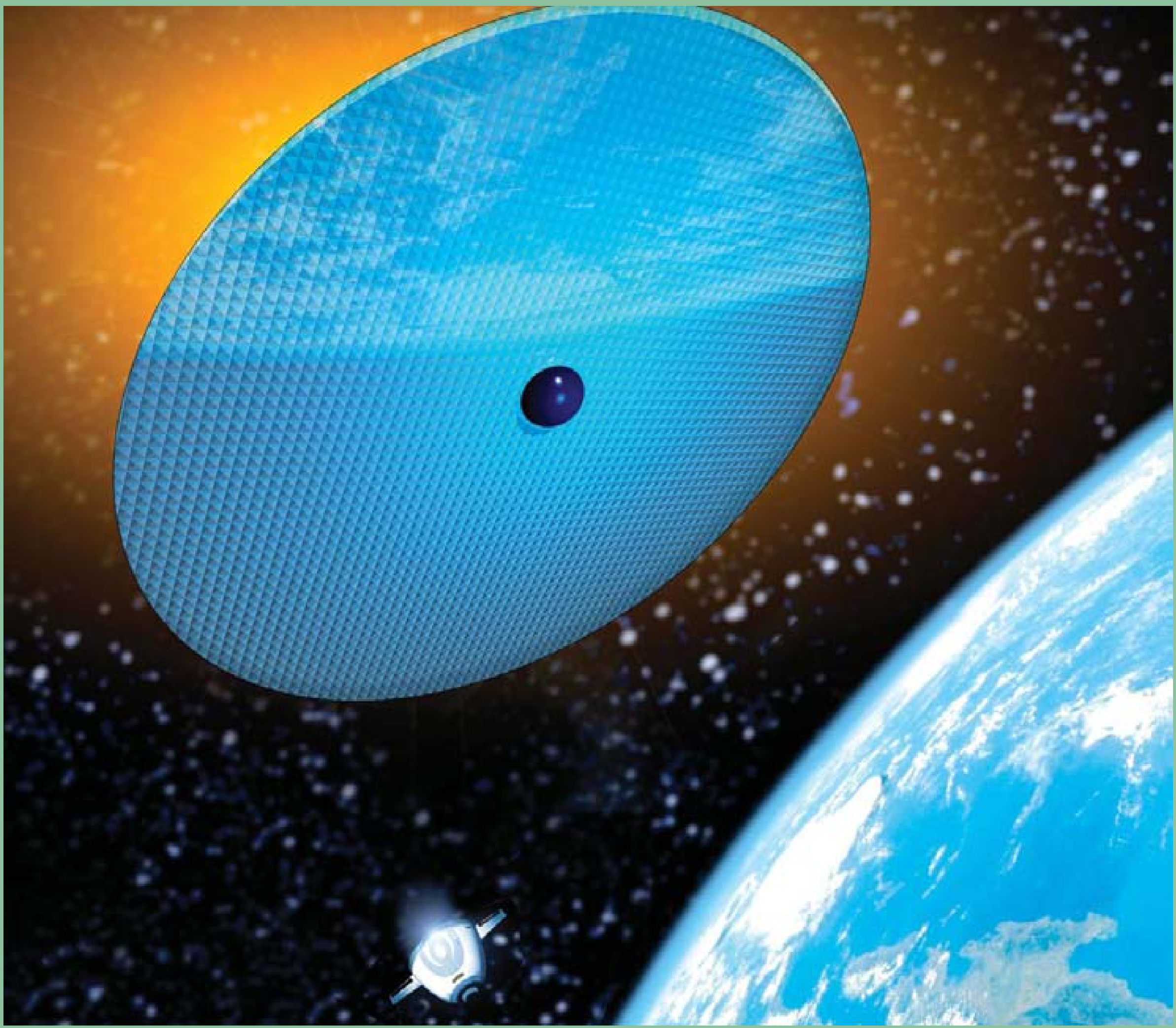
Geoengineering: Challenges and global impacts



Report of a seminar, held on 15 July 2009, that explored approaches to managing climate change based on strategic engineering of the environment on a global scale.

IOP Institute of Physics | RSC Advancing the Chemical Sciences | The Royal Academy of Engineering

Introduction

The Institute of Physics, the Royal Society of Chemistry and the Royal Academy of Engineering held a joint seminar at the House of Commons on 15 July 2009 to explore approaches to managing climate change based on strategic engineering of the environment on a global scale. This seminar is the latest in a series demonstrating key routes by which contemporary physics, chemistry and engineering affect life in the 21st century.

Geoengineering provides a set of options in which the Earth's climate is deliberately manipulated to offset the effects of global warming due to increasing levels of greenhouse gases in the atmosphere. The various proposals offer the potential to mitigate the worst effects of climate change, in some scenarios quite quickly, so buying more time to make the necessary reductions in man-made carbon dioxide (CO_2) emissions.

The seminar focused on several imaginative proposals and also considered the social and political implications of attempting to implement such technologies. **Dr Brian Iddon MP**, vice-president of the Parliamentary and Scientific Committee and member of the House of Commons Innovation, Universities, Science and Skills Committee (now the Science and Technology Committee), chaired the meeting. **Dr Alan Gadian** of the University of Leeds proposed a cloud-whitening strategy to reflect more solar radiation back into space and thus cool the planet. **Dr Dan Lunt** of the University of Bristol described a space-based scheme using mirrors to reflect sunlight away from the Earth. **Prof. Andrew Watson** of the University of East Anglia summarised methods of fixing atmospheric carbon by stimulating the growth of marine algae. Finally, **Prof. Steve Rayner** from the University of Oxford discussed public acceptability and policy issues relating to geoengineering schemes.

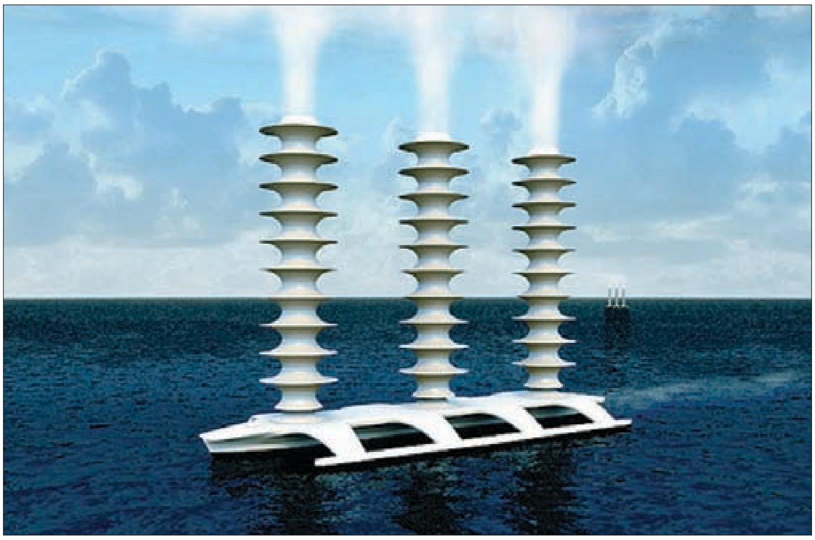
Responses to global warming

Most climate experts now agree that rising emissions of CO_2 are causing global warming, and if they are not brought down considerably they will lead to unacceptable levels of climate change. Before the Industrial Revolution, the atmospheric concentration of CO_2 was about 280 parts per million (ppm) but it has now risen to 385 ppm. With industrialisation and energy consumption in developing countries set to increase, CO_2 levels could rise much further – to as much as 1000 ppm by the end of the century, leading to an increase in global surface temperatures of up to 7 °C. Although there are uncertainties in climate models, they predict that concentrations above 550 ppm would result in massive, irreversible changes in the climate and the global environment. Most of the Greenland ice sheet would melt and sea levels would rise, with low-lying coastal countries such as Bangladesh becoming permanently flooded.

How should we respond? The answer has four strands. The most important and obvious solution is to reduce and manage energy use, so that much less CO_2 is emitted. The second is to control CO_2 emissions into the atmosphere through industrial carbon management and CO_2 storage. A third, pragmatic approach is to look at ways of adapting to the impact of climate change.

The fourth possibility is to engineer the planetary environment to counteract global warming. While this last option may seem drastic, it is likely that implementing the first and second approaches will not slow down the underlying processes driving climate change quickly enough. Even the most radical emissions reduction – say, by 80% over the next 30 years – will still leave atmospheric CO_2 at about 450 ppm. This is the EU's target (which may be unrealistic) and would lead to a stabilisation at 2 °C warming.

Climate change might happen even more rapidly than computer models have predicted: melting of the ice sheets will reveal darker surfaces beneath, which will warm up more quickly by absorbing sunlight. In addition, melting of the Arctic permafrost could release large amounts of methane, a much more powerful greenhouse gas than CO_2. Thus, in the short term, geoengineering solutions that can be implemented quickly and effectively over periods from a few years to decades, could provide the necessary breathing space to allow the longer-timescale CO_2 reduction efforts to take effect.

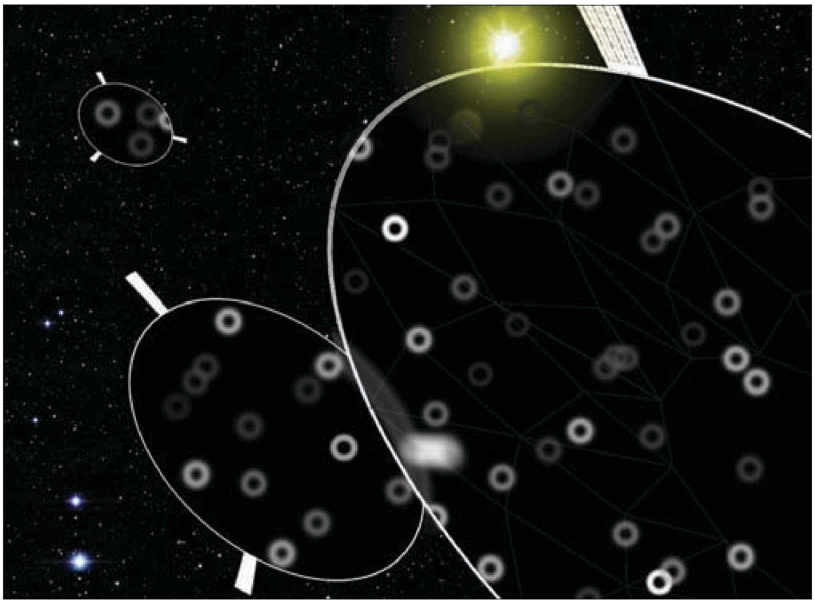


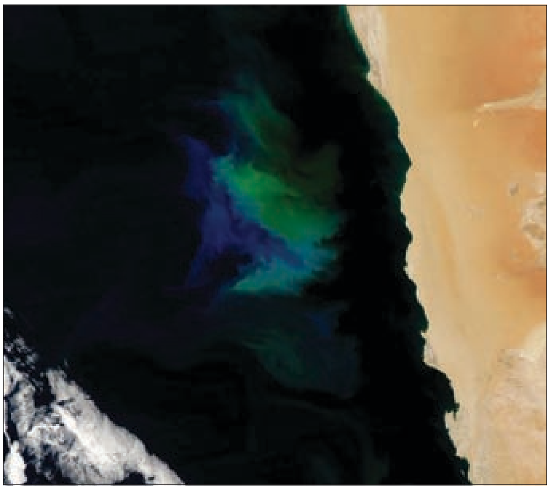
A conceptual spray vessel. Courtesy: J MacNeill and S Salter/University of Edinburgh

There are two main approaches: the first is to manage the amount of solar radiation reaching the Earth's atmosphere; and the second is to reduce atmospheric CO_2, particularly by engineering the global carbon cycle. The seminar speakers explained three of the candidate schemes.

Cloud albedo modification

Stratocumulus clouds cover more than 30% of the ocean and have a high reflectance, which depends on the number and size of the water droplets that they contain. Physics predicts that a greater number of smaller droplets in a cloud system increases its whiteness, and thus reflectivity, or albedo. More of the sunlight is then reflected back into space. Dr Gadian described a system developed by a team of UK and US scientists to increase the albedo of stratocumulus clouds by spraying droplets of seawater into the atmosphere from specially designed ships. The droplets, ideally of less than 1 μm in diameter, would ascend to cloud-base levels via thermals and turbulence. They would dissipate, spreading sea-salt particles that act as nuclei for cloud condensation. The system has the advantage of being an enhancement of a natural ocean process produced by breaking waves. When it is switched off, the effects would disappear within a few weeks.





Top: light reflectors stationed at L1. Courtesy: R Angel/ Steward Observatory, University of Arizona. Right: a phytoplankton bloom off the coast of south-west Africa. Courtesy: NASA

The spray mechanism has been designed by the British engineer Stephen Salter at the University of Edinburgh. The team's proposal is to build a fleet of wind-powered remote-controlled ships that would operate continuously. "They could be built for about £2 bn and would have a low ecological impact," said Dr Gadian.

Does cloud whitening work? The technology and concept has already undergone preliminary trials. Computer simulations have been carried out for a range of spray rates, which reveal that a cooling of 1.2 watts per square metre ($W m^{-2}$) could be achieved over about 20 years. This figure, when compared with the predicted increase in radiative heating of $3.7 W m^{-2}$ for a doubling of CO_2 concentrations, suggests that cloud albedo modification is a viable option. Dr Gadian warns that because of errors in current climate models, particularly relating to rainfall, more modelling is needed, as well as more atmospheric studies and field experiments. "The UK is still one of the leaders in atmospheric science, and we have a duty to do the research. It would take two years to build an experimental spray system and two years to carry out the field experiment. To give us the necessary breathing space of 20 years, however, we must start now," he said.

Sunshade engineering

A more ambitious engineering option is to place a giant reflector system between the Sun and the Earth. Roger Angel, a British astronomer at the University of Arizona in the US, has proposed launching a 100 000 km-long cloud of 15 trillion reflective discs, each 60–70 cm across, to shade the Earth. The sunshade would be positioned at the Lagrange, L1 point (the orbit 1 500 000 km out in space where an object sits in a gravitationally stable, fixed position between the Sun and the Earth). It could be done within 25 years and would cost a few trillion dollars, explained Dr Lunt.

Taking a climate model developed by the Met Office, Dr Lunt's team carried out a series of simulations to assess what happens when the amount of solar energy reaching the Earth is reduced by a sunshade. A control simulation was run with pre-industrial levels of atmospheric CO_2, with which a second simulation, with four times the amount of CO_2, could be compared. For the same CO_2 concentration, a third simulation introduced a lower level of solar radiation, as achieved with a sunshade. This demonstrated that a reduction in radiation of 4.2% was enough to eliminate global warming.

Closer examination revealed that the effects would be uneven, with warming in the polar regions and cooling in the tropics. However, reducing the shade strength to 75% brought the anomalous variations down to an acceptable level. "We need to do more research to look at the unforeseen effects of geoengineering," said Dr Lunt. "Reducing CO_2 emissions should always remain the focus of efforts to deal with global warming. Sunshade engineering is definitely a plan B," he added.

Ocean fertilisation

Curtailing the sunlight reaching the Earth's surface does not, of course, reduce the amount of atmospheric CO_2. "It treats the symptoms not the cause," said Prof. Watson. A more direct solution being considered is to remove CO_2 from the atmosphere and to store it. One approach, first proposed at the beginning of the 1990s, is to engineer the natural turnover of carbon in the biogeochemical cycle via ocean fertilisation. The idea is to stimulate the growth of marine algae by adding nutrients such as iron, or nitrogen and phosphorus. The resulting algal bloom then takes up and fixes increased amounts of CO_2 via photosynthesis. Eventually, the biomass sinks to the bottom of the ocean.

Experiments with iron fertilisation have already been carried out in iron-starved ocean regions, the Equatorial Pacific, North Pacific and Southern Ocean, and have been shown to stimulate blooms of phytoplankton. "While these results are important for our understanding of the oceans, they do not translate directly into carbon sequestration," said Prof. Watson. The amount of carbon sequestered is variable and unpredictable. Because the CO_2 is taken from the surface ocean rather than directly from the atmosphere, the net atmospheric carbon fixed is difficult to assess. Furthermore, the effectiveness depends on how much of the biomass sinks, how far it sinks and whether the material is eaten – which all depends on the alga species. The efficiency of iron fertilisation also seems to depend on location, working well in the Southern Ocean but not in the Equatorial Pacific.

Adding nitrogen and phosphorus, which are limiting nutrients over large areas of the oceans, would be effective anywhere – and proponents claim that they have the added bonus of increasing fish stocks. However, these materials are much more expensive than iron, and much more of them would be needed: whereas one atom each of nitrogen and phosphorus will fix six and 100 atoms of carbon respectively, 100 000 atoms of carbon are fixed by one atom of iron. Furthermore, their application to the oceans would compete with their essential land use as agricultural fertilisers. A negative feedback mechanism could also come into play, because adding nitrogen would slow down the ongoing natural fixation of nitrogen in the oceans.

Prof. Watson added that the capacity of ocean fertilisation to sequester atmospheric CO_2 is quite limited. "Our models for the ocean's carbon cycle suggest that it would be difficult to increase carbon fixation by more than 10 to 20%. We estimate that a few hundred million tonnes of carbon could be fixed a year, which is small compared with the annual emission rates

Box 1: Examples of geoengineering approaches

Solar-radiation management

Injection of sulphate particles into the stratosphere to reflect or absorb solar radiation

Pros:
- Known to work: the eruption of Mount Pinatubo in the Philippines threw up particulate matter into the atmosphere, which lowered global temperatures.
- Has a short lead time; 3–5 years.
- Relatively cheap.

Cons:
- Requires international agreement.
- There is a potential difficulty in gaining public acceptability.
- Could cause ozone depletion.

Cloud albedo modification (p3)

Pros:
- Has quite a short lead time; 20 years.
- Quick to turn off.
- Cheap.
- Natural process.

Cons:
- Effectiveness is uncertain.
- Needs to be carried out continuously.

Sunshade engineering (p4)

Pros:
- Would work immediately.
- Would be effective.

Cons:
- Expensive.
- Could be weaponised.
- Requires international agreement.

Painting rooftops of buildings with reflective paint

Pros:
- Cheap.

Cons:
- Would work only on a local scale, in cities that are usually hotter than the surrounding environment.

Selecting or engineering varieties of food crops to be more reflective

Pros:
- Much of Europe and North America could be cooled by up to 1 °C during the summer growing season, equivalent to an annual global cooling of more than 0.1 °C.

Cons:
- Would have limited efficacy on a global scale.

CO_2 reduction

Iron fertilisation of oceans to increase photosynthesis

Pros:
- Enhancement of a natural process.
- Cheap.

Cons:
- The efficacy is uncertain because of the limited uptake capacity of the oceans.
- Potential deleterious effects such as the release of nitrogen oxides.
- Possibility that the ocean nutrient balance would be disrupted.

Adding lime or other alkalis to oceans to lower the acidity and allow more CO_2 to be absorbed

Pros:
- Calculations indicate that it could be effective.

Cons:
- The material is energy-intensive to produce.
- Potential disruption to the ocean balance.

Direct extraction of CO_2 from the air using absorbents

Pros:
- Shown to be technically feasible.
- The equipment can be switched on and turned off at will.
- The amount of carbon captured can be measured accurately for the carbon-trading market.
- The technology can be located anywhere.

Cons:
- Might be socially unacceptable if the installations are large.
- The economics of large-scale use is not known.
- The time and effectiveness in mitigating climate change is uncertain.

Box 2: UK policy on geoengineering

The UK government has not yet put in place a policy for geoengineering, either as a way of gaining a "grace period" of two or three decades, or as a plan B to deal with the possibility that climate sensitivity turns out to be greater than expected. Two UK research councils, the Engineering and Physical Sciences Research Council (EPSRC) and the Natural Environment Research Council (NERC), fund research relevant to geoengineering, mostly in terms of modelling Earth and climate systems. For example, the NERC has allocated £2 m to a consortium studying cloud seeding and cloud formation and related albedo effects. In addition, the research councils' Energy Programme has recently announced that it plans to provide funding support for geoengineering research, and will hold a scoping workshop, led by the EPSRC, to identify the major challenges and potential research themes for future activity. The Royal Society has published its report, *Geoengineering the climate: Science, governance and uncertainty*, which is in line with the views expressed at the seminar. The group of experts who compiled it recommended that an international research programme on geoengineering should be set up immediately at a cost of £100 m, with the UK contributing around £10 m.

of 7–8 billion tonnes." In addition, undesirable changes in the marine ecosystem cannot be ruled out, and there are also ethical and legal issues to be considered.

Prof. Watson concluded that iron fertilisation could be carried out on a small, commercially based scale and would have a similar impact on reforestation programmes. However, he suggested that land-based engineering schemes to capture CO_2 were more promising (box 1, p5).

Social and ethical implications

In his talk, Prof. Rayner explained that although geoengineering had been around for a long time, the concept was highly politicised and was an approach that policy makers found difficult to talk about. The view has been that geoengineering solutions create a moral hazard by providing a "get-out-of-jail card" that permits society to continue to emit CO_2 with impunity. There are also concerns about interfering with large-scale Earth systems. In addition, it is difficult to make policy and management decisions about technologies that are largely undeveloped, and for which the consequences of implementation are far from understood. Prof. Rayner said that nevertheless, geoengineering needed to be considered for two reasons: the first reason is to buy time or to shave off the peaks from the rising CO_2 emissions profile – especially because they may not fall as originally predicted due to the rapid economic growth of China and India. The second is as an insurance policy against a climatic emergency.

Prof. Rayner divided concepts into two types: those involving tuning large-scale Earth systems; and encapsulated, hard-engineering solutions. All of them have their pros and cons, he said. Taking one example of the first kind – that of injecting sulphate aerosols into the atmosphere (box 1) – he said that it was known to work and was cheap. However, there were several issues: the results could be uneven with undesirable side effects; it would require international agreement before it could be legally implemented; and it might be difficult to gain public acceptability for a scheme that appears to involve deliberate environmental pollution. Similar issues arise for ocean treatments such as iron fertilisation or the addition of lime (box 1): as well as being slower to act, the effects are not proven and there may be unintended consequences on the ocean's ecosystems. There is also the question of international law. There are already two treaties that might claim jurisdiction, the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (commonly called the London Convention) and the UN Convention on Biological Diversity.

Hard-engineering solutions also have challenges. Space-based reflectors would require expensive launch facilities and might raise public concerns about weaponisation. Schemes involving carbon-capture machines that absorb CO_2 from the air and then store it in spent oil wells or saline aquifers are less controversial, and would not involve issues of international law (box 1). They can also be switched off instantly. The technology has the advantage of enabling accurate measurement of the carbon captured, as required for claiming carbon credits in the carbon-trading market. However, the economics of implementing any of these technologies is not known accurately on a large scale.

Prof. Rayner pointed out that to formulate a policy on geoengineering also required taking into account the timeframes over which they would be effective. Sulphate aerosols offer an emergency response, while air capture offers emission shaving over the medium term. He reiterated the views of the other speakers that, based on the precautionary principle, more research must be done, adding that the ethical, political, economic and legal aspects must also be considered. "We have a choice, we must exercise it wisely," he said.

Further information

1. National Centre for Atmospheric Science (NCAS), www.ncas.ac.uk.
2. The Bristol Research Initiative for the Dynamic Global Environment (BRIDGE), www.bridge.bris.ac.uk.
3. Tyndall Centre for Climate Change, www.tyndall.uea.ac.uk.
4. Geoengineering research, Parliamentary Office of Science and Technology, Postnote, March 2009, Number 327, www.parliament.uk/parliamentary_offices/post/pubs2009.cfm.
5. Engineering: turning ideas into reality, House of Commons Innovation, Universities, Science and Skills Committee, Fourth Report of Session 2008–09, Volume I, www.publications.parliament.uk/pa/cm200809/cmselect/cmdius/50/5002.htm.
6. Engineering: turning ideas into reality: Government Response to the Committee's Fourth Report, House of Commons Innovation, Universities, Science and Skills Committee, Fifth Special Report of Session 2008–09, 24 June 2009, www.publications.parliament.uk/pa/cm200809/cmselect/cmdius/759/75902.htm.
7. Geo-Engineering – Giving us time to act?, the Institution of Mechanical Engineers, August 2009, www.imeche.org/about/keythemes/environment/Climate+Change/Geoeng.
8. Geoengineering the climate: Science, governance and uncertainty, the Royal Society, September 2009, http://royalsociety.org/document.asp?tip=0&id=8729.
9. Engineering the climate, *Physics World*, September 2009, http://physicsworld.com/cws/article/print/40222.
10. Climate Change 2007, Intergovernmental Panel on Climate Change, Fourth Assessment Report, www.ipcc.ch/publications_and_data/publications_and_data_reports.htm.

About the societies

The Institute of Physics (IOP) is a scientific charity devoted to increasing the practice, understanding and application of physics. It has a worldwide membership of more than 36 000 and is a leading communicator of physics-related science to all audiences, from specialists through to government and the general public. Its publishing company, IOP Publishing, is a world-leader in scientific publishing and the electronic dissemination of physics.

The Royal Society of Chemistry (RSC) is a leading professional body for chemical scientists and we are committed to ensuring that an enthusiastic, innovative and thriving scientific community is in place to face the future. The RSC has a global membership of over 46 000 and is actively involved in the spheres of education, qualifications and professional conduct. It runs conferences and meetings for chemical scientists, industrialists, policy makers and the public around the world and from the Chemistry Centre at Burlington House in London – the world's best venue for showcasing the chemical sciences. It is a global scientific publisher, offering an exceptional range of peer-reviewed journals, magazines, books, databases and publishing services to the chemical science community. In all its work, the RSC is objective and impartial, and it is recognised throughout the world as an authoritative voice of chemistry and chemists.

The Royal Academy of Engineering is Britain's national academy for engineering, bringing together the country's most eminent engineers from all disciplines to promote excellence in the science, art and practice of engineering. Its strategic priorities are to enhance the UK's engineering capabilities, to celebrate excellence and inspire the next generation, and to lead debate by guiding informed thinking and influencing public policy.

Geoengineering:
Challenges and global impacts

For further information, or a large-print version, please contact:

Tajinder Panesor
Institute of Physics
76 Portland Place
London W1B 1NT UK
Tel +44 (0) 20 7470 4939
Fax +44 (0) 20 7470 4848
E-mail tajinder.panesor@iop.org
Web **www.iop.org**
Registered charity no. 293851

IOP Institute of Physics | RSC Advancing the Chemical Sciences | The Royal Academy of Engineering