[Wikipedia page]

[SPICE website]

Geoengineering by Solar Radiation Management

April 2010

There was a Royal Society report last year entitled [Geoengineering the Climate]

Here's what Martin Rees (President of Royal Society) says:

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

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

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

The EPSRC and the Natural Environmental Research Council (NERC) in partnership under the Living with Environmental Change (LWEC) programme, intend to provide support to research within the Climate Geoengineering remit through a joint sandpit event and aim to fund research which will allow intelligent and informed assessments about Geoengineering technologies to be made.

Cambridge University Engineering Department, in conjunction with Bristol and Reading Universities, has been successful in the Sandpit process and is likely to receive a £1.8m grant to run October 2010 - September 2013.

The SPICE project - Stratospheric Particle Injection for Climate Engineering

The SPICE project will investigate the effectiveness of Solar Radiation Management (SRM) using

stratospheric particles. It addresses the three grand challenges in solar radiation management: 1. How much, of what, needs to be injected where into the atmosphere to effectively and safely manage the climate system? 2. How do we deliver it there? 3. What are the likely impacts? These questions are addressed through 3 coordinated and inter-linked work packages which are summarised here and described in detail in section 3.
CUED is responsible for the Delivery systems (WP2):

WP2 Particles are to be injected into the stratosphere at heights upwards of 10km (mid-latitude) and 18km (equatorial). A range of delivery systems have at various times been proposed including batch delivery by aircraft, balloons or ballistics and steady-state delivery by thermal plumes, or from a fixed tower or pipe supported by a balloon. The rate required for global climate modification is upward of 1Mte p.a. and at this rate the delivery costs for batch methods are estimated to be well above £1bn p.a. but an order of magnitude less than 1/10 of this for the pipe delivery method.

WP2.0: Before SPICE begins a process to evaluate alternative delivery systems will take place so that WP2 can begin its primary tasks without delay. Delivery systems identified so far include aircraft, weather balloons, ballistics, towers, tethered balloons or dirigibles and tethered jet engine platforms. For each the preliminary investigation will outline engineering, development, capital and operating costs and timescales, environmental and social impact.

WP2.1: Pipe dynamics and design. The first main activity within WP2 is to finalize the review of alternative delivery systems and if current thinking is validated, the WP will proceed with a more detailed design of a tethered balloon approach which will involve the design of a pipe and associated pumping and deployment systems. The WP will begin with a preliminary technical evaluation of the pipe-balloon system and the associated fluid/structural mechanics. The pipe will be up to 25km long, subject to high tensile and bursting pressures. It will be a sealed unit, abrasion resistant, insulated to prevent freezing and made of a braided or filament wound fibre composite.
We will investigate deployment and recovery of the balloon and pipe, pipe and balloon dynamics in response to extreme weather conditions, using methods established for the analysis of oil riser dynamics (Low and Langley, 2008)The WP will investigate high-pressure pumping and the delivery of a fluid (possibly two-phase) into the pipe, nozzle design for a stable plume and safety and emergency situations. WP2.1 will advise WP2.2 with regard to the deployment of a 1km test pipe and the design of the complete 20-25 km delivery system. Instrumentation on the test pipe will be used to validate the model for balloon and pipe dynamics. In WP2.1 (b) we will evaluate complex issues regarding pipe construction: embedding fibres in resin, variation of filament lay angle with height, end construction and choice of fibre such as CFRP, aramid (e.g. Kevlar/Twaron/Technora) and PBO. For PBO it will be necessary to conduct stress tests at elevated pressure and temperature using established techniques (Alwis and Burgoyne 2005). IAramid fibres have adequate properties for the tether of the 1 km trial, but the time/temperature properties of the higher performance fibre PBO may be needed for the full-scale pipe.
Deliverables:

- (a) A model for the dynamics of a 20-25 km balloon-tethered pipe
- (b) A specification for a high-pressure pumping system
- (c) A design for a fibre-reinforced pipe with terminations
- (d) Properties of PBO at extremes of temperature and stress

WP2:2: 1km Testbed. WP2.2 (a) will produce a pipe-balloon system to deliver a 3kg/min water stream at a height of 1km. The pumping pressure required is around 120 bar. Safety issues will be explored, for instance a parachute-controlled drop test. The testbed will require a substantial project management and a systems-engineering approach is required, with close collaboration with an experience engineering contractor. Testbed manufacture will only begin after input from a Public Engagement has taken place.

A possible application is that the 1km testbed pipe and balloon has the potential to test some features of low-level cloud whitening. WP2.2 (b) will use lessons learned from the testbed and apply them to the design of a complete 20-25 km delivery system which will take pipe and pumping technology to its extremes.
Deliverables:

- (a) A 1km testbed for validating models of WP2.
- (b) A design for a complete 20-25 km delivery system

Here is the full project description, with Bristol in charge of WP1, Cambridge in charge of WP2 and Reading in charge of WP3

Stratospheric Particle Injection for Climate Engineering (SPICE)

1. Background

Anthropogenic climate change is a major threat to humankind. Observational evidence for warming of the climate system is now unequivocal (IPCC, 2007), based on increased temperatures, sea level rise and widespread melting of snow and ice. Future projections by climate models indicate substantial changes in future decades, much of which is on a regional scale that will severely impact regions of the world that are already under stress.

There has been a greatly improved understanding of the serious nature of global warming both by politicians and the general public in recent years. However, there is great concern that efforts to mitigate future change by reduced greenhouse gas (GHG) emissions, including the outcome of the international meeting in Copenhagen 2009, are proceeding too slowly to avoid the risk of dangerous climate change and the possibility of certain 'tipping points' being reached. This has prompted consideration of intervention by alternative means. Although considered by the majority to be the 'Plan B' that should be avoided if at all possible, there is increased consensus that the benefits, risks, costs and feasibility of this as an option requires consideration, particularly because of the long time constants of the natural processes involved: even if all human emissions of greenhouse gases ceased immediately when the likelihood of such a tipping point became apparent, greenhouse gas levels in the atmosphere would not return to pre-industrial levels for several centuries.

A variety of 'geoengineering' options have been proposed, which fall into the two broad categories of (1) carbon dioxide removal and (2) solar radiation management (SRM). The latter involves offsetting the effects of GHG increases by causing the Earth to absorb less radiation from the Sun. Crutzen (2006) and Wigley (2006) rekindled interest in the idea of reducing incoming solar radiation at the surface by injecting sulphate aerosol into the stratosphere and this option has been further investigated and debated in recent years (e.g. Rasch et al. 2008, Robock et al. 2008, 2010, Hegerl and Solomon 2009; Blackstock and Long 2010). It was considered the most rapidly deployed, affordable and effective option by the recent Royal Society report on Geoengineering the Climate (RS2009).

Injection of aerosols into the lower stratosphere ensures longer residence times and less rapid scavenging than in the troposphere. Depending on the latitude of injection, the aerosol cloud will be dispersed across the globe within a period of weeks to months. Volcanic eruptions provide evidence that stratospheric sulphate particle injection leads to reductions in globally-averaged surface temperatures (Robock 2000). However, there are significant concerns that there will be substantial regional impacts, not only on temperatures but on rainfall and other aspects of climate. There are also uncertainties concerning the timescales on which geo-engineering takes place i.e. how rapidly injection might act, how quickly it could be 'turned off' and whether the climate responds differently to continued injection of aerosols compared with the episodic nature of volcanic eruptions.

For radiation management in geoengineering, the natural volcanic analogue of sulphate particle injection into the stratosphere may not be optimum, and there may be better candidate particles for injection. Related to this, there are significant issues of cost and feasibility of injecting particles into the stratosphere and the sustainability of injection technologies that require much further investigation. Some methods discussed in the literature require significant fuel expenditure and consequent greenhouse gas production.

2. Research Objectives and Hypothesis

The SPICE project will investigate the effectiveness of SRM using stratospheric particles. It addresses the three grand challenges in solar radiation management: 1. How much, of what, needs to be injected where into the atmosphere to effectively and safely manage the climate system? 2. How do we deliver it there? 3. What are the likely impacts? These questions are addressed through 3 coordinated and inter-linked work packages which are summarised here and described in detail in section 3.

Evaluating candidate particles: What is the 'perfect' particle, that maximizes solar radiation scattering, minimizes the greenhouse effect and the impact on the stratospheric ozone layer and has minimal impact on climate, weather, ecosystems and human health?

Delivery Systems: What are the various options for delivery of particles? What is the feasibility of using a tethered-balloon pipe to inject particles and/or gases into the stratosphere in a more cost-effective and sustainable way than alternative methods?

Climate and environmental modelling: What are the most effective locations for injection? How can we best use past volcanic analogues? What are the climate and environmental impacts of stratospheric particles?

3. Programme and Methodology

WP1: Evaluating candidate particles. Critical in this project is the understanding of the interaction of radiation (of various wavelengths) with aerosol particles, and likely chemical effects on the stratosphere of injection of significant additional surface area as a potential catalyst for multiphase chemistry. We will develop metrics of the suitability of various particle compositions, sizes and surface properties for stratospheric aerosol geoengineering (including scattering efficiency, greenhouse effect, chemical reactivity, lifetime, cost of fabrication, health impact, capability to serve as ice nuclei, etc) and perform an assessment of candidate aerosol particles (sulphuric acid, sea-salt, other salts, minerals, and metal oxides) from the available literature and simple modelling of the key reactions, surface properties, agglomeration and sedimentation rates, and light scattering theory.

WP1.1 Optical Chacteristics of candidate particles. Where optical properties are not known (e.g. in the longwave for most particle types, and throughout the spectrum for more exotic aerosol particles) we will use the Molecular Spectroscopy Facility (MSF) at the Rutherford Appleton Laboratory (RAL) to investigate the optical properties at a range of size distributions. This will involve characterising the Mie scattering properties of a cloud of particles suspended in the 1m3 chamber at RAL. Sulphate will be characterised first, for a range of narrow particle size distributions, made using chemical and nebulizer techniques, over a range of droplet concentrations and used as a benchmark. Subsequent analysis will focus on naturally occurring particles including ice, salts, clays and mineral aerosols. All measurements would be conducted at atmospherically relevant temperatures and pressures.

Deliverables:
(a) A series of metrics for benchmarking candidate particles against sulphate
(b) A comprehensive database of optical constants for a range candidate particles

WP1.2 Catalysis of O3 reactions. After a first order investigation of optics, the second phase will be to look at the potential chemical properties of optically suitable candidate particles. Specifically, in order to investigate the effects upon O3 chemistry, we will use the optical tweezers at the Central Laser Facility (CLF) at RAL to suspend single particles and investigate the surface catalysis effects upon the production of radicals that destroy O3. The optical tweezer rig uses Raman spectroscopy to probe the surface of particles, again at atmospherically relevant temperatures and pressures. In conjunction with naturally existing particles, we will employ a number of techniques, in particular Tapered Element Oscillating Microbalance (TEOM) measurements, in order to characterise the Langmuir isotherms and reactivity of industrial analogue particles within packed-beds. Candidate adsorbents will be identified in collaboration with RAL and Reading University.

Deliverables:
(a) Langmuir isotherms for the suite of candidate particles
(b) Reaction rates of key stratospheric gases and radicals for a range of particle types at stratospheric temperatures and pressures.

WP1.3 Investigating agglomeration. Agglomeration rates will be key to the success of any stratospheric aerosol geoengineering attempt. If particles agglomerate too quickly, rapid fallout will be enhanced, reducing residence times. We will use the RAL-MSF rig to investigate agglomeration by running extended experiments that measure accurate particle size distributions over time.

Deliverables:
(a) Agglomeration rates for the candidate particle suite

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WP3: Climate and Environmental Impacts. The impact of particle injection into the stratosphere will be evaluated using the UK Met Office Unified Model (UM) as the primary tool. A range of model configurations is available to the project, including (a) the standard 38-level (L38) ocean-atmosphere coupled model that extends to ~40 km and is the prime tool for the next IPCC climate assessment, (b) a vertically-extended version with 60 levels (L60) up to ~80 km and (c) a version of the L60 model with fully coupled chemistry (UKCA model). Until very recently the L60 and UKCA models have been run only with imposed sea surface temperatures only (i.e. not fully coupled to the ocean). As part of the next IPCC project, a fully coupled ocean-troposphere-stratosphere L60 model has been developed (Gray is a PI of this joint NERC-MO project). A fully coupled version of the L60 UKCA model is also under development (a joint NCAS-MO initiative) and will be available when required for WP3 (see below).

WP3.1 Improving our Confidence in Impact Assessment. In this work package essential groundwork will be carried out to assess and optimise the accuracy of the model and an extensive list of metrics and diagnostics will be developed to assess the impact of particle injection in the atmosphere.

Nature has performed pilot studies of particle injection in the stratosphere in the form of volcanic eruptions. To have any confidence in a model assessment of impacts, we must be able to demonstrate the accuracy of the model to capture the observed impacts of these known, quantifiable volcanic forcing events. While the broad response in the lower stratosphere is captured, (Robock 2000) the surface Arctic

Oscillation response is minimal, and the wintertime warming signal over Europe is underestimated (Stenchikov et al. 2006, Marshall et al. 2009). In this WP the volcanic response in the L60 IPCC simulations will be analysed and compared with observations. Additional Pinatubo ensemble simulations will be carried out to investigate stratosphere-troposphere coupling at high latitudes, with a focus on coupling through wave propagation from the troposphere into the polar stratosphere. This part of the WP will be funded by NCAS-Climate as part of its core model development activities.

In addition, a comprehensive list of metrics and the diagnostic code to extract and calculate them from the UM will be developed e.g. aerosol distribution, radiative forcing, surface temperature (global, regional, land/sea), rainfall (including e.g. monsoon indicators), surface UV, cloud cover, ITCZ latitude, Arctic sea ice, Arctic Oscillation, North Atlantic Oscillation, stratosphere - troposphere exchange, stratospheric temperature, polar vortex strength, frequency of sudden stratospheric warmings.

Deliverables:
(a) Improved modelling of observed response to natural volcanic particle injection
(b) Set of metrics with which to evaluate the impact of geo-engineered particle injection

WP3.2 Optimisation of Geoengineering Injection Options. The radiation and chemical components of the UM will be employed to test the characteristics of the identified candidate particles and a series of sensitivity studies carried out to provide guidance on the optimum particle and its mode of injection. This will be through an iterative process in which (a) the candidate particle characteristics are incorporated into the radiation scheme, (b) the model is run to assess its efficacy, e.g. its lifetime, scattering efficiency, ability to reflect at short wavelengths with minimal absorption at long wavelengths etc and (c) the particle requirements adjusted in light of the results and fed back to WP1. Similarly, the chemical impact on ozone will be assessed by adjusting the surface catalysis reactions in the chemical component of the model according to the results of measurements taken in WP1. An extensive set of model simulations will also be carried out to assess sensitivity to the mode of injection. Sulphate aerosols will be injected in pre-defined height bands, latitude bands and at various different rates and periods. Sensitivity to ambient conditions will be explored e.g. to season, QBO, ENSO phase, CO2 and O3 levels.

Deliverables:
(a) Radiative / chemical input to specification of the 'candidate particle' (WP1)
(b) Radiative / dynamical / chemical input to injection delivery (WP2) and full impact assessment (WP3.3).

WP3.3 Impact Assessment. Climate model simulations will be carried out and analysed using both sulphate aerosols and the candidate particle to carry out an assessment of the impact on both climate and ozone.

Studies have been performed by international modelling groups (e.g. Rasch et al. 2008, Robock et al. 2008, Tilmes et al. 2009, Jones et al. 2010), but each employs slightly different injection rates, height, latitude, longevity etc. Kravitz et al. (2010) have proposed a standard suite of model scenarios, as part of GeoMIP (Geoengineering Model Inter-comparison Project). In this WP, GeoMIP experiments will be performed so that results may be inter-compared with other international efforts, using both sulphate aerosols and the 'candidate particle'. 5 sets of simulations will be performed: (a) idealised GeoMIP simulations in which CO2 levels are increased while simultaneously reducing the solar constant to counteract this forcing, (b) realistic IPCC scenarios with RCP4.5 forcing, starting in 2020, with a gradual ramp-up of sulphate aerosols so that surface temperatures are kept nearly constant, with switch-off in 2070 to assess how quickly the impact can be turned off, (c) repeat of (b) but with the 'candidate particle' and injection method, (d) repeat of (b) but using the UKCA coupled chemistry model to assess impacts on ozone chemistry and to allow ozone feedback processes, (e) repeat of (d) but with 'candidate' particle and injection method.

Impacts will also be assessed at the bio-surface. Because albedo is not an intrinsic property of the surface, but a function of direction of incident radiation, we will quantify how the surface radiation budget of the Earth changes. This will include further off-line plant and terrestrial ecosystem modelling, including the effects on altering the relationship between direct and diffuse radiation and will be used to assess potential impacts on plant productivity and hence feedback via changes in atmospheric pCO2.

Deliverables:
(a) Assessment of climate impacts associated with sulphate aerosol injection
(b) Assessment of climate impacts of the candidate particle compared with sulphate aerosol impacts
(c) Assessment of stratospheric particle injection impacts on ozone chemistry.
(d) Assessment of stratospheric particle injection on the biosphere.

4. Programme Management
PI Watson will have overall responsibility for management of the project, with assistance of an administrator at the 40% level to help organise meetings, reports, PR and outreach. Management of each work package will be the responsibility of the Watson (WP1), Hunt (WP2) and Gray (WP3). This will involve detailed planning and coordination of the work to ensure that project targets are met, relevant inputs to other WPs and the specific WP deliverables are provided on time and to budget. A detailed risk register will be developed and reviewed regularly at project meetings. Quarterly meetings of the whole project will be held (see GANTT chart), with more frequent meetings / teleconferences held at least every 2-3 weeks for each individual WP, attended by appropriate personnel as required; the latter will include sub-contractors (e.g. from the Met Office, RAL, testbed contractors) and relevant external collaborators. Where appropriate, PDRAs and PhD students will spend extended periods at other relevant institutions e.g. Bristol / Cambridge personnel at RAL for WP1 activities and Reading personnel at the Met Office for WP3 activities etc. 2 workshops are also proposed, each of 3 day duration with an estimated 35-40 attendees, one at mid-term to review progress and one at the end of the project to present results.

5. Relevance to Academic Beneficiaries
This research will provide significant benefits both to those in the immediate field of geoengineering and the broader community. The key deliverables of WP1 are optical constants, Langmuir isotherms and agglomeration rates for a range of particles (including ash particles from volcanic eruptions) . WP2 delivers an understanding of balloon-suspended pipes on a scale never-before envisaged and where engineering is pushed to its limits in the fields of dynamics, polymer science and pumping systems. WP3 will significantly improve our understanding of troposphere-stratosphere coupling,and will develop a suite of impact metrics for assessing geoengineering impacts and contribute to international impact modelling assessment inter-comparisons.