibility of society's commitment to a technology, and the ease of remediation if problems arise. Indicators of a technology's relative 'inflexibility' include: long lead times from idea to application; capital intensity; large scale of production units; major infrastructure requirements; closure or resistance to criticism; and hype about performance and benefits (RCEP 2008). As a general guide, the more of these factors that are present, the more caution should be exercised in committing to the adoption of a particular technology.

When analysing potential problems associated with geoengineering in relation to long-term climate change, the language of 'risk' is often used, implying some knowledge about both potential outcomes of geoengineering technologies and their probabilities. But so embryonic are geoengineering technologies that there is commonly little knowledge yet about the nature of (potentially unwanted) outcomes and still less knowledge of probabilities (Stirling 2008). This is a situation of 'indeterminacy' (or 'ignorance') rather than risk. Through research, and the accumulation of empirical evidence, uncertainties can sometimes be recast as risks and expressed as probabilities.

But the possibility remains that an unknown hazard may be revealed at a later time. One criticism of geoengineering proposals is that climate change is itself the unintended effect of the deployment of technologies once regarded as benign. Responding with further large-scale deployment of technologies may therefore simply exacerbate the problem. Advocates of this view invoke 'the law of unintended consequences' to suggest that the cure could be worse than the disease. So for example in the case of geoengineering, concerns have been raised regarding sulphate aerosols and whether they could have negative impacts on agriculture or precipitation patterns, and the risk of iron fertilisation methods causing dangerous algal blooms or disruption of marine ecosystems in ways that cannot be anticipated. Prudence suggests that technologies should be fully characterised for their potential negative environmental and social impacts prior to implementation. Yet it is impossible to know in advance the full range of possible consequences and so a precautionary approach to these, and other new technologies, may be appropriate (see Box 4.1). It is however important to place these concerns in the wider context of the impacts that are otherwise likely to occur under climate change and for relative risks and potential impacts to be compared.

The concepts of 'encapsulation' and 'reversibility' may be useful for characterising the risks and governance requirements for the different geoengineering methods.

Encapsulation refers to whether the method is modular and contained, such as is the case with air capture and space reflectors, or whether it involves material released into the wider environment, as is the case with sulphate aerosols or ocean fertilisation. Encapsulated technologies are sometimes viewed as more ethical in that they do not involve releasing 'foreign material' into the environment. This is not to suggest that encapsulated technologies may not have environmental impacts: depending on the nature, size and location of the application, there may be direct and indirect impacts, for example on habitat, landscape and/or species, or unintended consequences on other elements of the climate system. Furthermore, the application or effects of methods may have transboundary consequences, especially if such activities are located near the border with another State.

Reversibility refers to the ability to cease a technological programme and have its effects terminate in a short time. In principle, all of the options considered in this report could be abandoned. Air capture technologies could be switched off instantly and have no further climate effect. With other methods, for example sulphate aerosols or

Box 4.1 Reversibility and the precautionary approach

Reference to a precautionary approach, or principle, is contained in a number of soft law instruments (eg Rio Principle 15) and in treaty texts binding on the Parties (eg Art 3(1) London Protocol (LP); Art 3(3) UNFCCC). The former articulates the precautionary approach as requiring that, 'where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation'.

No single articulation of the precautionary principle or approach has emerged as a norm of customary international law. Articulations of the principle vary from instrument to instrument, as does the threshold of harm. For example, Rio Principle 15 and the UNFCCC require risk of 'serious or irreversible harm' before the principle is applicable, while marine environmental treaties such as the 1972 London Convention (LC) and 1996 LP do not. Nor does it necessarily place a burden of proof on the promoter of the harmful activity to prove that there is no risk of harm.

A precautionary approach may apply where, for example, the impacts of geoengineering on the environment are not yet fully known but believed potentially to be serious, if not irreversible; the response to ocean fertilisation experiments under the LC and CBD, discussed further in Box 4.3, is an example. However, the precautionary principle is not a 'one-stop shop' for decision-making. Although it 'helps to identify whether a legally significant risk exists by adding the role of scientific uncertainty, . . . it says nothing about how to control that risk, or about what level of risk is socially acceptable' (Birnie *et al.* 2009). These are wider policy questions to be addressed by society as a whole in deciding if to assume the risk, and how to manage it. As the experience of implementation of the Article 3 UNFCCC commitment to take precautionary measures shows, consensus on the appropriate action to be taken is often difficult to achieve.

However, the precautionary principle may impact on how treaties are interpreted and applied. And where its application is mandated by treaty, such as under the LC, then in this form and context it will be binding on the States party to that treaty. It also informs national environmental policy and law.

In the EU the European Commission has defined the precautionary principle in terms of risk management and recommends that decisions taken on the basis of the precautionary principle be proportionate, non-discriminatory, consistent with other similar measures, based on an assessment of costs and benefits, and subject to regular scientific review and risk assessment so as to identify and assess areas of scientific uncertainty (EC 2000).

ocean fertilisation, there may be a time lag after abandonment for the effects of methods to cease, if they have caused environmental changes. However, the issue of reversibility applies to more than just the ability to 'switch off' the technology. The solar radiation management (SRM) methods for example do not affect the greenhouse gases in the atmosphere and if efforts to remove CO_2 are not undertaken in parallel, the abandonment of such methods would result in a rapid temperature rise. And while there would be no immediate ill-effect from 'switching off' air capture technologies, any moves to abandon these technologies could meet strong resistance due to the investments made in construction and maintenance of the physical infrastructure; just as getting vested interests to abandon the use of fossil fuels is a challenge for conventional mitigation.

4.3 Ethics

Decisions to deliberately modify the Earth's climate undoubtedly raise a number of different ethical issues. To explore these, the Royal Society invited a panel of ethicists to consider three questions (Annex 8.3).

1. Would deliberate geoengineering be unethical and are some geoengineering techniques more ethically acceptable than others—if so, which and why?
2. Is a higher standard of proof or confidence needed for geoengineering interventions than for other mitigation actions?
3. What are the main ethical considerations that the design of a regulatory framework for geoengineering research or deployment would need to take into account?

Three main ethical positions were identified in relation to geoengineering, including:

- *consequentialist*, in which the value of outcomes is the predominant consideration;
- *deontological*, where the primary consideration is the issue of duty and 'right behaviour' (with less interest in outcomes);
- *virtue-based*, concerned primarily in this context with dilemmas of hubris and arrogance.

Common to all positions, though to varying degrees, were concerns of consequence, justice and the effects (of geoengineering) on agents.

The moral hazard argument has been important in earlier debates about geoengineering and is plausible. It directly parallels arguments made in earlier years to oppose adaptation policy (Pielke *et al*. 2007). However there is little empirical evidence to support or refute the moral hazard argument in relation to geoengineering, (although there has been little research in this area), and it is possible that geoengineering actions could galvanise people into demanding more effective mitigation action. Clarifying the existence or extent of any moral hazard associated with geoengineering should be part of the social science research agenda.

For reasons both of justice and the moral hazard argument, mitigation is likely to be preferable to geoengineering. However this does not necessarily rule out geoengineering, especially at the research stage, where a consequentialist case in favour can be made. Scientific momentum and technological and political 'lock-in' may increase the potential for research on a particular method to make subsequent deployment more likely, and for reversibility in practice to be difficult even when technically possible. These factors need to be taken into account when decisions are being made regarding which methods should be prioritised for research.

Many of the ethical issues associated with geoengineering are likely to be specific and technology-dependent. For example, small-scale, familiar, and reversible methods are likely to be preferable ethically to those that are inherently large-scale, irreversible and unencapsulated. This suggests that the engineered carbon dioxide removal (CDR) methods may be more ethically acceptable than SRM or ecosystem based methods.

It has been suggested that the standard of proof for predictability, reliability, and absence of adverse consequences should be set higher for geoengineering than for other research enterprises (Jamieson 1996). However the rationale for this is not completely clear and it could prove extremely restrictive. An alternative approach would be to focus research initially on methods for which small-scale, constrained experiments are feasible so as to help reduce areas of uncertainty and inform the development of risk management guidelines to enable larger scale research programmes where these seem ethically defensible.

As geoengineering methods, like climate change, will have global consequences, a flexible framework for international regulation is necessary. As explained in more detail in Section 4.4 and Box 4.2 the current geoengineering regulatory context is fragmented and uncertain. In general however, any future improvements to the regulatory context should be democratic, transparent and flexible enough to take account of the wide range of CDR and SRM methods, and should discourage unilateral action.

Overall it is clear that ethical considerations are central to decision-making in this field. However when evaluating the role that different approaches to geoengineering could play, it is not possible to make simple yes or no decisions on the basis of ethical reasoning. For example, if it could be shown empirically that the moral hazard issue was not serious, one of the main ethical objections to geoengineering would be removed.

4.4 International frameworks

The governance of geoengineering has significant international dimensions. For example, although injecting sulphate aerosols into the upper atmosphere is designed to limit global average temperature increases, the actual benefits and drawbacks of doing this are unlikely to be evenly distributed across regions. And there are inevitably concerns that the application of such technologies may exacerbate existing economic disparities between wealthy and less developed nations.

Some options, such as iron fertilisation and sulphate aerosols are likely to be affordable to a nation of modest means, or even to a very wealthy individual. Concern about the possibility of unilateral implementation has already been expressed by several commentators (eg, Victor 2008). Geoengineering may therefore become a threat to achieving global solidarity on other aspects of climate policy.

There are also issues of jurisdiction and who has control over the deployment of CDR and SRM technologies. Although the analogy is flawed, some commentators have asked 'Whose hand will be on the global thermostat?' (Robock *et al*. in press). At present international law provides a largely permissive framework for geoengineering activities under the jurisdiction and control of a particular state, so long as these activities are limited in their scope and effects to that state's territory. However, further obligations for environmental protection (ie, air pollution control, or species and habitat conservation) may apply depending on the nature, size and location of such activities.

Geoengineering projects that deliberately change the physical or biogeochemical properties of the atmosphere or the ocean clearly require some level of consensus among governments about the appropriate arrangements for managing and monitoring their implementation. It is however likely that many issues of international coordination and control could be resolved through the

Box 4.2 International law and geoengineering

In addition to the potential application of a range of treaty instruments to geoengineering, there are a number of customary law and general principles which might apply to such activities. The duty not to cause significant transboundary harm is recognised in many treaty instruments (CBD, UNFCCC, UN Law of the Sea Convention (UNCLOS), UN Convention to Combat Desertification (UNCCD)) (Submission: Environmental Defenders Office). States are not permitted to conduct or permit activities within their territory, or in common spaces such as the high seas and outer space, without regard to the interests of other states or for the protection of the global environment. This has the twin prongs of imposing on states the duty to prevent, reduce and control transboundary pollution and environmental harm resulting from activities within their jurisdiction and control; and the duty to cooperate in mitigating transboundary environmental risks and emergencies, through notification, consultation, negotiation and, in appropriate cases, environmental impact assessment (Birnie *et al.* 2009).

This principle does not amount to a prohibition on activities that create a risk of transboundary harm, provided these obligations are observed. In the absence of express prohibition. States are required to exercise due diligence in regulating activities under their jurisdiction and control. Where the activities in question have transboundary implications, or take place beyond national jurisdiction (as would be the case for ocean fertilisation on the high seas and space-based techniques for reducing solar radiation) international cooperation for their regulation will be necessary.

For ocean space, there is the global 1982 UNCLOS, which has widespread participation, and although some States (eg the US) have yet to ratify it, many of its provisions are now reflected in customary international law. UNCLOS applies to all ocean space from territorial waters seawards of baselines out to the high seas. It imposes on States a general obligation to protect and preserve the marine environment, which goes beyond the specific obligations it contains to prevent, reduce and control pollution.

There is no global instrument comparable to the UNCLOS that governs the atmosphere. States have sovereignty over the air space above their territory (and territorial sea) upwards to where outer space commences, although the precise point where this limit is reached is not entirely settled as a matter of law. The injection of aerosols is subject to the jurisdiction and control of the sovereign whose air space it is injected into. Countries must regulate such activities to ensure that transboundary harm is not caused. In addition, regional agreements govern air pollution, such as the 1979 Long-range Transboundary Air Pollution Convention (CLRTAP), which includes a number of protocols on the control and reduction of certain pollutants in the atmosphere, including sulphur emissions. In addition, if one of the effects of stratospheric aerosols is to increase ozone depletion, its injection could constitute a breach of the 1985 Convention for the Protection of the Ozone Layer.

Beyond the atmosphere, the 1967 Outer Space Treaty (OST) preserves outer space for peaceful uses, but does not establish a robust governance structure. States are required to subject the use of outer space to a regime of authorisation and supervision; if an activity or experiment planned in outer space could potentially cause harmful interference with the peaceful exploration and use of outer space, 'consultation' may be requested. The utilisation of dust particles from the moon (and/or other celestial objects in the solar system) would also be governed by the 1979 Moon Treaty. This treaty recognises the freedom of scientific investigation and proclaims the moon and its resources the 'common heritage of mankind'.

application, modification and extension of existing treaties and institutions governing the atmosphere, the ocean, space, and national territories, rather than by the creation of specific new international institutions.

For all geoengineering proposals, some of the provisions of the 1992 UNFCCC and 1997 Kyoto Protocol (KP) will apply, such as the general obligation to 'use appropriate methods, eg. impact assessment . . . with a view to minimising adverse effects on . . . the quality of the environment of projects or measures undertaken to mitigate or adapt to climate change'. The UNFCCC and KP create a significant institutional structure for international governance of the climate regime, and the climate change secretariat already cooperates with the other Rio Conventions (the CBD and UNCCD) on mutually supportive activities, suggesting a possible role for such linkages and common approaches.

A question for all CDR methods is whether they will be eligible for certification under the KP (or its successor instrument), under the clean development mechanism (CDM) or joint implementation (JI). Discussion by the CDM Executive Board about CCS and its eligibility under the CDM has been ongoing since 2005 and illustrates the methodological difficulties related to project boundaries, monitoring and remediation. While the carbon removed and sequestered through air capture would be very straightforward to measure directly, measurement problems are more serious for more diffuse techniques such as ocean fertilisation, where problems of verification and ownership of any carbon credits would complicate the situation. There is also no general accounting for greenhouse gases such as CO_2 stored in the oceans, as these fall outside the present IPCC reporting guidelines, making periodic monitoring and verification difficult to ensure.

4.5 Governance of geoengineering research and development

Even before the world needs to face these issues in regard to deployment, whether on land, at sea, or in space, the question of control over geoengineering research and experimentation needs to be resolved. Research and development into the most promising methods identified in Chapters 2 and 3 will be required to enable informed decisions to be made regarding whether they should ever be implemented, and if so, under what conditions. However, objections to deliberate manipulation of natural systems may in some cases also extend to undertaking research (especially field trials). In some cases (eg sulphate aerosols) it is not clear that field trials can usefully be conducted on a limited scale, or without appreciable and widespread environmental impacts.

There is a clear need for governance of research involving large-scale field testing of some geoengineering techniques, especially SRM and ecosystem intervention methods, which could have significant undesirable effects, and which might not easily be confined to a specific area. Given the uncertainties surrounding scientific knowledge of geoengineering activities and their effects, a precautionary approach may be adopted. Possible responses range across a continuum of prohibition to permission.

For ocean fertilisation for example, a cautious approach to permitting carefully controlled legitimate scientific research to proceed has been adopted under the LC and LP. In 2008, the Parties to the LC and LP, adopted a resolution agreeing that ocean fertilisation is governed by the treaty, but that legitimate scientific research is exempted from its definition of dumping. However, pending the drafting of an assessment framework to be developed by the Scientific Groups under the LC and Protocol, States are urged to use the 'utmost caution and best available guidance' when considering scientific research proposals (see Box 4.3). In addition, the resolution sets down a marker that ocean fertilisation activities apart from legitimate scientific research 'should not be allowed', are not exempted from the definition of dumping, and 'should be considered as contrary to the aims of the Convention and Protocol'. The resolution is to be reviewed in the light of any new scientific knowledge and information.

The parties to the CBD debated adopting a moratorium on all ocean fertilisation activities[13] but ultimately followed the LC approach. States are urged to ensure that ocean fertilisation activities do not take place until there is an adequate scientific basis on which to justify such activities *and* a 'global transparent and effective control and regulatory mechanism is in place for these activities'. An exception is made for small-scale research studies within 'coastal waters' for scientific purposes, without generation or selling of carbon offsets or for any other commercial purposes.[14] Given that 'coastal waters' is ambiguous, and that small-scale near-shore studies are meaningless for ocean fertilisation field trials (see Section 2.3.1), the negative impact that this step could have on scientific research led to a swift response by the Intergovernmental Oceanographic Commission's Ad Hoc Consultative Group on Ocean Fertilisation, which drew attention both to the need for clarification of the language of the CBD decision and challenging the scientific assumptions underpinning it.

Beyond identification of the applicable legal principles lie questions of implementation and enforcement. International law recognises the responsibility of states for breach of their international obligations, but the problems of enforcement in relation to transboundary harm are numerous. And international law does not directly address the liability of private actors who are most likely to have been the direct agent of the harm. For some activities under the territorial jurisdiction of States, such as air capture and surface albedo enhancement, issues of liability will largely be for domestic law to determine. At this point it is not clear whether liability for damage caused by

13 A proposal included in bracketed text in SBTTA Decision XIII/6 and supported, inter alia, by the EU, Norway, Venezuela and the Philippines.
14 Convention on Biological Diversity Conference of the Parties (COP) 9 Decision IX/16 2008.

Box 4.3 Ocean fertilisation research under the 1972 London Convention

The assessment framework to be developed by the Scientific Groups under the LC and LP will provide the parameters for assessing whether a proposed ocean fertilisation activity is 'legitimate scientific research' consistent with the aims of the Convention. Until this guidance is available, Contracting Parties are to use 'the utmost caution and the best available guidance' in evaluating scientific research proposals to ensure protection of the marine environment consistent with the Convention and Protocol.[15] The 'best available guidance' includes previous agreements of the parties, certain annexes of the Convention and Protocols, previous work by the Scientific Groups (including the Working Group on Ocean Fertilisation), and existing generic waste assessment guidance. Considerations might include:

- What will be added and where? Characteristics and composition of (a) the matter and (b) the water column where the matter will be placed, including detailed description and characterisation of their chemical, physical and biological properties, toxicity, persistence, and accumulative and biotransformative effects.
- Assessment of how the material will be added, in particular: (a) Form (eg solid, particle size, liquid solution (concentration)); (b) mode of application; (c) area and depth of addition; and (d) rate of application (amount per metre^2/time).
- Assessment of potential effects on the marine environment including their nature, temporal and spatial scales and duration of the expected impacts based on 'reasonably conservative assumptions'.
- Monitoring that is appropriate to the scale of experiment, the data from which should be made publicly available as soon as possible, and with the impact hypotheses forming the basis of the monitoring.
- Contribution to scientific knowledge and the likelihood of the activity achieving its stated purpose (though where the purpose is to mitigate climate change, this goes beyond the LC and may involve cooperation with other fora, eg the UNFCCC).

geoengineering beyond national jurisdiction is best resolved through new or existing mechanisms.

4.6 Public and civil society engagement

Geoengineering research that may impact the environment, or any moves towards potential deployment, should not proceed in the absence of a wider dialogue between scientists, policymakers, the public and civil society groups. The consequences of geoengineering—known and unknown, intended and unintended—would be felt by people and communities across the world. As with other emerging technologies, public participation in the development of research, governance and policy frameworks will be critical (Wilsdon & Willis 2004; RCEP 2008).

After decades of environmental policy efforts directed towards removing pollutants from air and water, the public is likely to be concerned about the unintended impacts of deliberate large-scale releases of sulphates into the atmosphere or nutrients into the oceans. Given the precedent of public disquiet over the environmental release of genetically modified crops, it is possible that similar actions could be taken against geoengineering projects. Just as field trials of genetically modified crops were disrupted by some NGOs, it is foreseeable that similar actions might be aimed at geoengineering experiments involving the deliberate release of sulphate or iron (for example) into the air and oceans.

One response to this concern would be simply to gather intelligence on public perceptions of geoengineering options, in the hope of averting a backlash. But diverse publics and civil society groups could play a much more positive and substantive role in the development of the field, by contributing to analysis of the social, ethical and equity basis of geoengineering proposals. They also have a legitimate right to access and influence the policy process on a topic of considerable public interest.

However, the full potential of any public engagement will not be realised if it is motivated primarily by a desire by advocates to secure public consent to geoengineering. Rather, as the Royal Commission in Environmental Pollution has argued, we need 'to recognise the importance of continual 'social intelligence' gathering and the provision of ongoing opportunities for public and expert reflection and debate ... if, as a society, we are to proceed to develop new technologies in the face of many unknowns' (RCEP 2008).

Experience with other similar issues indicates that public perceptions of geoengineering are likely to be dominated by the risk of something going wrong, and it appears that other important factors involved are whether the methods proposed involve:

- contained engineered systems, or the manipulation of the natural environment and ecosystems;
- intervention only in physical and chemical processes, or in biological processes and systems;

15 Resolution LC-LP.1 (2008), paras.4-7.

- activities (and/or substances) which are localised (intensive), or are widely distributed or dispersed (extensive);
- effects which are primarily local/regional, or which are of global extent;
- 'big science' and centralised control, or small-scale activity and local control;
- processes which are perceived as familiar, or novel and unfamiliar (see also Box 4.4).

Some geoengineering options (such as reflectors in space) have provoked public concern about potential militarisation (Robock *et al*. in press). To some extent, these concerns have already been addressed in international law through the 1977 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), UNCLOS, and the 1967 OST.

Other concerns have been expressed about the desirability of commercial involvement in the development and promotion of geoengineering. There are already a number

Box 4.4 Geoengineering and public engagement

A preliminary investigation of public perceptions and attitudes towards geoengineering technologies was undertaken as part of this study. Four public focus groups were convened by British Market Research Bureau (BMRB) to discuss attitudes to climate change, climate technologies, climate politics and the possibilities of geoengineering. The groups were broadly stratified by environmental beliefs and behaviours, ranging from 'positive greens', holding the most pro-environmental attitudes and beliefs, to 'honestly disengaged', people who are dubious about the environmental threat from climate change and less likely to see a link to their own behaviour.

The groups discussed what they thought caused climate change, how it had changed their behaviours, if at all, and who they felt was responsible for dealing with it. Several geoengineering technologies were then introduced: stratospheric aerosols, ocean iron fertilisation and CO_2 capture from air. The groups discussed the different technologies and possible benefits, risks and uncertainties of geoengineering.

Even this very limited and preliminary exercise in public engagement demonstrated a wide range of opinion on the acceptability or otherwise of deliberate intervention in the climate system. Perception of geoengineering techniques was generally negative, but multi-faceted and method-specific. Some people perceive ethical objections to geoengineering in principle; others do not.

Aspects which are especially likely to underpin perceptions include:

- transparency of actions, motivations and purpose;
- lack of vested commercial and other interests driving research or deployment;
- demonstrable concern and responsibility for environmental impacts.

There may be a big difference in public attitudes to engineered CDR methods compared with those to SRM and ecosystem-based CDR methods, reflecting their different technical attributes and the ethical issues that they raise. This range of public opinion needs to be further explored, so that policy makers can decide whether and in what way these opinions should inform their decisions.

The focus groups provided some tentative evidence that, rather than presenting a 'moral hazard' issue, the prospect of geoengineering could galvanise people to act, and demand action, on greenhouse gas emission reductions. Although participants were generally cautious, or even hostile, towards geoengineering proposals, several agreed that they would actually be more motivated to undertake mitigation actions themselves (such as reducing energy consumption) if they saw government and industry investing in geoengineering research or deployment. It was noteworthy that this reaction was most pronounced in the some of the more 'climate-sceptical' participants. There was also a general concern that geoengineering was not the right focus for action, and that low carbon technologies should be developed rather than climate intervention methods.

In addition to the focus groups, BMRB conducted some public polling on attitudes to geoengineering. A nationally representative sample of 1,000 adults aged 16+ across Great Britain took part in a short telephone survey. It would be wrong to place too much emphasis on what was a preliminary polling exercise but the results showed mixed support for ocean fertilisation, with 39% for, and 34% against, considering it to address climate change. There was a more negative perception of stratospheric aerosols, with 47% of respondents disagreeing that this should be considered for use, compared to 22% in favour.

These results indicate that further and more thorough investigations of public attitudes, concerns and uncertainties over geoengineering should be carried out in parallel with technological R&D, and accompanied by appropriate educational and knowledge exchange activities, to enable better informed debate and policy making.

of start-up companies active in engineered CDR and ocean fertilisation. This may be positive, as it mobilises innovation and capital, which could lead to the development of more effective and less costly technology at a faster rate than in the public sector. On the other hand, commercial involvement could bypass or neglect the socio-economic, environmental and regulatory dimensions of geoengineering. Commercial activities have so far been concentrated on CDR methods, where there is clear potential for future earnings through carbon trading mechanisms. For SRM methods, a clear financial incentive does not yet exist, although there may be future income opportunities from publicly funded deployment (especially of proprietary technology). A sufficiently high carbon price, credits for sequestration, and financial support for reduced radiative forcing would be necessary to stimulate greater entrepreneurial activity in developing geoengineering technology. It is not yet clear if this would be desirable.

4.7 Economic factors

Economists have already started to try to model optimal, least-cost paths to geoengineering development and even to develop comparisons with mitigation in a common framework. These attempts are of scientific interest but are of limited practical or policy value. This is partly because the present lack of knowledge about geoengineering costs and risks means that the outputs of any cost modelling are determined by uncertain input assumptions. Also, quite apart from the limited capacity of simple economically focussed cost-benefit climate impacts assessment models to provide policy-relevant results, analyses of whether to do either geoengineering or emissions mitigation are inappropriate. A more relevant question is what combination of mitigation and geoengineering might be desirable? There is therefore significant potential for further economic research to contribute to policy decisions about geoengineering.

Costs

According to Stern (2007) the costs of conventional mitigation are likely to be of the order of 1 or 2% of global GDP (currently ~$70 trillion per year), that is about $1 trillion per year, to avoid current emissions, which are approaching 10 GtC/yr. This corresponds to a carbon price of around $100 per tonne of carbon (equivalent to ~$27 per tonne of CO_2). To be affordable, the costs of SRM methods to offset a doubling of CO_2 would need to be in the order of $1 trillion per year. Similarly the costs of CDR methods would need to be comparable to mitigation costs of $100 per tonne of carbon.

Establishing accurate cost estimates for geoengineering technologies is however an inherently difficult process, and only extremely tentative estimates are available for most of the methods considered. There are two reasons for this uncertainty. The first is that there is genuine technical uncertainty about all the geoengineering options covered in this report, as little serious research and development has yet been carried out, let alone commercial scale demonstration. The second is that there are systematic biases towards under-estimating the costs of novel projects and technologies of these kinds (Merrow *et al.* 1979; Bacon *et al.* 1996; Flyvjberg *et al.* 2003).

These biases towards what the UK Treasury calls ‘appraisal optimism’ arise from relatively straightforward political and economic factors. Those players who stand to gain most from the approval of large, new and risky projects are rarely those who stand to lose if the costs of those projects turn out to be far higher than forecast, or the benefits far lower. This creates a powerful incentive for advocates of new projects to underplay the risks and costs.

In addition, cost-benefit comparisons between geoengineering and mitigation options need to be handled with care. For many mitigation options, there is substantial commercial-scale experience and estimates will usually be based on solid empirical evidence. Attempts to establish the relative cheapness of geoengineering should therefore be treated with caution.

Financing

The tendency towards appraisal optimism usually extends to estimates of R&D costs. However, when measured against current international expenditure on energy or mitigation R&D, it is likely that a relatively modest investment in geoengineering research would enable substantial progress to be made. Already there are moves underway to support international collaborative research, within Europe, the United States and across the G8. At this early stage in the development of the field, government and public sources can reasonably be expected to bear many of the costs.

The economic attractiveness of CDR activities clearly improves if there is a well-established international valuation and trading system for carbon. Views on the merits of carbon trading vary widely and it is easy to place excessive reliance on emissions trading as a policy instrument. However other systems of carbon valuation are also plausible within the next few years, including a carbon tax, or more likely, international agreement within a carbon trading system to establish a stable minimum carbon price.

Should such a minimum value of carbon be established, the economic attractiveness of CDR methods (as well as mitigation) R&D would be much improved. However it is important to stress that the absolute cost of geoengineering R&D, even on a national UK basis, is unlikely to be a critical constraint, provided that political approval and sufficient public support for such R&D is forthcoming.

4.8 Option of last resort?

Even vocal advocates of geoengineering are mostly somewhat reluctant champions. It is usually presented as an insurance policy against the possible failure of conventional mitigation policies; an option of last resort

Submission: Evans; Submission: IOP). This raises the obvious question of who decides when the point of last resort has been reached and how such a decision should be made? Different political ideologies, theories of government and of international relations give very different answers to these questions.

The view of geoengineering as an option of last resort overlooks the possibility that some options may offer the possibility of stabilising atmospheric carbon concentrations at lower costs than some forms of conventional mitigation. The question then is why they should only be implemented in extreme circumstances?

From the standpoint of carbon removal, there seems to be no reason to regard direct air capture technologies as inherently inferior to biological methods (afforestation), especially where they could be located in desert or arid environments, powered by solar energy, and placed close to spent oil and gas wells suitable for sequestration (eg in the Middle East). Similarly, if a rigorous programme of research was to show that adding calcium (as chalk or lime) to sea water increases ocean uptake of carbon and counteracts ocean acidification, at an acceptable cost, and without negative consequences for biodiversity, this might then be regarded as an attractive way to reduce CO_2 concentrations. Assuming that acceptable standards for effectiveness, safety, public acceptance and cost were established, why should appropriate geoengineering options not be added to the portfolio of options that society will need and may wish to use to combat the challenges posed by climate change?

SRM methods should however be treated with caution as they create an artificial and only approximate balance between greenhouse warming and reduced solar radiation which must be maintained actively, potentially for many centuries. Given that they do not reduce greenhouse gas concentrations, SRM methods are widely regarded only as options of last resort, and they should not be deployed without a clear and credible exit strategy, involving strong mitigation policies and (perhaps) the use of CDR methods which are sustainable.

4.9 Conclusion

There appear to be three distinct perspectives on the potential role for geoengineering:

1. that it is a route for buying back some of the time lost in the international mitigation negotiations;
2. that it represents a dangerous manipulation of Earth systems and may be intrinsically unethical;
3. that it is strictly an insurance policy against major mitigation failure.

There is often an assumption that geoengineering represents a moral hazard, and could undermine popular and political support for mitigation or adaptation. Although this prospect should be taken seriously, there is as yet little empirical evidence on whether the prospect of climate intervention galvanises or undermines efforts to reduce emissions. The moral hazard argument requires further investigation to establish how important an issue this should be for decision makers. Because of the possibilities that geoengineering could have unintended and undesirable environmental or social effects, priority could be given to forms of CDR geoengineering research that are encapsulated and reversible. When considering the issue of reversibility, the potential for social and economic 'lock-in' to such technologies should also be taken into consideration.

A variety of ethical positions on geoengineering research and deployment are possible. Utilitarian traditions, which emphasise consequences, will probably tend towards a more favourable view, while deontological traditions, which emphasise morally-right behaviour, tend towards greater scepticism.

Because the technologies involved in geoengineering are at such an early stage of development, and uncertainties are pervasive, conventional economic approaches to cost-benefit analysis will likely give misleading results. The history of projects with similar characteristics suggests that cost estimates in such a state of uncertainty will almost certainly be highly optimistic. Moreover, the costs to develop and eventually deploy geoengineering technologies may not prove to be a major factor in determining which (if any) of them is ever actually deployed, as the costs of the impacts that they seek to avoid are themselves likely to be very large.

Geoengineering, like other emerging areas of technology, requires flexible frameworks of governance and regulation, which can be adapted in light of fresh evidence and analysis. The legal landscape is both fragmented and uncertain and relevant controls necessarily span domestic, regional and international law. While no single international instrument applies, there are a number of existing treaties and customary rules which could be brought to bear, depending on where the activity and its effects occur. However, many of the questions and uncertainties over geoengineering extend beyond the realm of economic assessments, regulation or risk management, to encompass broader questions about direction, ownership and control. Research into ethical, legal and social issues associated with both research into geoengineering and the implications of implementing geoengineering options will require some targeted funding from governments and, in the UK, from the Research Councils, alongside larger-scale investments in the scientific and technical aspects of geoengineering. Scientists and policymakers also need to find meaningful ways of engaging diverse publics and civil society in debates over geoengineering and in the development of governance frameworks.

5 Discussion

5.1 Geoengineering methods and their properties

The IPCC (2007c) concluded that geoengineering proposals are 'largely speculative and unproven, and with the risk of unknown side-effects'. However, a very wide range of potential geoengineering methods has been proposed, which vary greatly in their technical aspects, scope in space and time, potential environmental impacts, timescales of operation, and the governance and legal issues that they pose. It is therefore unhelpful to lump them all together, and there are rather few general statements about them that can usefully be made. A more useful approach is to classify methods according to whether they directly reduce CO_2 concentrations (carbon dioxide removal—CDR) or operate directly on the radiative fluxes in the Earth's energy balance (solar radiation management—SRM). On this basis a more detailed comparative analysis of the merits and deficiencies of various techniques is presented here.

5.1.1 The two classes of geoengineering methods

CDR methods operate on the atmospheric stock of CO_2, and require the draw-down of a significant fraction of this before affecting the energy balance. Whilst CDR methods therefore immediately augment efforts to reduce emissions, there is inevitably a delay of several decades before they would actually have a discernable effect on climate, even if it were possible to implement them immediately. The global-scale effect of CO_2 removal would be essentially the same as that of emissions reduction, except that if deployed on a large enough scale, it would also potentially allow global total net emissions to be made negative, therefore enabling (at least in principle) a return to lower concentrations on timescales of centuries rather than millennia.

By contrast, SRM methods operate directly on the radiative fluxes involved in the Earth's energy balance, and so take effect relatively rapidly (although not immediately as the large thermal capacity of the ocean will slow the temperature response). SRM methods are the only way in which global temperatures could be reduced at short notice, should this become necessary. Careful attention should therefore be paid to the timescales (lead-times, response times and potential durations) of CDR and SRM methods, so that their implementation could (if needed) be effectively phased, under different scenarios of climate change, and alongside other abatement strategies.

As discussed in Chapter 4, whether methods are engineered technological interventions (eg, air capture or white roofs), or manipulate or enhance natural processes by adding biological or chemical materials to the environment (eg, ocean fertilisation or stratospheric aerosols) is also an important distinction when assessing the relative feasibility of the different methods. Engineered technologies are generally perceived to be contained and therefore to present a lower environmental risk than ecosystem based methods, which tend to involve the release of material into the environment. Furthermore, the spatial scale over which geoengineering methods are applied, or have effect (ie, are localised or extensive), and their familiarity or degree of novelty are important considerations as they may influence the public acceptability of these methods (see Chapter 4).

5.2 Criteria and methods for evaluation

As geoengineering is an emerging issue, until recently there has been little discussion of the relative merits of alternative methods, or appropriate criteria by which techniques should be assessed. The objective of both SRM and CDR methods is to intervene in the Earth's climate system, so assessment methods and criteria must include relevant scientific and technological aspects. While there are deficiencies with existing climate models (see Box 1.2) both the intended effects and the foreseeable environmental impacts of all methods should be evaluated in an Earth system context using state-of-the-art Earth system models and existing climate models that are sufficiently holistic (eg include an adequate representation of all known relevant physical, ecological and biogeochemical processes) and are adequately resolved, in both space and time, to capture the dominant features and processes of interest. Such model studies should also inform any large-scale financial investment into technological development.

Like all major potential industrial-scale developments, geoengineering methods should in principle be evaluated on a full life-cycle basis (McDonough & Braungart 2002), especially since some of them may involve substantial inputs of energy and materials. In addition CDR techniques should of course result in overall negative emissions when the full life-cycle is taken into account. Unfortunately the information available is insufficient for these ideals to be realised at present. However, the internationally approved standards for Life cycle assessments (LCA),[16] could in future be used as the basis for such analyses of geoengineering methods.

Ideally geoengineering methods should be assessed against a wide range of both technical and non-technological criteria, as discussed in Chapters 1 and 4. However, in this report, because of the preliminary nature of almost all of the information available, the methods assessed in Chapters 2 and 3 were evaluated only against four primary technical criteria (refer to Section 1.5).

Non technological issues will also be important determinants of the feasibility of geoengineering methods

[16] See ISO 14040 & ISO 14044.

and although a detailed assessment against social, political and legal criteria was beyond the scope of this report, the analysis in Chapter 4 emphasises the need for future assessments to explicitly take account of relevant issues (on which perceptions may also change over time) such as public acceptability, political feasibility, ethical aspects, equity, legality, and aesthetics.

5.3 Overall evaluation

So far as is possible given the information available, the various methods of geoengineering have been considered and evaluated in terms of their ability to moderate or reverse the increase in global mean temperature. The different characteristics of SRM and CDR methods however mean that, while this is the primary metric, it must be applied differently to the two classes of methods. For SRM methods, this metric is closely related via the climate sensitivity to the radiative forcing attainable. For CDR methods however, the obvious metric is mass of CO_2 removed, and for the purposes of comparison with SRM this must be translated into temperature or radiative forcing. The relationship however actually depends on the CO_2 concentration level and the time schedule of emissions and removals, and the effect is not instantaneous. This is discussed by Lenton & Vaughan (2009) who suggest that 1000 GtC is broadly equivalent in the long term to 1.5 W/m^2 of radiative forcing. However, the IPCC (2007a) estimates that the radiative forcing in 2005 due to CO_2 was about 1.6 W/m^2 resulting from total CO_2 emissions of about 460 GtC up to 2005. In this report, the comparisons assume where necessary that removal of 300 GtC (achieved over a century or so) broadly equates to 1 W/m^2 of radiative forcing.

Given the present incomplete state of knowledge, any evaluation including that presented below is inevitably still somewhat subjective, and the criteria are therefore only judged on a fairly coarse semi-quantitative scale, as follows.

Numerical rating	General evaluation	Positive attributes	Negative attributes
5	Very good	Very large	Very small
4	Good	Large	Small
3	Fair	Medium	Medium
2	Poor	Small	Large
1	Very poor	Very small	Very large

No attempt has been made to reduce this multi-criterion evaluation to determine a single overall "winner" because these criteria are incommensurable, and any such synthesis or selection process must involve explicit consideration of the trade-offs between them. As discussed in Chapter 4, the reduction of such an evaluation to a simple cost-benefit analysis in order to seek a single 'optimum' solution by mechanistic means is not advised.

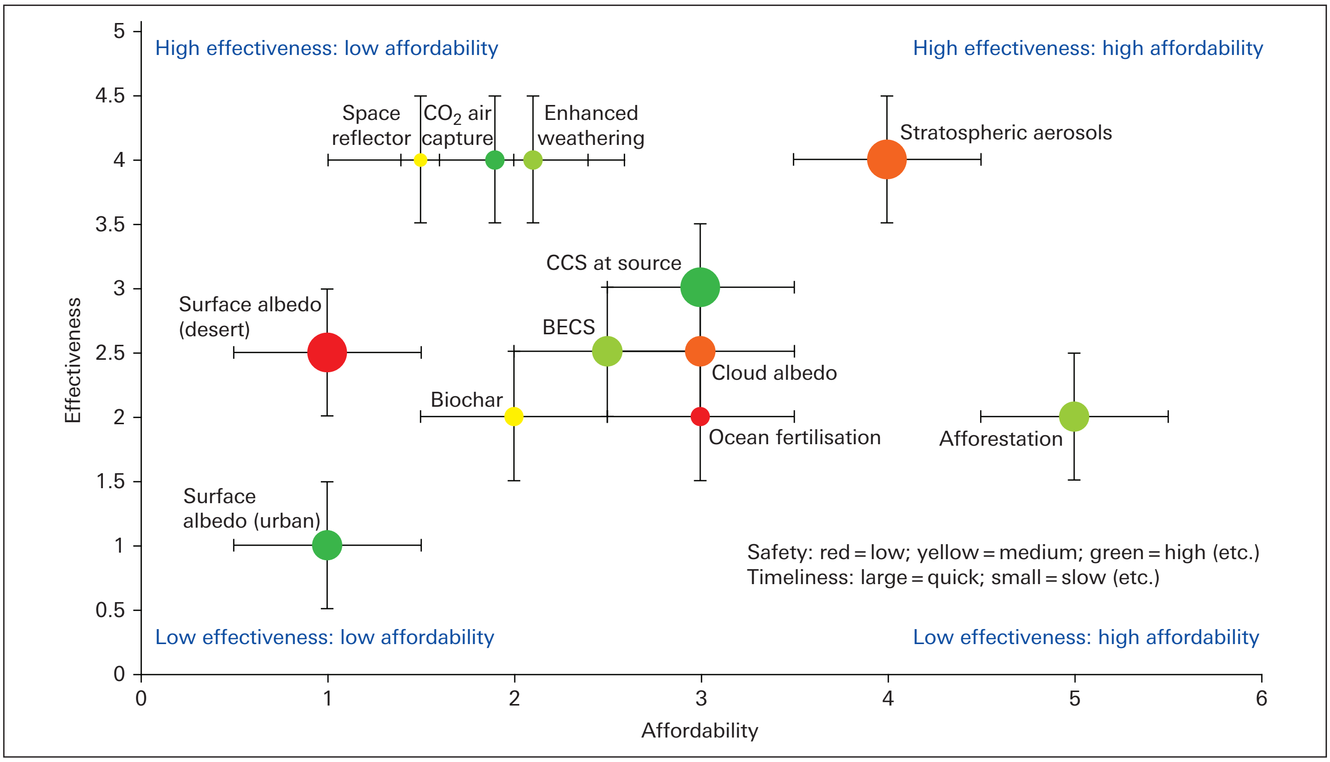
On the basis of this information, a provisional overall evaluation based on the summary tables for the different methods provided in Chapters 2 and 3 is presented in Table 5.1 and Figure 5.1 below (in two cases the entries have been adjusted minimally to avoid confusion caused by over-plotting of the symbols).

For comparative purposes only, a judgement of where certain other mitigation methods not considered in detail in this report (Afforestation, CCS at source, and BECS) would fit in this evaluation has also been made, and the results

Table 5.1. Summary of ratings accorded to the methods assessed in Chapters 2 and 3.

Method	Effectiveness	Affordability	Timeliness	Safety
Afforestation	2	5	3	4
BECS	2.5	2.5	3	4
Biochar	2	2	2	3
Enhanced weathering	4	2.1	2	4
CO_2 air capture	4	1.9	2	5
Ocean fertilisation	2	3	1.5	1
Surface albedo (urban)	1	1	3	5
Surface albedo (desert)	2.5	1	4	1
Cloud albedo	2.5	3	3	2
Stratospheric aerosols	4	4	4	2
Space reflectors	4	1.5	1	3
CCS at source	3	3	4	5

Figure 5.1. Preliminary overall evaluation of the geoengineering techniques considered in Chapters 2 and 3.



included. The results of this exercise are illustrated in Figure 5.1. The effectiveness of the methods is plotted against their affordability (the inverse of the cost for a defined magnitude of effect), with the size of the points indicating their timeliness (on a scale of large if they are rapidly implementable and effective, through to small if not), and the colour of the points indicating their safety (on a scale from green if safe, through to red if not). Indicative error bars have been added to avoid any suggestion that the size of the symbols reflects their precision (but note that the error bars are not really as large as they should be, just to avoid confusing the diagram). This diagram is tentative and approximate and should be treated as no more than a preliminary and somewhat illustrative attempt at visualising the results of the sort of multi-criterion evaluation that is needed. It may serve as a prototype for future analyses when more and better information becomes available. However, even this preliminary visual presentation may already be useful, simply because an ideal method would appear as a large green symbol in the top right-hand quadrant of the figure, and no such symbol exists. The nearest approximation is for stratospheric aerosols, which is coloured amber, because of uncertainties over its side-effects, as discussed in Section 3.3.3.

5.3.1 Analysis of technical feasibility and risks of different methods

Geoengineering by CDR methods is technically feasible but slow-acting and relatively expensive. The direct costs and local risks of particular methods would differ considerably from each other but could be comparable to (or greater than) those of conventional mitigation; in particular there would be major differences between contained engineered methods and those involving environmental modification. The technologies for removing CO_2 and many of their consequences are very different from those of technologies for modifying albedo. While CDR methods act very slowly, by reducing CO_2 concentrations they deal with the root cause of climate change and its consequences.

The most desirable CDR techniques are those that remove carbon from the atmosphere without perturbing other Earth system processes, and without deleterious land-use change requirements. Engineered air capture and enhanced weathering techniques would be very desirable tools if they can be done affordably, without unacceptable local impacts. Both warrant further research to establish how much carbon they can remove, at what cost.

CDR techniques that sequester carbon but have land-use implications (such as biochar and soil-based enhanced weathering) may make a useful contribution, but this may only be on a small scale, and research is required to find out the circumstances under which they would be economically viable and socially and ecologically sustainable. Techniques that intervene directly in Earth systems (such as ocean fertilisation) would require much more research to determine whether they can sequester carbon affordably and reliably, without incurring unacceptable side effects.

Implementation of SRM methods is also likely to be technically feasible at a direct financial cost of implementation that is small compared to the costs of the impacts of foreseeable climate change, or of the emissions reductions otherwise needed to avoid them. However, as explained in Chapter 4 such comparisons should be undertaken with caution until better information is available on the costs involved in SRM development and implementation. The additional indirect costs associated with the effects of SRM cannot reliably be estimated at present but would need to be considered, and could be significant.

SRM methods, if widely deployed, could achieve rapid reductions in global temperatures (over a few years to a decade) at a rate and to a level that could not be achieved by mitigation, even if carbon emissions were reduced to zero instantly. However, all SRM methods suffer from the termination problem, and modelling studies indicate that the resulting climate would not be the same as the climate that would be achieved if CO_2 concentrations were reduced. For example, with a uniform reduction of solar radiation, tropical precipitation would probably be reduced. Studies show that it is not generally possible to accurately cancel more than one aspect of climate change at the same time, but there are serious deficiencies in the ability of current models to estimate features such as precipitation and storms, with corresponding uncertainties in the effects of SRM on such features. Nevertheless, it is very likely that a high-CO_2 climate, together with some reduction in solar forcing (achieved by engineering a small increase of albedo), would be much closer to a pre-industrial climate than to an unmodified high-CO_2 climate. SRM methods may serve as a useful backup in the future if their risks prove to be manageable and acceptable, and mitigation action proves to be inadequate, or if it is believed that a tipping point of the climate system is approaching.

SRM techniques are however not an ideal way to deal with climate change as they do not address all the effects and risks of climate change (ocean acidification, for example), there would probably be undesirable side effects (eg, on stratospheric ozone), and they would introduce new, potentially large risks of possible unanticipated effects on the system. The large-scale adoption of SRM methods would create an artificial, approximate, and potentially delicate balance between continuing greenhouse warming and reduced solar radiation, which would have to be maintained, potentially for many centuries. It is doubtful that such a balance is really sustainable for such long periods of time, particularly if it results in continued and even increased emissions of CO_2 and other greenhouse gases (eg, through the exploitation of unconventional fossil fuels such as methane hydrates). Research to improve understanding of risks and impacts and to reduce the uncertainties to an acceptable level would be necessary before any of the SRM techniques could be deployed, and research on SRM methods is therefore prudent and desirable.

Subject to the caveats above, this evaluation suggests that the only sufficiently effective SRM technique that could be implemented rapidly (within a decade or two) would be the use of some form of stratospheric aerosol, although the potential side-effects (eg, on stratospheric ozone and high-altitude tropospheric clouds) would need to be determined and found to be acceptably small. It may be that on a century time-scale a space-based SRM approach would be considerably more cost-effective. If shown to be technically feasible, and free of undesirable side-effects, cloud albedo enhancement methods could also be deployed relatively rapidly.

It is important to note that relative to the impacts of climate change itself, the unintended impacts of geoengineering on the environment are likely to be less significant. However, the environmental impacts of most methods have not yet been adequately evaluated, but are likely to vary considerably in their nature and magnitude, and in some cases may be difficult to estimate. For all of the methods considered, but, particularly for SRM methods, the climate achieved is unlikely to be quite the same as that with the effects of climate change cancelled out exactly, particularly for critical variables other than temperature which are very sensitive to regional differences (such as eg, weather systems, wind-speed and ocean currents). Precipitation is very sensitive to detailed aspects of climate, and is thus especially likely to be so affected, and is also notoriously difficult to predict. In addition, all methods would most likely have unintended environmental effects, which would need to be carefully monitored and considered. In the case of SRM methods these would include the ecological impacts of a high CO_2 world, and the unpredictable effects of the changes in natural systems caused by a forced response to decreased temperatures under high CO_2 conditions. In the case of CDR methods these would be the environmental impacts of the process itself, rather than its effects on climate, but for methods involving ecosystem manipulation these may nevertheless be substantial.

5.4 Human and governance dimensions

All of the geoengineering methods considered in this report aim to affect the climate of the planet. Their consequences (even if they are uniform and benign) are therefore of concern to everyone, and the acceptability of geoengineering will be determined as much by social, legal and political factors, as by scientific and technical factors (Submission: Royal Swedish Academy of Sciences; Submission: IMPLICC).

As discussed in Chapter 4, the governance issues associated with geoengineering, and especially with SRM and ecosystem based methods, are substantial and serious. As has already occurred in the case of ocean fertilisation, the potential exists for geoengineering methods to be deployed by corporations, by wealthy individuals or individual nation states (Submission: IMPLICC; Submission: Spiegelhalter). There are at present no international treaties or institutions with a sufficiently broad mandate to address this risk and to regulate such activities. The existing legal framework is fragmented and includes a mix of existing national, regional and international controls. Effective mechanisms by which deployment (and, where necessary, research) activity could be controlled and regulated are needed. Public attitudes towards CDR and SRM methods, and public participation in discussions of how development and implementation is managed and controlled, will also be critical. Geoengineering methods should be responsibly and openly researched, and only deployed by common consent.

For technologies which can be applied within state territory and which do not have direct or large scale transboundary effects, such as air capture and surface albedo enhancement, existing national land use planning and environmental controls are likely to be applicable. For others, such as ocean fertilisation of the high seas, the injection of atmospheric aerosols, and space-based techniques, international regulations will be required. It may be possible to adapt existing instruments to new uses (eg, the 1972 London Convention). In some cases, new mechanisms, based on the principles of existing customary law, may be required. As some of these methods will inevitably fall under the jurisdiction of existing mechanisms created for the purpose of protecting the environment (for example the 1987 Montreal Protocol) careful consideration and international coordination will be required to resolve potential conflicts.

Although the UNFCCC is the most obvious international mechanism for taking on the role of governing geoengineering, it is by no means the only option. Other mechanisms are likely to be needed given the potential breadth and impact of geoengineering interventions. A review of existing international and regional mechanisms relevant to the activities and impacts of SRM and CDR methods proposed to date would be helpful for identifying where mechanisms already exist that could be used to regulate geoengineering (either directly or with some modification), and where there are gaps. This information could then be used as the basis for further discussions on the development of appropriate governance frameworks. Until such mechanisms are in place it would be highly undesirable for methods which involve transboundary activities or effects (other than the removal of greenhouse gases from the atmosphere) to be implemented either for large scale research, or deployment purposes.

As with climate change, any governance structures would need to take into consideration (and make provision for) the equity issues raised by geoengineering (Submission: Royal Swedish Academy of Sciences) as there will probably be winners and losers associated with the applications of the different methods. For example, even for a 'perfect' geoengineering method that returned climate to some prior state, those who had already adapted to climate change may be disadvantaged. Other issues will include the equitable participation in the use and deployment of new technologies, amelioration of transboundary effects, and potential liability and compensation regimes to address, if and when the technology is 'shut off'. While certain existing principles, such as the duty not to cause transboundary harm impose due diligence requirements on States in regulating activities under their jurisdiction and control, they are ill-suited to address issues of liability and responsibility for long-term environmental consequences. Consideration should therefore be given to the conditions under which liability and compensation provisions should apply.

The commercial sector has already demonstrated an interest in geoengineering and active investment in the development of some methods is now occurring (eg, biochar, ocean fertilisation, cloud enhancement and air capture). Such activities create the risk that geoengineering activity may be driven by profit motives rather than climate risk reduction. Provision will be needed in governance frameworks for international authorisation, monitoring, verification and certification so as to reduce risks and deficiencies that may result. Experience gained under the Kyoto Protocol will be applicable to the development of such tools for CO_2 capture methods. However, the development of such tools is likely to be more difficult for SRM methods for which no process for pricing the value of reductions in W/m^2 has yet been established.

Commercial activities have so far been concentrated on CDR methods, for which there is clearly potential for future earnings via carbon trading systems. For SRM methods, such a clear financial incentive does not exist, although some activity is also likely since there may be future income from publicly funded deployment (especially of proprietary technology). A sufficiently high price of carbon (and credits for that sequestered) and/or financial support for reduced radiative forcing would be necessary to stimulate commercial involvement in developing geoengineering technology, if this were regarded as desirable. Until appropriate governance structures are in place, it would be premature to create financial incentives for activities other than those that involve the long-term sequestration of verifiable quantities of carbon.

5.4.1 Governance of R&D

An internationally agreed (but initially voluntary) code of conduct and system for approval for geoengineering research would be highly desirable. This should include provisions for appropriate environmental monitoring and reporting, depending on the magnitude and spatial scale of the experiments. The emerging London Convention and Protocol system for regulation of ocean iron fertilisation experiments may be a model for this. In the long-term this might become the function of a UN agency. As an interim solution it is proposed that an internationally collaborative process to develop a Code of Practice be initiated to provide transparency for geoengineering research and guidance to researchers in the public, private and commercial sectors. The Code of Practice could follow the general principles provided by the London Convention (see Chapter 4) and require the characterisation of the what, where and how of the intervention, an assessment of potential effects, appropriate monitoring, and an assessment of the likelihood of achieving the desired climate impact.

Only experiments with effects that would in aggregate exceed some agreed minimum (*de minimis*) level would need to be subject to such regulation. The appropriate level would need to be decided collectively. Such regulation would probably not be needed for research on contained/engineered CDR processes such as air capture as these would already be controlled under local & national legislation.

It would be desirable to involve the commercial sector in the development of an R&D governance structure. Start-up companies may play an important role in mobilising individual innovation and private capital, and in increasing the rate at which effective and low cost technologies may be developed. However, there are concerns that commercially driven research in this area may be undertaken without appropriate consideration of socio-economic, environmental and regulatory constraints. A collaborative process involving scientists from the private and public sectors could contribute to the development of best practice guidance that would maximise the transparency and scientific robustness of geoengineering research while at the same time maximising the potential for support in implementation from across the different interest groups.

5.5 Research requirements

It is clear that the available evidence is not yet sufficient for any well-informed decisions to be taken on the acceptability of any of the geoengineering techniques that have the potential to make a significant contribution to the moderation of anthropogenic climate change. The uncertainties, especially about potential environmental impacts, are still serious particularly with respect to the SRM methods that could have a beneficial effect in the shortest time (the next few decades). In particular, the spatial heterogeneity of their effects needs further study.

Rather little research has actually so far been undertaken on most of the methods considered, despite a great deal of interest in recent years from the scientific and engineering community, from concerned citizens (see eg, the Geo-engineering discussion group established in 2006),[17] and from the media. There have been no major directed programmes of research undertaken anywhere. Much of the work done has been curiosity-driven and funded piecemeal from public and private sources. Similarly, until recently much was reported informally (eg, on-line) rather than in the peer-reviewed literature, with some recent notable exceptions, including the Royal Society's special issue of Philosophical Transactions (Launder & Thompson (eds) 2008). Few of the methods have yet advanced much beyond the outline/concept stage, although some (eg, BECS among CDR methods, and the use of 'white' high albedo roofs and pavements among SRM methods) are clearly technically feasible, with relatively predictable costs and environmental impacts. However such methods are not necessarily capable of making a substantial contribution to the overall problem (although as with "white roofs" there may be energy-saving co-benefits), and the more effective methods are generally less well researched and less readily implementable.

Much more research on the feasibility, effectiveness, cost, environmental impacts and potential unintended consequences of most methods would be required before they can be properly evaluated. In particular, better understanding is required of the potential risks posed by SRM methods, and specifically the implications of a high CO_2 world for biological systems. More and better information is required to decide whether any form of geoengineering might be necessary or desirable, and if so what methods would be preferred, how they should be implemented, and where, and when.

Options for capturing non-CO_2 greenhouse gases have not yet been subject to detailed research and could provide useful alternatives to CDR methods. For example, although CH_4 has a much shorter lifetime than CO_2 (about 12 years as opposed to centuries) it has a global warming potential (GWP) of 25 (relative to CO_2 over 100 years). N_2O has a lifetime of about 114 years and GWP of 298 relative to CO_2 over 100 years) (IPCC 2007a). Methods which aim to reduce emissions of these gases at source, or remove them from the atmosphere could have a quicker effect on reducing global temperatures, and so also should be the subject of research.

A R&D programme on geoengineering methods closely linked to climate change and low-carbon research programmes could reduce many of the uncertainties within 10 years, and is therefore recommended. Such a program should address both the risks and the effectiveness of climate geoengineering, and the technical means of achieving it and should be balanced between the slow-acting but sustainable CDR methods and the fast-acting SRM methods. Priorities for research are suggested in Box 5.1. This would enable progressive refinement both of the practical details and information on the costs and environmental consequences of the more promising methods, and thus also of the portfolio of options for consideration in due course.

Research activity should be as open, coherent, and as internationally coordinated as possible, and as discussed in the previous section, large-scale experimental intervention in the environment should be subject to some form of international oversight. A coherent programme of research on all aspects of the most promising methods, preferably coordinated internationally, should be established, with the aim of providing an adequate evidence base within ten years. The research framework should include provision for environmental monitoring and reporting. The difficulties of measuring and monitoring small reductions of radiative forcing should not be underestimated. Methods for such monitoring have been considered recently in some detail (Blackstock *et al*. 2009). Some methods do not however require large-scale experimental intervention in the environment (eg engineered air capture, small-scale bio-sequestration, etc), and research in these can and should be encouraged without delay.

17 http://groups.google.com/group/geoengineering?hl=en

Box 5.1 Research priorities

1. Cross-cutting priorities include:

   - Extensive climate and Earth-system modelling studies, and where appropriate pilot-scale laboratory and field trials, to improve understanding of costs, effectiveness and impacts, and to enable the identification and characterisation of preferred methods;
   - A comprehensive evaluation is needed of environmental, ecological, and socio-economic impacts of the different methods, relative to those expected under climate change (without geoengineering);
   - A review of geoengineering governance and jurisdictional issues including an analysis of existing international and regional regulatory mechanisms of relevance to the application of geoengineering methods and their effects, and identification of gaps;
   - Economic analysis and multi-criteria assessment of the costs, benefits, impacts and risks associated with the range of geoengineering methods, and evaluation of value of CDR and/or SRM methods relative to mitigation interventions;
   - Analysis of potential for certification of CDR methods under Kyoto Protocol and carbon trading schemes;
   - Analysis of ethical and social issues associated with research and deployment including the potential for social and technological lock-in of the different methods;
   - The impact of geoengineering research and/or deployment on attitudes to climate change, mitigation and adaptation;
   - Evaluation of public engagement needs and improved methods for public engagement in development and management of geoengineering methods.

2. General research priorities for all CDR methods should include:

   - Estimates of effectiveness at achieving CO_2 concentration reductions, technical efficiency, and costs;
   - Evaluation of the time between deployment and achieving the intended effect on CO_2 concentrations, and delay between cessation of activity and CO_2 effect and other environmental impacts;
   - Investigation of material consumption, mining, processing and waste requirements;
   - Life cycle analysis of carbon and economic costs of (for example) extraction of raw materials, infrastructure development, material processing, transport and disposal;
   - Potential side-effects (pollution and environmental impacts) of the processes and their products.

3. Specific research priorities for CDR methods should include:

   - *Land-use management for carbon storage and sequestration*: Modelling, observational and experimental research focused on ecosystems important in the climate system (including tropical and boreal forests, peatlands and wetlands), (refer to Royal Society 2008b for more detail);
   - *Biochar*: Effectiveness and residence time of carbon in soils, effects on soil productivity, influence of conditions of pyrolysis on yield and stability. Resource requirements (eg, land, feedstock) and implications for other land-uses. Potential co-benefits of biochar for water, biodiversity, soil fertility, agricultural production;
   - *Land-based enhanced weathering*: Effectiveness and carbon residence time, economic viability, and social and ecological sustainability of mining and application including impacts on soil processes. Investigation into feasibility of *in-situ* mineral carbonation methods;
   - *Ocean based enhanced weathering (alkalinity addition)*: Biogeochemical and ecological effects of inputs, development of methods for verification and monitoring. Quantitative evaluation of potential effects on ocean acidification;
   - *Ocean fertilisation*: Effectiveness in terms of carbon sequestered and residence time, marine ecological and biogeochemical impacts including nutrient robbing, development of monitoring and verification methods;
   - *CO_2 capture from ambient air*: Further technological R&D, life cycle analysis and comparison with BECS methods. Evaluation of sites/technologies for deployment and sequestration. Detailed investigation into risks of carbon sequestration (as for CCS).

4. General research priorities for all SRM methods should include:
   - Life cycle analysis of the financial and carbon costs associated with the development and implementation of the method;
   - Estimates of effectiveness at achieving the desired climate state, technical efficiency and costs;
   - Time between deployment and achieving the intended effect on climate, and delay between cessation of an activity and climate response, and other environmental impacts;
   - Assessment of the full range of climate effects including properties other than global mean temperature, and including the extent and spatial variation of the impacts;
   - Investigation into the effects on atmospheric chemical composition and on ocean and atmospheric circulation;
   - Detailed modelling studies to resolve seasonal and regional effects as well as global and annual averages;
   - Modelling, theoretical studies and long-term empirical research into the impacts and consequences of persistent high CO_2 concentrations in a low temperature world for ecosystem processes and ecological communities.
5. Additional R&D priorities for specific SRM methods should include:
   - *Surface albedo methods*: Climate modelling studies of local effects on atmospheric circulation and precipitation. Evaluation of ecological, economic and social impacts (including aesthetics);
   - *Cloud albedo methods*: Impacts on regional ocean circulation patterns and biological production, near surface winds, and regional effects on climate over land; methods for CCN creation and delivery, and small-scale experimental field trials;
   - *Stratospheric albedo methods*: Effects on monsoons, stratospheric ozone, and high-altitude tropospheric clouds. Assessment of possible feedback processes including stratospheric-tropospheric exchange, and the carbon and hydrological cycles, and regional scale modelling. Evaluation of aerosol size and distribution effects, improved estimates of source strength and delivery methods;
   - *Space based albedo methods*: Modelling studies on effectiveness and climate effects including impacts on regional climate and weather patterns including changes in seasonality and variability, impacts on polar ice cover and ocean circulation. Desk based engineering design studies on likely feasibility, effectiveness, timescales for development and for deployment and costs of proposals.

In most cases much useful information could be gained fairly rapidly from new modelling and pilot-project scale engineering studies, and field trials. The cost of such research would initially be quite modest in comparison with, for example, the cost of R&D on low carbon technology and mitigation, which is itself a small fraction of total expenditure on energy (Royal Society 2009). However, at a later stage the costs of large scale engineering and field studies and new dedicated computing infrastructure would be more substantial. Moreover it is acknowledged that existing models have known deficiencies (IPCC 2007a). The limitations of current models in modelling of regional change on decadal timescales is a major challenge for geoengineering (and climate) studies, and limits the adequate assessment of many of the geoengineering approaches. Better representations of cloud processes, precipitation, and both marine and terrestrial carbon cycles are required, as they are for mainstream climate models. In addition to improved Earth System Models, new and improved spatially resolving Integrated Assessment Models are required, that allow climate change and land use scenarios to be jointly assessed, within realistic social and economic settings. One may reasonably require a higher level of confidence in the model predictions for those geoengineering methods that would create a novel and artificial state of the Earth system, compared to those which would return it to something closer to a former state to which the model parameters have been calibrated. The development and use of suitable and more advanced Earth System and Integrated Assessment Models, and improved computing facilities and infrastructure should therefore be a high priority.

5.6 Guidance for decision makers

It is clear that geoengineering must not divert resources from climate change mitigation or adaptation. However, the preceding analysis suggests that CDR methods, if they can be proven to be safe and affordable, could play a useful role alongside mitigation in reducing CO_2 concentrations. As SRM methods do not reduce greenhouse gas concentrations and because of their associated risks and uncertainties, it is unclear whether they should have a role as anything other than an option of last resort, or as a time-limited temporary measure. However, given their potential for rapidly reducing the global temperature, these methods should not be dismissed.

The two major classes of geoengineering methods have distinct characteristics, summarised in Box 5.2.

As there is now intense interest being shown in geoengineering, there is an immediate need for the establishment of frameworks and mechanisms by which the public and other stakeholders can be informed and engaged, and R&D and deployment can be responsibly considered within the broader context of climate change action.

To help guide decisions regarding whether to proceed with geoengineering research or deployment, decision makers are advised to consider the following (refer to Annex 8.1 for more detail):

1. Legality of the method proposed (national/regional/international);
2. Effectiveness (proven/unproven);
3. Timeliness (of implementation and climate effect);
4. Environmental, social and economic impacts (including unintended consequences);
5. Costs (direct financial and carbon life cycle);
6. Funding (support for R&D and security over term for deployment);
7. Public acceptability (novelty/containability/scale of intervention/control frameworks);
8. Reversibility (technological, political, social and economic).

When developing climate change strategies, and considering a potential role for geoengineering, decision makers are advised to also consider the following:

a) The appropriate balance of the relative contributions of mitigation, adaptation, and both CDR & SRM methods of geoengineering;

Box 5.2 Characteristics of the two major classes of geoengineering methods

CDR methods

- treat the cause of climate change by removing greenhouse gases;
- would only slowly become fully effective (many decades);
- would reduce ocean acidification (and other CO_2 related problems);
- would not suffer from the 'termination problem';
- would lead to reduced plant productivity (compared to the elevated level expected with high CO_2 concentrations);
- for ecosystem-based methods, would likely involve major impacts on natural ecosystems, and may involve trade-offs with other desirable ecosystem services;
- for "engineered" methods, may require the construction of substantial infrastructure, and/or the secure disposal of large quantities of CO_2;
- would probably have costs similar to (or greater than) those of mitigation;
- can mostly be tested easily at small and medium scales;
- for engineered (air capture) methods would probably not require international agreement (until the atmospheric CO_2 level had declined to near the preindustrial level).

SRM methods

- could mostly be deployed relatively quickly and would take effect rapidly;
- could provide a fairly good approximate cancellation of increased temperatures, but could not generally cancel changes of other aspects of climate (eg, precipitation) at the same time;
- would create an artificial (and only approximate) balance between greenhouse warming and reduced solar radiation, which might have to be maintained, potentially for many centuries;
- would create a risk of severe and rapid greenhouse warming if and when they ever ceased operation suddenly (the 'termination problem');
- would do little or nothing to reduce atmospheric CO_2 levels, or the associated problem of ocean acidification;
- could prove to be relatively inexpensive (compared to the costs of mitigation);
- would most probably require international cooperation when conducted beyond national boundaries or when impacts are transboundary.

b) The extent to which the risks of climate change may or may not outweigh the risks associated with geoengineering options;

c) The appropriate timing and duration of all potential responses and interventions.

5.7 Conclusion

There are large uncertainties associated with most geoengineering methods, but these should not as yet be regarded as sufficient reason to dismiss them.

Geoengineering methods are often presented as an emergency 'backstop' to be implemented only in the event of unexpected and abrupt climate change, but this tends to focus attention primarily on methods which could be implemented rapidly, to the detriment of those with longer lead and activation times. Methods should be evaluated as part of a wider portfolio of responses, together with mainstream mitigation and adaptation efforts. This could eventually lead to a portfolio approach to climate change, in which a range of different options can be pursued, and adaptively matched to emerging conditions balancing risks, uncertainties and benefits. It is possible therefore that properly researched geoengineering methods, and in particular the CDR methods, could eventually be useful to augment conventional mitigation activities, even in the absence of an imminent emergency.

However, none of the methods considered is free of potential disadvantages and uncertainties, and too little is known at present about any of the methods for them to provide any justification for reducing present and future efforts to reduce CO_2 emissions. CDR methods offer a longer-term approach to addressing climate change than SRM methods and generally have fewer uncertainties and risks. Caution is required when considering the large-scale adoption of SRM methods as they would create an artificial, approximate, and potentially delicate balance between continuing greenhouse warming and reduced solar radiation, and it is doubtful that such a balance could be sustained for the duration needed. Furthermore, SRM methods do not address the direct impacts of CO_2 on the environment, the implications of which on biological systems are still not well understood. Decisions to implement SRM methods should therefore be guided by the risks associated with living in a geoengineered but high CO_2 world. It would be risky to embark on major implementation of SRM methods without a clear and credible exit strategy, for example a phased transition after a few decades to more sustainable CDR methods. This implies that research would be needed in parallel on both SRM and CDR methods, since CDR methods have a longer lead-time.

Geoengineering raises a range of governance issues that would need to be resolved in advance of the implementation of any large-scale research programmes or deployment. Ultimately decisions about potential deployment would need coordinated consideration by several international Conventions: among these it may be appropriate for the UNFCCC to take on a leading role. Public attitudes towards geoengineering will have a critical influence on its future. Public dialogue, engagement and research to explore public and civil society attitudes, concerns and uncertainties should therefore be a central part of any future programmes of work on geoengineering.

6 Conclusions and recommendations

Due to the limited number of peer-reviewed publications on scientific, technological, economic and social research undertaken on the concept of geoengineering, and on specific carbon dioxide removal (CDR) and solar radiation management (SRM) methods, the assessments provided in this report are necessarily based on preliminary and incomplete information. Sufficient information is however available to enable a general assessment of whether geoengineering could and should play a role alongside climate change mitigation and adaptation activity, of which methods have the most promise, and of priorities for future work.

6.1 The future of geoengineering

The analysis provided in this Report suggests that geoengineering is likely to be technically feasible, and could substantially reduce the costs and risks of climate change. However, all of the geoengineering methods assessed have major uncertainties in their likely costs, effectiveness or associated risks and are unlikely to be ready for deployment in the short to medium term. The report concludes that while some geoengineering methods may provide a useful contribution to addressing climate change in the future, this potential should not divert policy focus and resourcing away from climate change mitigation and adaptation.

Climate change mitigation efforts have so far failed to achieve the rapid rates of decarbonisation necessary to avoid global average temperatures exceeding 2°C above pre-industrial levels this century. Decarbonisation at the magnitude and rate required remains technically possible. However even if emissions were immediately cut to zero climate change would continue for the forseeable future due to the long residence time of CO_2 in the atmosphere. The global failure to make sufficient progress on mitigation of climate change is largely due to social and political inertia, and this must be overcome if dangerous climate change is to be avoided. If this proves not to be possible, geoengineering methods may provide a useful complement to mitigation and adaptation if they can be shown to be safe and cost effective.

Recommendation 1

1.1 *Parties to the UNFCCC should make increased efforts towards mitigating and adapting to climate change and, in particular to agreeing to global emissions reductions of at least 50% of 1990 levels by 2050 and more thereafter. Nothing now known about geoengineering options gives any reason to diminish these efforts.*

1.2 *Emerging but as yet untested geoengineering methods such as biochar and ocean fertilisation should not be formally accepted as methods for addressing climate change under the UNFCCC flexible mechanisms until their effectiveness, carbon residence time and impacts have been determined and found to be acceptable.*

1.3 *Further research and development of geoengineering options should be undertaken to investigate whether low risk methods can be made available if it becomes necessary to reduce the rate of warming this century. This should include appropriate observations, the development and use of improved climate models, and carefully planned and executed experiments.*

1.4 *To ensure that geoengineering methods can be adequately evaluated, and applied responsibly and effectively should the need arise, three priority programmes of work are recommended:*

a) *Internationally coordinated research and development on the more promising methods identified in this report;*

b) *International collaborative activities to further explore and evaluate the feasibility, benefits, risks and opportunities presented by geoengineering, and the associated governance issues;*

c) *The development and implementation of governance frameworks to guide both research and development in the short term, and possible deployment in the longer term, including the initiation of stakeholder engagement and a public dialogue process.*

6.2 Major characteristics of geoengineering methods

In evaluating the potential effectiveness of geoengineering techniques the best overall measure is ultimately their ability to moderate or reverse the increase in global mean temperature. However, the potential methods available are diverse, aim to address different aspects of the climate system by either reducing greenhouse gas concentrations, or incoming solar radiation, and their impacts in the short term, and over time depend on other factors (such as the level of greenhouse gases in the atmosphere).

The term 'geoengineering' now includes such a broad spectrum of methods that general statements can be very misleading.

CDR methods take effect over several/many decades, and so do not provide an emergency response option, but by removing greenhouse gases from the atmosphere, contribute to reducing climate change at its source.

SRM methods take effect rapidly, and provide the only option for reducing, or slowing the increase of, global temperatures over the short term (years/decades).
They would not contribute to any reduction in greenhouse

gases, and could introduce new risks into the global climate system.

The major differences between the two classes of methods concern the timescales over which they could become effective, their long-term sustainability, their effects on CO_2 related problems other than climate change (such as ocean acidification), and the governance issues that they raise.

Recommendation 2

Evaluations of geoengineering methods should take account of the major differences between the main two classes of methods; that is those that remove CO_2 from the atmosphere (CDR); and those that modify the albedo (reflectivity) of the planet (SRM) as summarised below.

6.3 Preliminary evaluation of CDR and SRM methods

None of the methods assessed offers an immediate solution to climate change and too little is understood about their potential future effectiveness, risks and uncertainties to justify reducing present and future efforts to reduce greenhouse gas emissions. This report does not therefore identify a single overall preferred option and emphasises that the most appropriate method will depend on whether the objective is to reduce temperatures over the short (a few years to a decade) or long (several/many decades) term.

CDR methods may augment conventional emissions reduction and even allow future reductions (negative emissions) of atmospheric CO_2 levels (thereby addressing ocean acidification) if safe and low cost methods can be developed at an appropriate scale. Ecosystem based CDR methods could produce substantial and unintended ecosystem impacts, and may involve trade-offs with other desirable ecosystem services. CDR techniques offer a longer term approach to addressing climate change than SRM methods and generally have fewer uncertainties and risks.

CDR methods can be grouped in order of preference according to the degree to which their application has an impact on other natural systems and the scale of land use change required.

1. The most promising CDR methods are those that remove CO_2 from the atmosphere without perturbing other natural systems, and without large-scale land-use change requirements; such as engineered air capture and possibly also enhanced weathering techniques.
2. Techniques that sequester carbon but have land-use implications (such as biochar and soil based enhanced weathering) may make a useful contribution at a small scale but require further assessment of their life cycle effectiveness, economic viability, and social and ecological sustainability.
3. The least promising are those methods that involve large-scale manipulation of ecosystems (such as ocean fertilisation) due to their potential environmental impacts, trans-boundary effects, and associated equity and governance issues.

SRM techniques can rapidly limit or reduce global temperatures. However, in order to maintain lower temperatures, they create an artificial (and only approximate) balance between greenhouse warming and reduced solar radiation, which must be actively maintained (potentially for many centuries) and so they suffer from 'the termination problem'.

The climate achieved by SRM methods, especially those which have regionally variable impacts, will only approximate to that with less greenhouse warming. Critical variables other than temperature (such as precipitation) are very sensitive to regional differences, as are weather systems, wind speeds and ocean currents.

SRM methods also do little or nothing to reduce atmospheric CO_2 concentrations or ocean acidification. The implications for marine and terrestrial biological systems of a high CO_2 and low temperature world are poorly understood and difficult to predict.

Prior to undertaking large scale SRM experiments or deployment, unintended environmental effects should be carefully assessed. It would be risky to embark on major implementation of SRM methods without a clear and credible exit strategy.

The most promising SRM methods are (in order of priority):

1. *Stratospheric aerosol methods*. These have the most potential because they should be capable of producing large and rapid global temperature reductions, because their effects would be more uniformly distributed than for most other methods, and they could be readily implemented. However, potentially there are significant side-effects and risks associated with these methods that would require detailed investigation before large-scale experiments are undertaken.
2. *Cloud brightening methods*. Although these are likely to be less effective and would produce primarily localised temperature reductions, they may prove to be readily implementable, and should be testable at small scale with fewer governance issues than other SRM methods.
3. *Space based SRM methods*. Space methods would provide a more uniform cooling effect than surface or cloud based methods, and if long-term geoengineering is required, may be a more cost-effective option than the other SRM methods although development of the necessary technology is likely to take decades.

Recommendation 3

3.1 *Geoengineering methods are not a substitute for climate change mitigation, and should only be considered as part of a wider package of options for addressing climate change. CDR methods should be regarded as preferable to SRM methods as a way to augment continuing mitigation action in the long term.*

However SRM methods may provide a potentially useful short-term backup to mitigation in case rapid reductions in global temperatures are needed.

3.2 *CDR methods that have been demonstrated to be safe, effective, sustainable and affordable are ultimately preferable to SRM methods, and should be deployed alongside conventional mitigation methods as soon as they can be made available.*

3.3 *SRM methods should not be applied unless there is a need to rapidly limit or reduce global average temperatures. Because of uncertainties over side effects and sustainability they should only be applied for a limited period and accompanied by aggressive programmes of conventional mitigation and/or CDR, so that their use may be discontinued in due course.*

6.4 Criteria and methods of assessment

The methods used, and criteria by which CDR and SRM approaches are assessed in the future, will have a significant influence on the perception of geoengineering in the climate change debate. Scientific issues will continue to play an important role in this debate, and all methods should be assessed in an Earth systems context using the best available Earth system and climate models. Life cycle analysis will also be important for establishing the carbon (and other) benefits and costs of the different methods. To determine the potential effectiveness and feasibility of methods, a mixture of technical and non-technical criteria should be applied.

A direct comparison of the costs associated with the development and deployment of the different geoengineering methods, particularly the SRM methods, with conventional climate change mitigation approaches is problematic due to the lack of knowledge about geoengineering costs and risks. To be affordable relative to the costs of mitigation, the costs of SRM methods to offset a doubling of CO_2 would need to be of the order of $1 trillion per year, and CDR methods $100 per tonne of carbon. However, direct economic cost comparisons should be undertaken with caution. Significant research is required to improve understanding of the costs associated with the different methods.

Recommendation 4

Prior to any large scale experimentation or deployment future assessments of geoengineering methods should consider the following criteria (see Annex 8.1 for more detail):

1. *Legality;*
2. *Effectiveness;*
3. *Timeliness (both of implementation and climate effect);*
4. *Environmental, social and economic impacts (including unintended consequences);*
5. *Costs (direct financial and carbon life cycle);*
6. *Funding mechanisms;*
7. *Public acceptability;*
8. *Reversibility (technological, political, social and economic).*

6.5 Public attitudes and engagement

It is clear that public attitudes towards geoengineering, and public engagement in the development of individual methods, will have a critical bearing on its future. Factors that are likely to affect this include:

- the transparency of actions, motivations and purposes;
- a lack of vested commercial and other interests driving research or deployment;
- demonstrable concern and responsibility for environmental impacts.

A limited investigation of socio-economic and ethical aspects, and public attitudes towards geoengineering proposals, was undertaken as part of this study. On the basis of this initial analysis, it seems that public attitudes tend to be dominated by the risk of something going wrong. This can be influenced by the extent to which the method:

- is a contained engineered system, or involves the manipulation of the natural environment and ecosystems;
- involves intervention only in physical and chemical processes, or in biological processes and systems;
- involves activities (and/or substances) which are localised (intensive), or are widely distributed and dispersed (extensive);
- has effects which are primarily local and regional, or are of global extent;
- involves 'big science' and centralised control, or small-scale activity and local control;
- involves processes which are perceived as familiar, or novel and unfamiliar.

There are a wide range of public opinions on the acceptability or otherwise of deliberate intervention in the climate system. Perceptions of geoengineering proposals are generally negative, but are complex and method-specific. Some people perceive ethical objections to geoengineering in principle: others do not. This range of public opinion needs to be further explored, so that policy makers can decide whether and in what way these opinions should influence their decisions. More thorough investigations of public attitudes should be carried out in parallel with any further technological research and development, through a broad process of dialogue, knowledge exchange and public participation. In particular, a formal effort to ascertain the extent of the moral hazard issue would be desirable.

Recommendation 5

The Royal Society, in collaboration with other appropriate bodies, should initiate a process of dialogue and engagement to explore public and civil society attitudes, concerns and uncertainties about geoengineering as a response to climate change. This should be designed so as to:

a) *Clarify the impact that discussion of the possible implementation of geoengineering may have on general attitudes to climate change, adaptation and mitigation;*

b) *Capture information on the importance of various factors affecting public attitudes, including: novelty/familiarity, scale of application and effect, aesthetics, the actors involved, centralisation of control, contained versus dispersed methods and impacts, and the reversibility of effects;*

c) *Provide participants with objective information as to the potential role of geoengineering within the broader context of climate change policies, the differences between CDR and SRM methods, and their relative risks and benefits.*

6.6 Governance

The governance issues associated with geoengineering, and especially with SRM and ecosystem-based CDR methods are substantial and serious. As with climate change, there will be winners and losers associated with the implementation of geoengineering methods. The potential benefits and risks to society will need to be identified and assessed as part of any process to establish new, or modify existing, geoengineering governance mechanisms. Tools for international monitoring, verification and certification will also be required.

There are at present no international treaties or institutions with a sufficiently broad mandate to regulate the broad range of possible geoengineering activities and there is a risk that methods could be applied by individual nation states, corporations or one or more wealthy individuals, without concern for their transboundary implications. Mechanisms by which deployment (and where necessary, research) can be controlled and regulated are therefore necessary. Some methods could be effectively governed and managed by employing or amending existing treaties and protocols of international law where activities have cross border implications, and under national regulations where activities and their impacts are confined within national boundaries. However, others (such as atmosphere and space-based methods) may require new international mechanisms.

Appropriate governance mechanisms for regulating the deployment of geoengineering methods should be established before they are needed in practice, and these mechanisms should be developed in the near future if geoengineering is to be considered as a potential option for mitigating climate change. They should allow for the international control and governance requirements of large-scale methods, and the local or national regulation of contained methods.

Financial incentives will need to be established for if and when deployment is necessary. This may require the valuation of reductions of radiative forcing and of atmospheric CO_2 removal, the creation of new and future extension of, existing mechanisms such as carbon trading schemes and the Clean Development Mechanism. However, it is concluded that it would for the time being be premature to create financial incentives for activities other than those that involve the long-term sequestration of verifiable quantities of carbon.

Some people object to deliberate manipulation of natural systems (although it has long been associated with human development), and this may in some cases also extend to undertaking research (especially field trials) involving environmental interventions. In some cases (eg sulphate aerosols) it is also not clear that field trials can easily be conducted on a limited scale, or without appreciable and widespread environmental impacts. The development of an internationally agreed code of conduct and system of approval for R&D would have the benefit of increasing the transparency with which geoengineering related research is undertaken and could contribute to building public confidence in this field. Scientists from across the public and private sectors should be invited to collaborate in the process.

It would be highly undesirable for geoengineering methods which involve activities or effects (other than simply the removal of greenhouse gases from the atmosphere) that extend beyond national boundaries to be subject to large scale research or deployment before appropriate governance mechanisms are in place.

Recommendation 6

6.1 *The governance challenges posed by geoengineering should be explored in more detail, and policy processes established to resolve them.*

6.2 *An international body such as The UN Commission for Sustainable Development should commission a review of international and regional mechanisms to:*

a) *Consider the roles of the following bodies: UNCLOS, LC/LP, CBD, CLRTAP, Montreal Protocol, Outer Space Treaty, Moon Treaty, UNFCCC/KP, ENMOD.*

b) *Identify existing mechanisms that could be used to regulate geoengineering research and deployment activities.*

c) *Identify where regulatory gaps exist in relation to geoengineering methods proposed to date.*

d) *Establish a process for the development of mechanisms to address these gaps.*

6.3 *The UNFCCC should establish a working group to:*

a) Specify the conditions under which CDR methods would be considered as mechanisms under the Convention.

b) Establish the conditions that CDR methods would need to meet to be eligible under the Clean Development Mechanism and Joint Implementation mechanisms.

6.7 Geoengineering research and development

None of the methods evaluated in this study offer an immediate solution to the problem of climate change and it is unclear which, if any, may ever pass the tests required for potential deployment, that is: be judged to be effective, affordable, sufficiently safe, timely and publicly acceptable. However, with appropriate R&D investment some of those considered could potentially complement climate change mitigation and adaptation in the future and contribute to reducing the risks of climate change. As highlighted previously, if geoengineering is to play a future role, effort is needed to develop appropriate governance frameworks for R&D as well as deployment. Critical to the success of these will be an active and internationally coordinated programme of research, and an active programme of stakeholder engagement.

Research is urgently needed for evaluating which methods are feasible, and to identify potential risks (see Box 5.1).

The principal R&D requirements in the short-term are for small/medium scale research (eg pilot experiments and field trials) and much improved modelling studies on the feasibility, costs, environmental impacts and potential unintended consequences of geoengineering techniques. In particular investment in the further development of Earth system and climate models is needed to improve the ability of researchers to assess the impacts of CDR and SRM methods on changes in climate and weather patterns (including precipitation and storminess) around the world. This will require improved computing facilities and infrastructure.

The social and environmental impacts of most geoengineering methods have also not yet been adequately evaluated, and all methods are likely to have unintended consequences. These need to be strenuously explored and carefully assessed.

In most cases much useful information could be gained fairly rapidly and at quite modest cost. Funding at a level of a few percent of the modest amount spent on R&D for new energy technology would be sufficient to enable substantial progress. Research activity should be closely linked to climate change research programmes, should be as open, coherent and as internationally coordinated as possible, and should conform with existing environmental safeguards.

R&D should be prioritised for CDR methods that remove atmospheric CO_2 without affecting other natural systems and which do not require large-scale land-use changes (eg engineered air capture and land-based enhanced weathering). In addition to technological aspects, research should be focused on establishing their effectiveness, financial costs of deployment, overall carbon benefits, and environmental impact over the full life-cycle. The economic viability and social and ecological sustainability of those CDR techniques that sequester carbon but do have land-use implications (such as biochar and soil based enhanced weathering) should also be investigated. A lower priority should be assigned to those methods that involve large-scale manipulation of natural ecosystems (such as ocean fertilisation).

Although CDR methods have so far been focused on methods to reduce CO_2 concentrations, it may also be possible to develop methods for removing other greenhouse gases such as CH_4 and N_2O from the atmosphere. The potential for the development of new methods aimed at reducing non-CO_2 greenhouse gas atmospheric concentrations should be considered as an additional component of CDR-related research.

For the SRM methods, research should include the assessment of the full range of climate effects including properties other than global mean temperature, the extent and spatial variation of impacts, and effects on atmospheric chemical composition and ocean and atmospheric circulation. Emphasis should be given to improving understanding of the implications of reducing temperatures in a high CO_2 world for biological systems. Stratospheric aerosol methods should be the highest priority for research for SRM methods. However, before large scale experiments are undertaken careful work is needed to evaluate the potential side-effects and risks associated with these methods. Cloud-brightening methods should also be investigated but as a lower priority. The feasibility of space-based methods should be the subject of desk-based research

Recommendation 7

7.1 *The Royal Society in collaboration with international scientific partners should develop a code of practice for geoengineering research and provide recommendations to the international scientific community for a voluntary research governance framework. This should provide guidance and transparency for geoengineering research and apply to researchers working in the public, private and commercial sectors. It should include:*

a) Consideration of what types and scales of research require regulation including validation and monitoring;

b) The establishment of a de minimis standard for regulation of research;

c) Guidance on the evaluation of methods including relevant criteria, and life cycle and carbon/climate accounting.

7.2 *Relevant international scientific organisations including the WMO, ICSU, Earth System Science Partnership and UNFCCC/IPCC should coordinate an international programme of research on geoengineering methods with the aim of providing an adequate evidence base with which to assess their technical feasibility and risks, and reducing uncertainties within ten years. This should include a programme of observational work aimed at better understanding possible responses of ecosystems, atmospheric chemistry, clouds, and other components of the Earth System. These observations should be integrated into a programme of work to develop and use Earth System models, Integrated Assessment Models and state-of-the-art climate models for the purposes of evaluating both SRM and CDR methods.*

7.3 *The European Commission (DG Research in consultation with DG Environment) should consider the inclusion of climate change, and a specific theme on geoengineering, within the EU 8th Research Framework Programme.*

7.4 *Relevant UK Government Departments (DECC & DEFRA) in association with the Research Councils (BBSRC, ESRC, EPSRC, and NERC) should together fund a 10 year programme of research on geoengineering and associated climate science focused on addressing the priorities identified in Box 5.1. A realistic cost for a UK programme of research on geoengineering would be of the order of £10M per annum. The UK should make an active contribution to the international programmes recommended above.*

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8 Annexes

8.1 Evaluation criteria

Prior to any large scale experimentation or deployment it is recommended that geoengineering methods be evaluated based on the following criteria:

1) Legality:
    - Need for prior authorisation under national or international law or policy;
    - Likelihood of environmental impacts that would contravene national or international laws.
2) Effectiveness:
    - Strength of scientific basis of method;
    - State of development of the technology;
    - Whether demonstrated to be technically feasible;
    - Potential magnitude of effect;
    - Spatial scale of influence on the climate system and uniformity of the effect;
    - Scaleability of the intervention (from small to large).
3) Timeliness:
    - Timescale to be ready for implementation;
    - Time taken to affect the climate system and duration of effect;
    - Time required for the climate system to stop responding if the method is stopped.
4) Impacts:
    - State of understanding of intended effects on the climate system?
    - Verifiability of intended effects;
    - Potential for the method and its effects be stopped once deployed;
    - Likely effects on the climate system of turning the method off;
    - Foreseeable environmental impacts (nature, spatial scale and magnitude);
    - Potential for mitigation of environmental impacts;
    - Potential for human health impacts;
    - Potential for predictable, but unintended consequences, and scope for management of these;
    - Potential liability issues from adverse environmental, economic or social impacts.
5) Costs: to be based so far as possible on full life cycle assessment, including:
    - The direct financial costs of any R&D required;
    - For deployment: the direct financial costs of set up, implementation and ongoing operational costs;
    - Magnitude of expected net carbon accounting benefit, where applicable.
6) Funding support:
    - Availability of funding for R&D;
    - Mechanism for funding of deployment and long term operation;
    - Costs of development and implementation compared to those of conventional mitigation.
7) Public acceptability:
    - How novel is the method, (have similar technologies already been successfully applied)?
    - Who is proposing to do the R&D or deployment? Do they have vested interests? What benefits are they likely to gain?
    - Does the method involve releasing material into the environment?
    - Are the activities localised, or widely dispersed?
    - Will activities be controlled locally, or centrally?
    - Can the activity, and its effects be contained?
8) Reversibility; what are the technical, political, social and economic implications of ceasing the activity?

8.2 Project terms of reference

To consider, and so far as possible evaluate, proposed schemes for moderating climate change by means of geoengineering techniques.

Specifically:

1) To consider what is known, and what is not known, about the expected effects, advantages and disadvantages of such schemes;
2) To assess their feasibility, efficacy, likely environmental impacts, and any possible unintended consequences;
3) To identify further research requirements, and any specific policy and legal implications.

Scope

The scope of the study includes all methods intended to moderate climate change by deliberate large-scale intervention in the working of the Earth's natural climate system, but excludes (a) methods for reducing emissions of greenhouse gases such as carbon capture & storage (CCS) at the point of emission, and (b) conventional afforestation and avoided deforestation schemes. The methods under consideration will be grouped within the following broad technological categories:

1) Greenhouse gas reduction schemes:
    - a) Removal of CO_2 (and other greenhouse gases (GHGs)) from the atmosphere or oceans
        - i) Methods utilising terrestrial biological systems;
        - ii) Methods utilising oceanic biological systems;
        - iii) Methods using non-biological or engineered biological systems (chemical/biochemical engineering etc).
    - b) Novel ways to prevent CO_2 (and other GHGs) from entering the atmosphere and oceans
        - i) Methods involving engineered biological systems;
        - ii) Methods using non-biological systems (chemical engineering approaches).
2) Albedo modification (shortwave reflection/deflection) schemes:
    - a) Surface-based schemes (land or ocean albedo modification);
    - b) Troposphere-based schemes (cloud modification schemes, etc);
    - c) Upper atmosphere schemes (tropopause and above, ie stratosphere, mesosphere);
    - d) Space-based schemes.

Notes

i) CCS at the point of emission, and the methods listed under 1(b) were considered by the IPCC (2005).

ii) This study will concentrate on approaches that could potentially diminish radiative forcing by 1 W/m^2 or more, but may discuss things that could possibly provide a few tenths of W/m^2. Schemes that could deliver no more than 0.1 W/m^2 will not be considered unless there are some compelling reasons to do so. For GHG absorption or emissions reduction, the corresponding upper and lower guidelines may be taken as 1 GtC/yr and 0.1 GtC/yr.

8.3 Ethics panel

The Royal Society convened a small workshop on April 24 2009 that was aimed at gathering information about the ethical dimensions of the geoengineering issue.

Three experts in environmental or climate change ethics and social science were invited to attend:

Professor Martin Bunzl	Eagleton Institute of Politics, Rutgers University, USA.
Professor John O' Neill	School of Social Sciences, University of Manchester, UK.
Professor Michael Northcott	School of Divinity, University of Edinburgh, UK.

The other participants of the workshop were as follows:

Rachel Garthwaite	Senior Policy Adviser, Environment, Energy & Climate Change.
Professor Gordon MacKerron	Science and Technology Policy Research Unit, University of Sussex.
Andy Parker	Science Policy Adviser.
Professor Steve Rayner	Saïd Business School, University of Oxford.
Professor Catherine Redgwell	Faculty of Laws, University College London.
Professor John Shepherd FRS (chair)	National Oceanography Centre, University of Southampton.

The following questions formed the basis of the discussions throughout the day.

- What are your general thoughts on deliberate climate modification?
- Would deliberate geoengineering be unethical? (If so, why, and if not, why not?)
- Would we need a higher standard of proof/confidence about the consequences of deliberate interventions (*cf*. just abating accidental intervention)?
- Are there ethical aspects of the 'whose hand on the thermostat?' problem? If so, what? Can they conceivably be overcome? If so, how?
- Are some schemes more or less ethically acceptable than others? If so, which, and why?
- What are the main ethical considerations that would have to be taken into account when designing a regulatory framework for geoengineering research or deployment?
- How should future enquiry into the ethics of geoengineering proceed, and how can it contribute to policymaking? What are the immediate priorities for geoengineering ethics?

8.4 Call for submissions

Copies of the submissions received for which permission was received to make them publicly available can be obtained from the Royal Society website (http://royalsociety.org/geoengineeringclimate).

The following organisations and individuals provided written submissions to inform the study. Organisations and individuals who asked not to be listed have been omitted from the list below.

Submissions on behalf of individuals

Submitter(s)	Affiliation
Professor Kevin Anderson	Tyndall Centre for Climate Change Research, UK
Professor Robert Anderson	Lamont-Doherty Earth Observatory, Columbia University, USA
Timothy Barker	–
Dr Philip Boyd	NIWA Centre for Chemical and Physical Oceanography, University of Otago, New Zealand
John Brady	–
Professor Wallace Broecker ForMemRS	Lamont-Doherty Earth Observatory, Columbia University, USA
Ian Brunt	–
Professor Harry Bryden FRS	University of Southampton, UK
Dr Ken Buesseler	Woods Hole Oceanographic Institution, USA
Professor Marcos Carvalho Campos	Federal University of Paraná, Brazil
Mark Capron	PODenergy, USA
Dr Alan Carlin	US Environmental Protection Agency, USA
Professor Tom Choularton	The University of Manchester, UK
Professor Nick Cowern and Dr Chihak Ahn	Newcastle University, UK
John Duke	–
Professor Julian Evans	University College London, UK
Dr Alan Gadian[a], Professor Alan Blyth[a], Laura Kettles[a] and Professor John Latham[b]	[a]University of Leeds, UK [b]National Center for Atmospheric Research, USA
Dr Andrew Gettelman and Dr Simone Tilmes	National Center for Atmospheric Research, USA
Malcolm Gorton, Sarah Bardsley, Jennifer de Lurio, Dr Sarah Webb	UK Environment Agency Horizon Scanning Team
Rosemary Jones	–
Professor Jonathan Katz	Washington University, USA
Dr Haroon Kheshgi	ExxonMobil
Professor Richard Lampitt, Professor Eric Achterberg, Dr Thomas Anderson, Dr Alan Hughes, Dr Debora Iglesias-Rodriguez, Dr Boris Kelly-Gerreyn, Dr Mike Lucas, Dr Ekaterina Popova, Dr Richard Sanders, Professor John Shepherd FRS, Dr Denise Smythe-Wright, Dr Andrew Yool	UK National Oceanography Centre
Professor John Latham[a], Dr Phil Rasch[b], Dr C.C. (Jack) Chen[a]	[a]National Center for Atmospheric Research, USA [b]Pacific Northwest National Laboratory, USA
Professor Tim Lenton and Naomi Vaughan	University of East Anglia, UK
Emily Lewis-Brown	WWF

Dr Dan Lunt and Professor Paul Valdes	University of Bristol, UK
Professor Colin McInnes FREng FRSE, Professor Jason Reese FRSE	University of Strathclyde, UK
Malcolm Newell	–
John Nissen	–
Dr Tim Palmer FRS	European Centre for Medium-Range Weather Forecasts, UK
Dr Greg Rau	Lawrence Livermore National Laboratory, USA
Dr Peter Read	Massey University, New Zealand
Dr David Reay	University of Edinburgh, UK
Roger Remington	–
Professor Alan Robock	Rutgers University, USA
Jim Roland	–
Professor Stephen Salter	University of Edinburgh, UK
Dr Robert Samuels	–
Professor R D Schuiling	University of Utrecht, The Netherlands
Professor Jeffrey Severinghaus	Scripps Institution of Oceanography, USA
Dr Mark Sheldrick	–
Martin Sherman	Seavac
Professor Keith Shine FRS, Dr Andrew Charlton-Perez, Professor Lesley Gray, Dr Eleanor Highwood, Dr Giles Harrison, Professor Anthony Illingworth, Dr Manoj Joshi, Dr Nicola Stuber, Professor Rowan Sutton	University of Reading, UK
Denis Skeet	–
Brian Spiegelhalter	–
Ray Taylor	–
Dr Simone Tilmes, Dr Rolando Garcia and Dr Andrew Gettelman	National Center for Atmospheric Research, USA
Naomi Vaughan and Professor Tim Lenton	University of East Anglia & Tyndall Centre for Climate Change Research, UK
Matt Woodhouse, Professor Ken Carslaw, Dr Graham Mann	University of Leeds, UK
Professor Ning Zeng	University of Maryland, USA

Submissions on behalf of organisations

Institution	Contact
2 Percent for the Planet	Contact: Richard Mountford
Antarctic Climate & Ecosystems (ACE) Cooperative Research Centre, University of Tasmania	Contact: Tom Trull
Atmocean Inc	Contact: Philip Kithil
Biofuelwatch	Contact: Deepak Rughani
Carbfix	Contact: Hólmfríður Sigurðardóttir and Dr Sigurdur Gislason
Climos	Contact: Kevin Whilden

CQuestrate	Contact: Tim Kruger
Convention on Biological Diversity	Contact: David Cooper
The Engineering Committee on Oceanic Resources	Contact: Martin Renilson
Environment Agency Horizon Scanning Team, Science Department	Contact: Jennifer de Lurio
Environmental Defender's Office, New South Wales	Contact: Professor Rosemary Rayfuse
ETC Group	Contact: Jim Thomas
The Grantham Institute for Climate Change, Imperial College, London, UK	Contact: Sir Brian Hoskins FRS
Greenpeace	Contact: Dr Doug Parr
Heat Island Group, Lawrence Berkeley National Laboratory	Contact: Hashem Akbari
IMPLICC Steering Committee, Max Planck Institute for Meteorology	Contact: Dr Hauke Schmidt
Institute for Research on Environment and Sustainability at Newcastle University	Contact: Professor David Manning
The Institute of Physics	Contact: Professor Peter Main
Ocean Nourishment Corporation	Contact: Martin Lawrence
Plymouth Marine Laboratory, UK	Contact: Beverley Tremain
Research Councils UK	Contact: Dr Daniel Leary
Royal Swedish Academy of Sciences	Contact: Professor Kevin Noone
Science for Humanity Trust	Contact: Dr. Andrew Meulenberg
Scripps Institution of Oceanography, USA	Contact: Professor Lynn Russell
UK Biochar Research Centre, University of Edinburgh	Contact: Dr Simon Shackley
UK Met Office	Contact: Dr Olivier Boucher

9 Glossary

AOGCMs	Atmosphere-ocean general circulation models.
Acid rain	Precipitation that is unusually acidic. Acid rain is mostly caused by human emissions of sulphur and nitrogen compounds which react in the atmosphere to produce acids.
Aerosols	A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 μm that reside in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: directly through scattering and absorbing radiation, and indirectly by acting a cloud condensation nuclei or modifying the optical properties and lifetime of clouds.[18]
Afforestation	Planting of new forests on lands that historically have not contained forests.[19]
Albedo	The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the surface albedo of soils ranges from high to low, and vegetation-covered surfaces and oceans have a low albedo. The Earth's planetary albedo varies mainly through varying cloudiness, snow, ice, leaf area and land cover changes.[20]
Alkali	A substance that has the ability to neutralise acids. It has a high pH containing hydroxyl ions.
Anion	A negatively charged ion.
Anoxic	No oxygen is present.
Anthropogenic	Caused or produced by humans.
Aqueous	Relating to, similar to, containing, or dissolved in water; watery.
Avoided deforestation	Avoiding deforestation by providing alternative incentives or disincentives to deforestation.
BBSRC	Biotechnology and Biological Sciences Research Council.
BECS	Bioenergy with CO_2 capture and sequestration.
Base	An alkali substance that yields hydroxyl ions when dissolved in water and has a high pH.
Bicarbonate	An acid salt of carbonic acid, containing the ion HCO_3^-. Bicarbonates, or hydrogen carbonates, are formed by the action of carbon dioxide on carbonates in aqueous solution; this reaction is reversed on heating.
Bio-oil	A carbon-rich liquid produced by pyrolysis of plant material, which can be used to produce chemicals and fuels.
Biodiversity	The total diversity of all organisms and ecosystems at various spatial scales (from genes to entire biomes).[21]
Biofuel	A fuel produced from organic matter or combustible oils produced by plants. Examples of biofuel include alcohol, black liquor from the paper-manufacturing process, wood, and soy-bean oil.[22]
Biological pump	The process by which CO_2 fixed by photosynthesis is transferred to the deep ocean as dead organisms, skeletal and faecal material resulting in storage of carbon for periods of decades to centuries or even permanently in the sediment.[23]
Biogeochemical	Involving the geochemistry of a region and the animal and plant life in that region.

18 IPCC WG I (2007) The Physical Science Basis.
19 IPCC WG I (2007) The Physical Science Basis.
20 IPCC WG I (2007) The Physical Science Basis.
21 IPCC WG II (2007) Impacts, Adaptation and Vulnerability.
22 IPCC WG II (2007) Impacts, Adaptation and Vulnerability.
23 Sir Alastair Hardy Foundation for Ocean Science.

Biomass	The total mass of living organisms in a given areas or volume; recently dead plant material is often included as dead biomass. The quantity of biomass is expressed as a dry weight or as the energy, carbon or nitrogen content.[24] Term also sometimes used to refer to any biological material that can be used either directly as a fuel or in industrial production or fibre production.
Biome	Major and distinct regional element of the biosphere, typically consisting of several ecosystems (eg, forests, rivers, ponds, swamps) within a region of similar climate. Biomes are characterised by typical communities of plants and animals.[25]
Boreal forest	Forests of pine, spruce, fir and larch stretching from the east coast of Canada westward to Alaska and continuing from Siberia westward across the entire extent of Russia to the European Plain.[26]
CBD	Convention on Biological Diversity.
CCN	Cloud condensation nuclei. Small particles in the air become surfaces on which water vapour can condense and forms cloud droplets. Sources of cloud condensation nuclei can be both natural and human-caused. Natural sources of cloud condensation nuclei include volcanic dust, sea spray salt, and bacteria. Humans also release unnatural chemicals into the air from the burning of fossil fuels and from industrial sources.[27]
CCS	Carbon capture and storage. A process consisting of the separation of carbon dioxide from industrial and energy related sources, transport to a storage location, and long-term isolation from the atmosphere.[28]
CDM	(KP) Clean Development Mechanism. The CDM allows emission-reduction (or emission removal) projects in developing countries to earn certified emission reduction (CER) credits, each equivalent to one tonne of CO_2. These CERs can be traded and sold, and used by industrialised countries to a meet a part of their emission reduction targets under the Kyoto Protocol.[29]
CDR	Carbon Dioxide Removal (CDR) methods: which reduce the levels of carbon dioxide (CO_2) in the atmosphere, allowing outgoing long-wave (thermal infra-red) heat radiation to escape more easily.
CH_4	Chemical symbol for methane.
CFC	Chloroflourocarbons. A group of synthetic compounds consisting of chlorine, fluorine and carbon.
CLRTAP	1979 Convention on Long-Range Transboundary Air Pollution.
CO_2	Chemical symbol for carbon dioxide.
$CaSiO_3$	Chemical symbol for calcium silicate.
$CaCO_3$	Chemical symbol for calcium carbonate (eg limestone).
$Ca(OH)_2$	Chemical symbol for calcium hydroxide.
Carbonic anhydrase	Enzymes that catalyze the rapid conversion of carbon dioxide to bicarbonate and protons.
Carbonate	CO_3.
Carbonation of silicates	To change from a silicate (SiOx) to a carbonate (CO_3).
Cation	A positively charged ion.
Consequentialist	The view that whether an act is morally right is dependent on the consequences.[30]

24 IPCC WG II (2007) Impacts, Adaptation and Vulnerability.
25 IPCC WG II (2007) Impacts, Adaptation and Vulnerability.
26 IPCC WG II (2007) Impacts, Adaptation and Vulnerability
27 http://weather.about.com/od/c/g/cloudnuclei.htm.
28 IPCC WG III (2007) Mitigation of Climate Change.
29 http://cdm.unfccc.int/about/index.html.
30 http://plato.stanford.edu/entries/consequentialism/.

DECC	(UK) Department of Energy and Climate Change.
Defra	(UK) Department for Environment, Food and Rural Affairs.
Deontological	In deontological ethics an action is considered morally good because of some characteristic of the action itself, not because the product of the action is good. Deontological ethics holds that at least some acts are morally obligatory regardless of their consequences for human welfare.[31]
Detritus	Non-living particulate organic material, typically consisting of bodies or fragments of dead organisms as well as fecal material.
Downwelling	Part of thermohaline ocean circulation where water from the surface sinks as a result of being at a lower temperature and higher density than the water below.
ESRC	(UK) Economic and Social Research Council.
EPSRC	(UK) Engineering and Physical Sciences Research Council.
Ecosystem	A system of living organisms interacting with each other and their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth.[32]
Electrolysis	A chemical change, especially decomposition, produced in an electrolyte by an electric current.
EMICS	Earth system Models of Intermediate Complexity.
ENMOD	1977 Convention on the prohibition of military or any other hostile use of environmental modification techniques.
El Niño (Southern Oscillation)	The basin-wide warming of the tropical Pacific Ocean east of the dateline associated with a fluctuation of a global scale tropical and subtropical surface pressure pattern called the Southern Oscillation. Occurs every 2 to 7 years. The cold phase of ENSO is called La Nina.[33]
Emission Scenario	A plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative scenario.[34]
Eutrophication	The enrichment of water by mineral and organic nutrients (normally nitrates and phosphates) that promote a proliferation of plant life, especially algae, which reduces the dissolved oxygen content and often causes the extinction of other organisms.
Flexible mechanisms (UNFCCC–KP)	Countries with commitments under the Kyoto Protocol to limit or reduce greenhouse gas emissions must meet their targets primarily through national measures. As an additional means of meeting these targets, the Kyoto Protocol introduced three market-based mechanisms: Emissions Trading. The Clean Development Mechanism (CDM), Joint Implementation (JI).
Flux	The rate of emission, absorption, transfer or deposition of a substance or energy from one reservoir to another. Often expressed as the mass or energy per unit area and per unit time (W/m^2).
Geoengineering	The deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change.
GCMs	General-circulation models.
GHGs	Greenhouse gases.
Greenhouse gases	Atmospheric gases of natural (eg water) and anthropogenic origin (CFC's) that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself and by clouds. This property causes the greenhouse effect.[35]

31 http://www.britannica.com/EBchecked/topic/158162/deontological-ethics.
32 IPCC WG I (2007) The Physical Science Basis.
33 IPCC WG I (2007) The Physical Science Basis.
34 IPCC WG I (2007) The Physical Science Basis.
35 IPCC WG I (2007) The Physical Science Basis.

GtC	1 Gigatonne of carbon = 10^9 tonnes carbon.
H_2S	Chemical symbol for hydrogen sulphide.
HCO_3^-	Chemical symbol for bicarbonate.
HNLC (High Nutrient Low Chlorophyll region)	Regions in the ocean where the major nutrient (eg N and P) levels are high but phytoplankton levels are low generally due to low iron availability.
Hydrophilic	Having an affinity for water, being readily absorbed or dissolved in water.
ICSU	International Council for Science.
IPCC	Intergovernmental Panel on Climate Change.
ITCZ	Inter-tropical convergence zone. An equatorial zonal belt of low pressure near the equator where the northeast trade winds meet the southeast trade winds. As the winds converge, moist air is forced upward, resulting in a band of heavy precipitation. This band moves seasonally.[36]
Iron hypothesis	In certain regions of the ocean (HNLC) iron is the limiting nutrient for primary productivity. Increasing iron in these regions will lead to an increase in primary productivity.
JI	Joint Implementation. A market-based implementation mechanism defined in Article 6 of the Kyoto Protocol, allowing developed countries or companies from these countries to implement projects jointly that limit or reduce emissions or enhance sinks, and to share the emission reduction units.[37]
KP	(UNFCCC) Kyoto Protocol.
LC London Convention	1972 London Convention.
LP	1996 Protocol (of the London Convention).
Mesosphere	The layer of the atmosphere above the stratosphere from about 50 to 90 km above the Earth's surface.
Moral hazard	One of two main sorts of market failure often associated with the provision of insurance. Moral hazard means that people with insurance may take greater risks than they would do without it because they know they are protected, so the insurer may get more claims than it bargained for.
N	Chemical symbol for nitrogen.
N_2O	Chemical symbol for Nitrous Oxide.
NPP	Net Primary Productivity.
NO	Chemical symbol for nitric oxide.
NCAR CAM3.1	National Center for Atmospheric Research Community Atmosphere Model 3.1.
NERC	(UK) Natural Environment Research Council.
OCS	Carbonyl sulphide.
OST	1967 Outer Space Treaty.
Ocean acidification	A decrease in the pH of sea water due to the uptake of anthropogenic carbon dioxide.[38]
Olivine	One of the most common minerals—magnesium iron silicate $(Mg,Fe)_2SiO_4$. Mineral names are forsterite and fayalite. Also known as chrysoline, evening emerald and peridot.
P	Chemical symbol for phosphorus.
pH	pH is a dimensionless measure of the acidity of water (or any solution) given by its concentration of hydrogen ion (H^+). pH is measured on a logarithmic scale where $pH = -\log_{10}(H^+)$. Thus, a pH decrease of 1 unit corresponds to a 10-fold increase in the concentration of H^+, or acidity.[39]

36 IPCC WG I (2007) The Physical Science Basis.
37 IPCC WG III (2007) Mitigation of Climate Change.
38 IPCC WG I (2007) The Physical Science Basis.
39 IPCC WG I (2007) The Physical Science Basis.

Peatlands	Typically a wetland such as a mire slowly accumulating peat. Peat is formed from dead plants, typically Sphagnum mosses, which are only partially decomposed due to the permanent submergence in water and the presence of conserving substances such as humic acid.[40]
Petagram	10^{15} grammes = 1 Gt = 10^{9} tonnes, one billion tonnes.
Ppm	Parts per million. The concentration of a pollutant in air in terns of molar ratio. A concentration of 1 ppm means that for every million (10^{6}) molecules in a volume of air, there is one molecule of the specified pollutant present.[41]
Primary production	All forms of production accomplished by plants, also called primary producers.[42]
Pyrolysis	The chemical decomposition of organic materials by heating in the absence of oxygen or any other reagents, except possibly steam. Heating biomass rapidly (fast pyrolysis) can help increase yields of liquid fuels, where the resulting bio-oil can then be transported for conversion into biofuels.
R&D	Research and Development.
REDD	Reducing emissions from deforestation and degradation.
Radiative Forcing (RF)	Radiative forcing is the change in the net, downward minus upwards, irradiance (expressed in W/m^2) at the tropopause due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the sun.[43]
Reforestation	Replanting of forests on lands that have been converted to some other use.[44]
Remineralised	Organic material converted back into inorganic form usually mediated by biological activity.
Sequestration	Carbon storage in terrestrial or marine reservoirs. Biological sequestration includes direct removal of CO_2 from the atmosphere through land-use change, afforestation, reforestation, carbon storage in landfills and practices that enhance soil carbon in agriculture.[45]
SRM	Solar Radiation Management (SRM) methods: which reduce the net incoming short-wave (ultra-violet and visible) solar radiation received, by deflecting sunlight, or by increasing the reflectivity (albedo) of the atmosphere, clouds or the Earth's surface.
SiO_2	Chemical symbol for silicon dioxide/silica.
SO_2	Chemical symbol for sulphur dioxide.
Silicate	Any of a large group of minerals that consist of SiO_2 or SiO_4 combined with one or more metals and sometimes hydrogen.
Sink	Any process, activity which removes a pollutant or precursor gas from the atmosphere or ocean.
Solar constant	The solar constant is the amount of energy that normally falls on a unit area (1 m^2) of the Earth's atmosphere per second when the Earth is at its mean distance from the sun.
Solubility pump	A physical-chemical process that transports carbon (as dissolved inorganic carbon) from the ocean's surface to its interior.
Stratosphere	The highly stratified region of the atmosphere above the troposphere extending from about 20 km (ranging from 9 km in high latitudes to 16 km in the tropics on average) to about 50 km.[46]
Syngas	A synthetic gas containing varying amounts of carbon monoxide and hydrogen.
Trophic	The relationship between different species in a food chain.
Tropopause	The boundary between the troposphere and the stratosphere.

40 IPCC WG II (2007) Impacts, Adaptation and Vulnerability.
41 IPCC WG I (2007) The Physical Science Basis.
42 IPCC WG II (2007) Impacts, Adaptation and Vulnerability.
43 IPCC WG I (2007) The Physical Science Basis.
44 IPCC WG I (2007) The Physical Science Basis.
45 IPCC WG III (2007) Mitigation of Climate Change.
46 IPCC WG I (2007) The Physical Science Basis.

Troposphere	The lowest part of the atmosphere from the surface to about 10 km in altitude in mid-latitudes (ranging from 9 km in high latitudes to 16 km in the tropics on average) where clouds and 'weather' phenomena occur. In the troposphere temperatures generally decrease with height.
UNCCD	United Nations Convention to Combat Desertification.
UNCLOS	UN Law of the Sea Convention.
UNFCCC	United Nations Framework Convention on Climate Change.
Urea	A water-soluble compound that is the major nitrogenous end product of protein metabolism and is the chief nitrogenous component of the urine in mammals and other organisms. Used as a fertiliser and feed supplement.
Upwelling	In thermo-haline circulation a region of the ocean where water driven by temperature and density is brought from the bottom of the ocean to the top bringing high levels of nutrients.
Virtue-based	Virtue-based ethical theories place less emphasis on which rules people should follow and instead focus on the development of good character traits, such as kindness and generosity, which will allow the correct decisions to be made in life.
W/m^2	Watts per metre squared. The amount of energy that falls on a square metre in one second sometimes known as a flux.
WMO	World Meteorological Organisation.
Weathering	Any of the chemical or mechanical processes by which rocks exposed to the weather undergo changes in character and break down.[47]

[47] IPCC WG I (2007) The Physical Science Basis.

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Professor John Latham, National Center for Atmospheric Research, USA.

Stuart Leckie, Royal Society Science Policy Centre, London, UK.

Professor Tim Lenton, University of East Anglia, UK.

Professor John O' Neill, School of Social Sciences, University of Manchester, UK.

Professor Michael Northcott, School of Divinity, University of Edinburgh, UK.

Dr Tim Palmer FRS European Centre for Medium-Range Weather Forecasts, UK.

Dr Phil Rasch, Pacific Northwest National Laboratory, USA.

Professor Stephen Salter, University of Edinburgh, UK.

Professor R.D Schuiling, University of Utrecht, The Netherlands.

Naomi Vaughan, University of East Anglia, UK.

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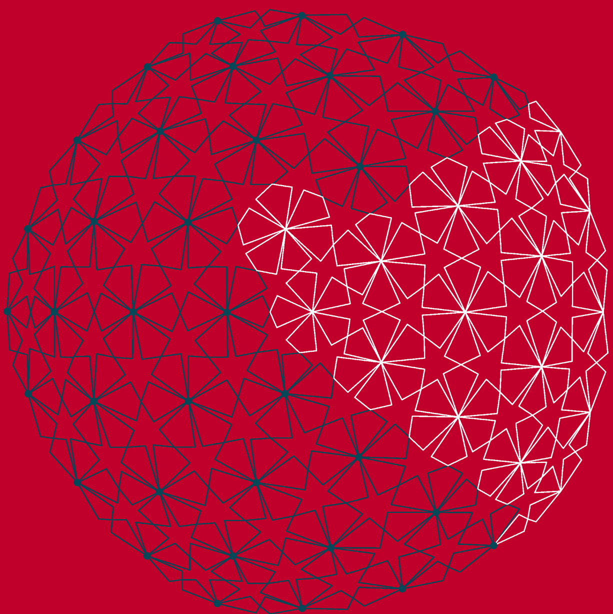

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