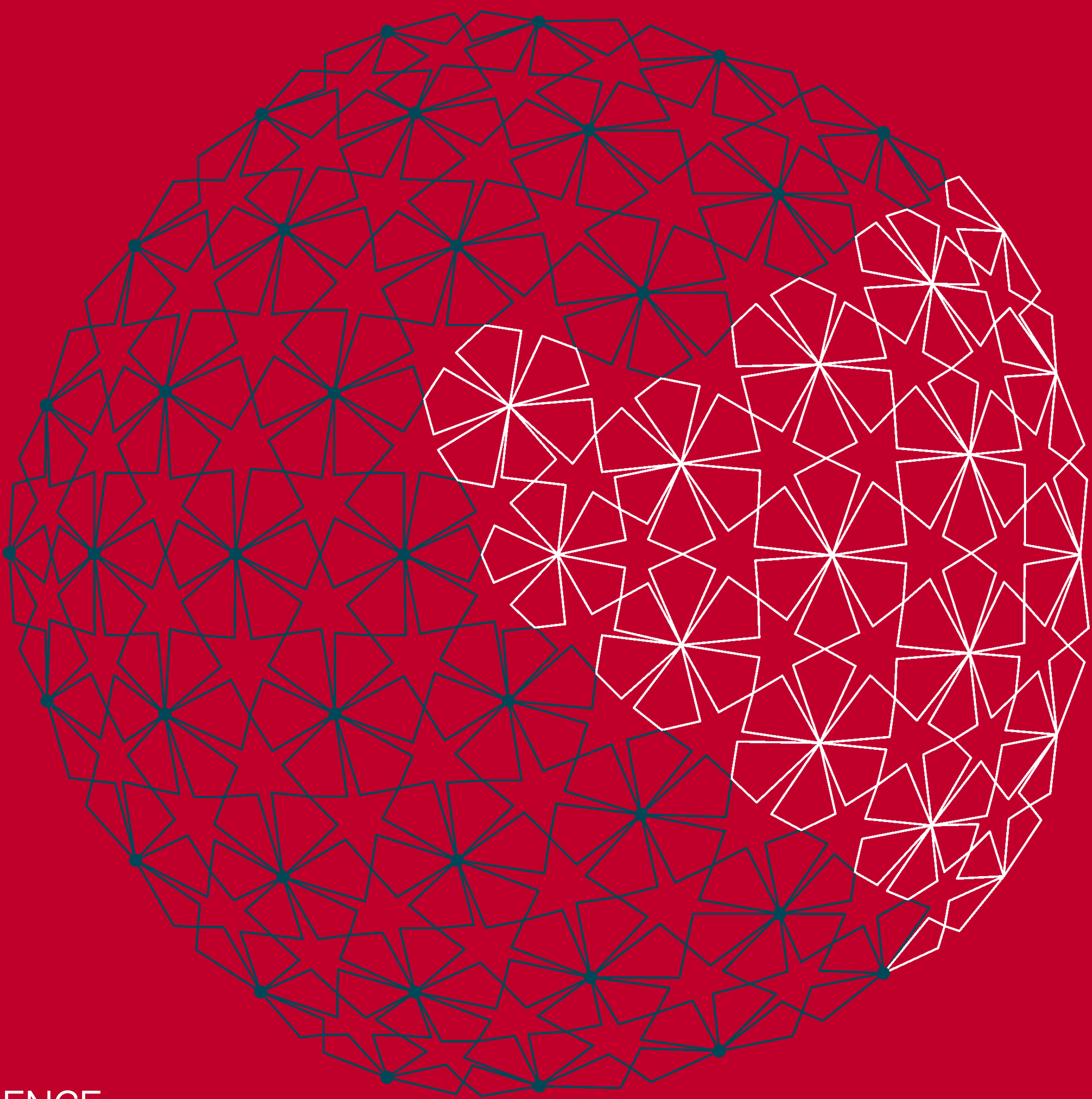
Geoengineering the climate

Science, governance and uncertainty

September 2009



EXCELLENCE IN SCIENCE

THE ROYAL SOCIETY

Geoengineering the climate: science, governance and uncertainty

Contents

Summary

Background

Climate change is happening. Its impacts and costs will be large, serious, and unevenly spread. The impacts may be reduced by adaptation, and moderated by mitigation, especially by reducing emissions of greenhouse gases. However, global efforts to reduce emissions have not yet been sufficiently successful to provide confidence that the reductions needed to avoid dangerous climate change will be achieved. It is hoped that post-2012 emission reduction targets will stimulate greater action through more effective mechanisms, but there is a serious risk that sufficient mitigation actions will not be introduced in time, despite the fact that the technologies required are both available and affordable.

It is likely that global warming will exceed 2°C this century unless global greenhouse gas emissions are cut by at least 50% of 1990 levels by 2050, and by more thereafter. There is no credible emissions scenario under which global mean temperature would peak and then start to decline by 2100. Unless future efforts to reduce greenhouse gas emissions are much more successful then they have been so far, additional action may be required should it become necessary to cool the Earth this century.

Such action might involve **geoengineering**, defined as the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming.

Headline messages

The safest and most predictable method of moderating climate change is to take early and effective action to reduce emissions of greenhouse gases. No geoengineering method can provide an easy or readily acceptable alternative solution to the problem of climate change.

Geoengineering methods could however potentially be useful in future to augment continuing efforts to mitigate climate change by reducing emissions, and so should be subject to more detailed research and analysis.

Geoengineering of the Earth's climate is very likely to be technically possible. However, the technology to do so is barely formed, and there are major uncertainties regarding its effectiveness, costs, and environmental impacts.

Methods that act rapidly by reflecting sunlight may prove to be ineffective in offsetting changes in rainfall patterns and storms, but current climate models are not sufficiently accurate to provide a reliable assessment of these at the regional level.

Methods that act by removing greenhouse gases from the atmosphere involve fewer uncertainties and risks, but would have a much slower effect on reducing global temperature. These methods could eventually make an important contribution to mitigating climate change.

The acceptability of geoengineering will be determined as much by social, legal and political issues as by scientific and technical factors. There are serious and complex governance issues which need to be resolved if geoengineering is ever to become an acceptable method for moderating climate change.

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

Key recommendations:

- 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% on 1990 levels by 2050 and more thereafter. Nothing now known about geoengineering options gives any reason to diminish these efforts;
- 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 climate models, and carefully planned and executed experiments.

Geoengineering methods

Geoengineering methods can usefully be divided into two basic 'classes':

1) Carbon dioxide removal (CDR) techniques which remove CO_2 from the atmosphere;
2) Solar Radiation Management (SRM) techniques that reflect a small percentage of the sun's light and heat back into space.

Both Carbon Dioxide Removal and Solar Radiation Management methods have the ultimate aim of reducing global temperatures, but there are major differences in their modes of action, the timescales over which they are effective, temperature effects and other consequences, so that they are generally best considered separately.

Carbon dioxide removal techniques address the root cause of climate change by removing greenhouse gases from the atmosphere.

Solar radiation management techniques attempt to offset effects of increased greenhouse gas concentrations by causing the Earth to absorb less solar radiation.

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

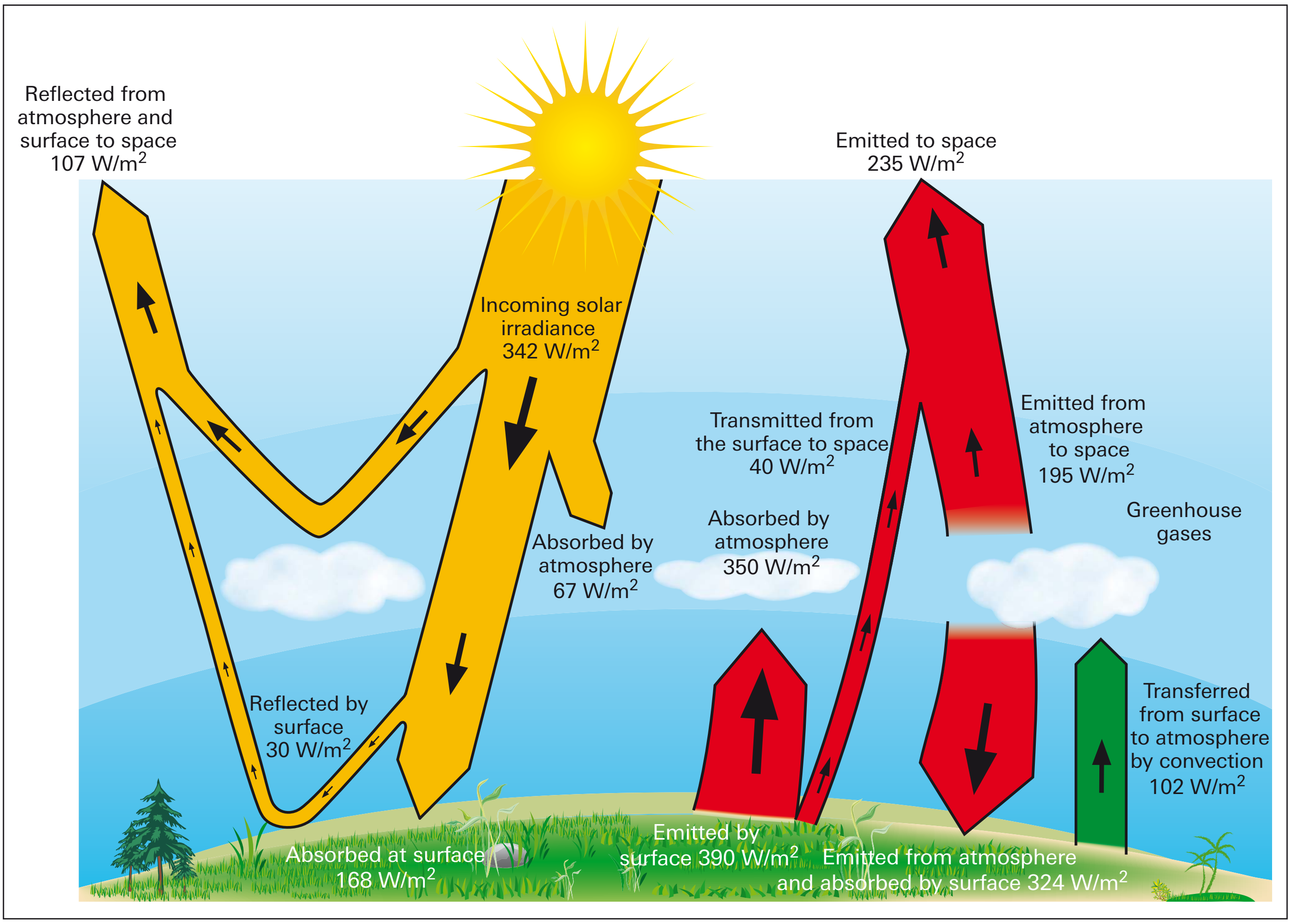
To understand the principles of geoengineering and the methods by which the range of interventions have effect it is necessary to understand the climate system. A detailed review of the science of climate change is provided in the IPCC Fourth Assessment working group 1 report (AR4) (IPCC 2007a). Here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

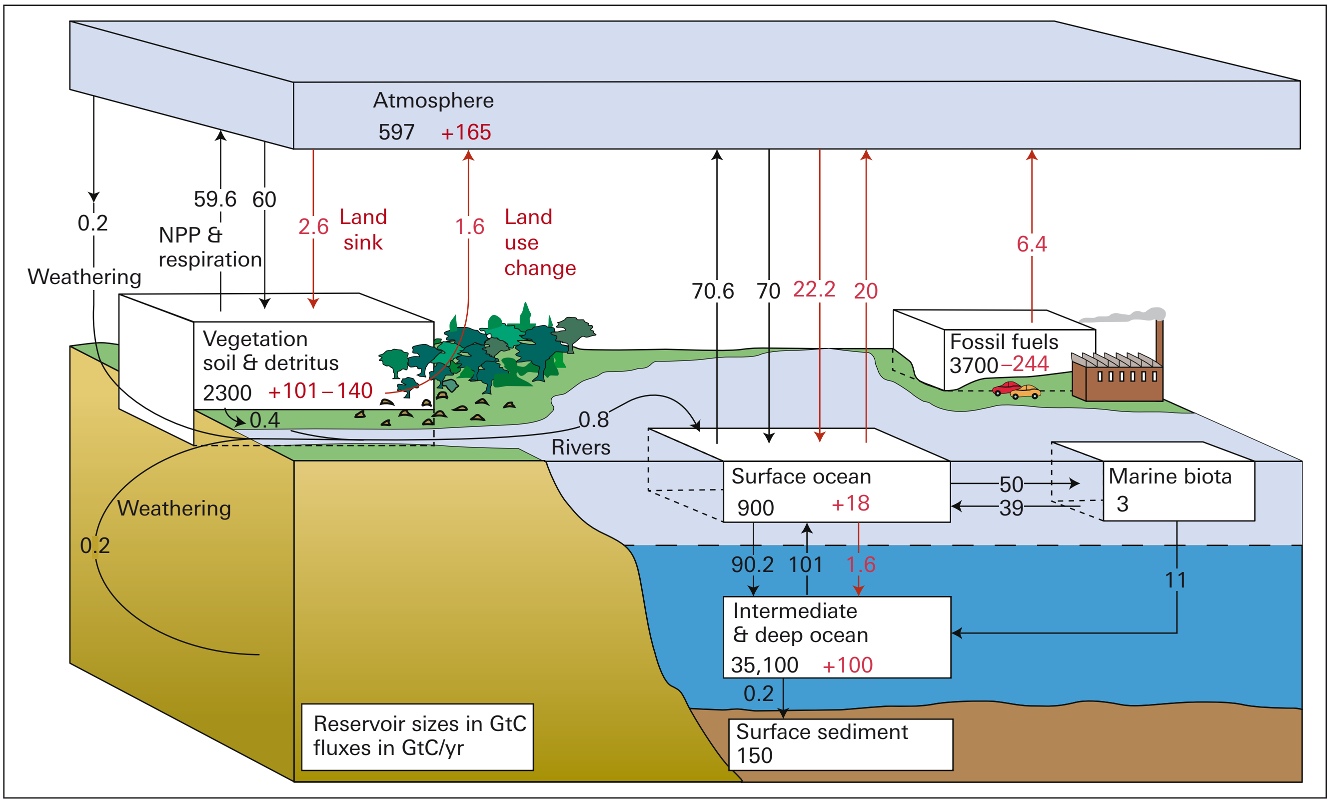
Increases in atmospheric greenhouse gas concentrations (eg, CO_2, CH_4, N_2O, ground level ozone (O_3) and chlorofluorocarbons (CFCs)) due to human activities such as fossil fuel burning, deforestation and conversion of land for agriculture, have upset this delicate balance as the gases restrict the 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.

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.

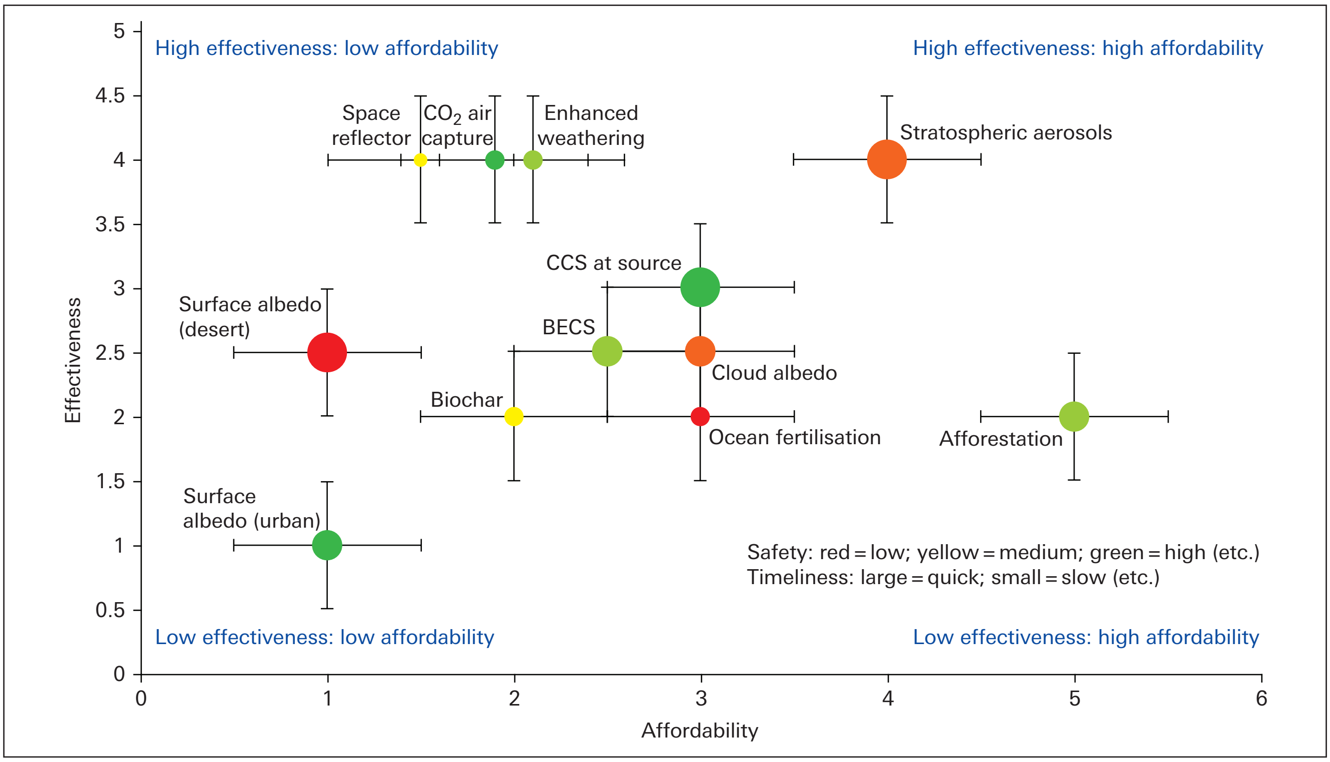
On the basis of this information, a provisional overall evaluation based on the summary tables for the different methods provided in Chapters 2 and 3 is presented in Table 5.1 and Figure 5.1 below (in two cases the entries have been adjusted minimally to avoid confusion caused by over-plotting of the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