MEMORANDUM FROM RESEARCH COUNCILS UK (RCUK) TO THE ROYAL SOCIETY GEOENGINEERING CLIMATE STUDY

Bulleted summary

- Geo-engineering is seen by some as having the potential to counteract global climate change; however, the feasibility of different conceptual options has yet to be rigorously examined, and it will be important to guard against unintended effects on the environment.
- The further development of geo-engineering ideas will require a combination of engineering, environmental and socio-economic expertise
- Whilst sophisticated model-based simulations are essential for feasibility assessments, there may be important differences between model climate behaviour and that of the real world at both regional and Earth system scales
- NERC and EPSRC support a wide range of research that is relevant to geo-engineering, particularly in the areas of climate dynamics and CCS (carbon capture and storage). New activities could build on this to explore the potential for geo-engineering development.

1. Research Councils UK is a strategic partnership set up to champion research supported by the seven UK Research Councils. RCUK was established in 2002 to enable the Councils to work together more effectively to enhance the overall impact and effectiveness of their research, training and innovation activities, contributing to the delivery of the Government's objectives for science and innovation. Further details are available at www.rcuk.ac.uk.

2. This evidence is submitted by Research Councils UK (RCUK) on behalf of the Natural Environment Research Council (NERC), the Engineering and Physical Sciences Research Council (EPSRC) and the Economic and Social Research Council (ESRC) and represents their independent views, developed in consultation with the Biotechnology and Biological Sciences Research Council (BBSRC). It does not necessarily reflect the views of the Department for Innovation, Universities and Skills.

3. NERC, EPSRC and ESRC fund and carry out impartial research and training in the sciences of the environment, physical and engineering sciences and economics and social research respectively, within their own remits. Funding is through support to universities and in the case of NERC, also to its Research and Collaborative Centres. Details are available at www.nerc.ac.uk, www.epsrc.ac.uk and www.esrc.ac.uk.

4. In preparing this submission, discussions were held with NERC-funded research centres, including the British Geological Survey (BGS); the Centre for Ecology and Hydrology (CEH); the National Centre for Atmospheric Sciences (NCAS); the National Oceanography Centre, Southampton (NOCS); Plymouth Marine Laboratory (PML) and the UK Energy Research Centre (UKERC).

Comments on the scope of the Royal Society study

5. We note the Terms of Reference of the study and the information provided on its scope, as given in the call for submissions. Table 1 summarises issues relating to a number of geoengineering options RCUK is aware of, alpha-numerically labelled according to the Scope guidance. Although this list is by no means exhaustive, comments from RCUK should be interpreted as pertaining to these examples.

6. The exclusion of carbon capture and storage (CCS) at the point of emission is consistent with the approach taken by the House of Commons Innovation, Universities, Science and Skills Committee (IUSSC) in the context of its recent geoengineering case study. There would, however, seem potential

ambiguity in the Royal Society's exclusion of CCS at the point of emission since Method 1b)ii explicitly includes chemical engineering approaches to prevent CO_2 and other greenhouse gases from entering the atmosphere or oceans.

[Q1] What do you consider to be the current state of knowledge regarding the feasibility, efficacy and predicted impacts of climate geoengineering schemes?

1.1 Climate geoengineering is an activity that is essentially hypothetical: whilst many ideas have been raised, none have yet been subject to rigorous feasibility analyses, cost-benefit calculations or proof-of-concept demonstrations. Whilst geoengineering is seen by some as having the potential to counteract global climate change, it will be important not only to guard against unintended effects on the environment but also to fully consider socio-economic issues relating to public acceptability, financing, cost-effectiveness, ethical considerations, verification and international governance.

1.2 NERC and EPSRC currently support a wide range of research that is relevant to climate geoengineering which may be used to inform future, more focussed developments. Information on relevant research currently funded by NERC and EPSRC (and sometimes involving other Research Councils) is summarised in Table 2. Known future projects and programmes, currently in the planning stage, are also shown.

1.3 Relevance to geoengineering is assessed in Table 2 as either low, medium or high. Whilst no high category is used for current work, EPSRC is considering holding a 'sandpit' (Ideas Factory[1]) activity that is explicitly directed at exploring geoengineering feasibility in an interdisciplinary context.

1.4 As indicated in (6.) above, there is a close link between CCS and the proposed geoengineering option of air capture of carbon dioxide ('artificial trees'; option 1ai, Table 1). Both initially involve energy-demanding techniques to remove the CO_2, and subsequently require its safe long-term storage. Whilst chemical removal processes are currently favoured for CCS, biological processes may be possible (e.g. involving oil-producing algae). Thus genetic engineering may have a role to play at the interface between geoengineering and CCS.

1.5 For climate geoengineering to achieve its intended benefits, it must have a direct or indirect effect equivalent to diminishing radiative forcing by around 1W m^{-2} (as noted in the Royal Society's call for submissions). However, interventions on this scale – other than by a geographically well-distributed air capture system – are near-certain to have complex, far-reaching and potentially undesirable consequences.

1.6 In particular, atmospheric or surface-based geoengineering schemes relating to shortwave reflection are most effective in tropical regions (where incoming radiation is greatest); however, anthropogenic global warming has greatest effects in polar regions, where increased levels of CO_2 and other greenhouse gases reduce planetary heat loss by absorbing longwave radiation. As a result of this spatial mis-match, an atmospheric or space-based albedo modification that achieves a global average cooling of, say, 1°C will not directly reverse a global average warming of 1°C due to greenhouse gases: weather patterns will be different, with the result that some countries and regions will be winners and others losers.

1.7 Ocean acidification can be considered a more fundamental impact of albedo-based geoengineering, since (unless coupled with strong mitigation measures), atmospheric CO_2 will continue to increase.

[1] http://www.epsrc.ac.uk/ResearchFunding/Opportunities/Networking/IDEASFactory/WhatIsASandpit.htm

1.8 Geoengineering schemes based on greenhouse gas reduction avoid that problem. Nevertheless, if ecosystem-based, changes in land use or ocean biology over large areas are necessarily involved. If chemically-based, relatively large quantities of raw materials (including water) and energy are likely to be needed for feedstock and infrastucture, and there also may be need to dispose of large quantities of waste, e.g. as sequestered carbon.   Significant economic and environmental impacts would therefore seem inevitable, requiring careful cost-benefit analyses, on a full lifetime ('cradle to grave') basis.

[Q2] How do you think research into climate geoengineering should be taken forward, and by whom?

2.1 As indicated above, the further development of geoengineering ideas (if considered desirable) will require a combination of engineering, environmental and socio-economic research. The UK government view, as expressed in written and oral evidence by Defra, DIUS and DECC to the IUSSC, is that the national interest is currently best served by focussing research and policy effort on mitigation, i.e. CCS and other measures that directly reduce the problem.

2.2 RCUK shares that view; nevertheless, such an approach is not incompatible with modest spend to obtain additional scientific information on the pros and cons of geoenginering, without any commitment for follow-through. Indeed, improved knowledge of the efficacy and potential impacts of geoengineering may be politically necessary to dissuade other countries from unilaterally implementing ineffective approaches, or to influence UN regulatory mechanisms (e.g. via carbon credit schemes), or to develop independent verification arrangements should climate geoengineering be carried out by others.

2.3 If more substantive research effort were considered to be scientifically and politically desirable, this should, ideally, be taken forward with international partners. The UK already has close engagement with governmental and non-governmental organisations with interests, in climate-related assessment, regulation and research (e.g. IPCC, UNFCCC, WMO, WCRP and IGBP); no new mechanisms or institutions would seem to be needed.

2.4 There is currently little, if any, direct engagement between UK researchers and industry with regard to geoengineering. At the current stage of development that is unsurprising; short-term (or even medium-term) return on private sector investment is unlikely, and governments have to ensure that they have access to independent advice on proposed geoengineering schemes. Nevertheless, there is non-governmental interest through philanthropic trusts, foundations and similar (e.g. the US Carnegie Institution; Richard Branson's Virgin Earth Challenge) and if western governments were to decide that geoengineering should proceed, the private sector might be made responsible for its implementation via schemes similar to carbon trading, subject to verification.

[Q3] What factors need to be considered before deploying any climate geoengineering schemes? Who should be responsible for any deployment?

3.1 Before deployment, the proposed geoengineering option must provide a measurable benefit that unambiguously outweighs the impacts arising from the full lifetime energy costs, carbon emissions and other adverse environmental consequences involved in establishing, maintaining and decommissioning the relevant technologies.

3.2 Sophisticated model-based simulations of relevant engineering and environmental processes are essential for feasibility assessments. However there may be important differences between model behaviour and that of the real world, particularly for climate processes at both regional and Earth system scales. Experimental studies and observational-based analyses will therefore also be required, over a range of scales

3.3 For both experimental work and actual deployment, the magnitude of the manipulation should be controllable, with the ability to switch off the effect relatively easily in the event of significant unforeseen adverse consequences.

3.4 In addition (yet more fundamentally) there must be public trust, long-term political commitment and international agreement on the acceptability of geoengineering activities that are financially rewarded through international arrangements, and/or those that may have adverse, as well as positive, effects on globally-shared resources.

3.5 It would seem essential that responsibility for deployment is at the governmental and inter-governmental level, ideally under UN auspices and fully subject to international law.

[Q4] What do you consider to be the most important political, social, legal or ethical issues raised by climate geoengineering?

4.1 The socio-economic agenda in relation to geoengineering is unpredictable given the imprecise understanding of what geoengineering interventions may be in the future. However, it is clear that the socio-economic effects of such large scale, complex and presumably resource-intensive investments are potentially huge, and social science has much to contribute to informed assessments of these problems.

4.2 There is a critical need for a clear understanding of what constitutes 'human benefit' prior to commencing geoengineering. Which humans, where and in what way will they benefit? Negative implications also need to be explored and questions of equity and ethics considered: who, if any, will suffer and how will they be compensated and by whom? The large-scale manipulations involved in geoengineering will undoubtedly require considerable investment. Cost benefit and risk assessment will therefore be essential.

4.3 The acceptability of associated infrastructure is also likely to be an important issue, in relation to land and ocean use, ownership, activity displacement, equity and security. Evidence in relation to installing power generation facilities (whether based on renewable or nuclear energy) demonstrates the need for policy and planning development in the context of need at all levels. For example, findings from the ESRC Sustainable Technologies Programme cite the strong influence of both local opinion and of local and national landscape and environmental protection groups in the refusal of planning for large scale facilities. In the geoengineering context this would include supra- and international, national, regional and local communities of interest covering issues as diverse as international law, regulation, and social acceptability (which may differ by any range of sectors or socio economic groups). Broader 'ownership' of large-scale projects, in the sense of engaging with affected communities at an early stage can provide an opportunity to mobilise support.

4.4 At the level of the development, planning and delivery of complex systems and products the social sciences are able to offer considerable insight into to how to best to take these forward. The ESRC Centre for Complex Products and Systems Research has provided critical insight to such problems (e.g.

work with Boeing on aircraft development). Lessons learnt and best practice tools developed though this research is expected, at least in part to be transferable to other large scale activities such as geoengineering.

4.5 There are also considerations of cultural responses in relation to religious and other belief systems should geoengineering lead to large-scale and purposefully-created changes in the environment. For land-based geoengineering options, the value attached to landscape can vary both within and between different countries, and may be an important factor in terms of where interventions are to be sited.

4.6 Note that Table 1 identifies some socio-economic issues associated with specific geo-engineering options, although this is not intended as a definitive assessment.

[Q5]. What do you see as the main barriers to, and opportunities offered by, climate geoengineering?

5.1 The unambiguous demonstration of net benefit (see 3.1) – is likely to be highly demanding, with major investments needed to scale-up from proof-of-concept to pilot trials and full deployment. The use of state-of-the-art climate models, including a range of biogeochemical feedback processes, is clearly necessary for 'safe' global-scale testing, to quantify potential benefits and assess the risk of undesirable impacts. A secure assessment of the full impact of geoengineering solutions requires a comprehensive Earth System Model.

5.2 Earth System Models (which must include for example the land surface, atmospheric chemistry, and biogeochemical processes occurring throughout the ocean) are still in their infancy but are in active development within NERC (in collaboration with other bodies such as the UKMO). Currently such models do not adequately represent regional climate and its variability. High resolution regional models will be needed to complement field trials, to verify that intended effects did not arise for other reasons. It is a priority research area to improve and assess these models. But model behaviour can never fully replicate real-world behaviour; at full scale-up, it would be prudent to expect the unexpected. Hence the importance that the manipulation is controllable, and can be easily stopped if net benefits are not achieved.

5.3 'Global planning permission' will undoubtedly be needed for schemes of sufficient scale to be climatically effective. As yet, the ethical and legal frameworks for purposeful climatic manipulation do not exist, and their development is unlikely to be straightforward. Any scheme would require international approval/verification (through a form of carbon credits, via UNFCCC or similar) for it to proceed; it is unlikely – although not impossible – that any single country would otherwise be willing to meet the financial cost.

5.4 The 'opportunity' offered by geoengineering is essentially preventive: avoiding dangerous (and potentially catastrophic) climate change, should mitigation measures be insufficient to prevent climatic tipping points being breached. Global temperature increases in the range 5-10°C and sea level rise of many metres are not beyond the bounds of possibility within our grandchildren's lifetimes.

[Q6]. Where do you feel that climate geoengineering fits in the greater scheme of climate research and action to mitigate and adapt to climate change?

6.1 The feasibility of geoengineering warrants attention on the basis that such an approach might 'buy time' or provide a future safety net. However, geoengineering *alone* is inherently unlikely to provide a sustainable, long-term solution to climate change. That is because: i) the scale of geoengineering interventions would need to be increased year-by-year to keep up with increased emissions (currently rising at more than 3% pa); ii) several schemes are limited in the scale of their effects, or constrained by other factors (e.g. storage capacity for captured carbon); and iii) ocean acidification would continue unabated if no measures are taken to limit the increase in atmospheric carbon dioxide.

6.2 RCUK is aware of concerns that over-optimistic reliance on geo-engineering might prove to be chimeric and diversionary. Thus attention given to 'technological fixes' could attract resources and effort away from more fundamental ways of tackling the problem of global warming, through a rapid transition to a low-carbon economy.

6.3 The 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) may provide an opportunity for the UK research community to assist in establishing international consensus on the viability of geoengineering options. However, IPCC's 4th Assessment Report (2007) considered that "geoengineering options ... remain largely speculative and unproven, with the risk of unknown side effects".

[Q7]. Are there any other issues related to climate geoengineering that you consider to be important?

7.1 The main issues of concern and interest to RCUK are covered above and in Tables 1 and 2. The tabled information is similar to that provided by RCUK to the House of Commons Universities, Innovation, Skills and Science Committee.

Table 1. Summary information on key issues for some geo-engineering options that have been proposed to counteract climate change. Options are alpha-numerically labelled in accordance to headings in the Scope section of the Royal Society's Terms of Reference for this study. Note: we do not provide any examples of 1aiii) or 1bi) and ii). Additional detail in Launder & Thompson (2008) "Geoscale engineering to avert dangerous climate change" *Phil Trans Roy Soc A* vol 366 (No.1882) and Vaughan & Lenton (review, in prep).

1) Greenhouse gas reduction schemes			
Geo-engineering option	**Engineering issues**	**Environmental issues**	**Socio-economic issues**
a)i Air capture of carbon dioxide	Development of efficient devices to remove CO_2 from (ambient) air; long term storage; links to CCS	Ensuring safe long term storage of captured carbon; assessment of energetic cost-effectiveness	Assessment of economic cost-effectiveness
a)i Enhanced carbon sequestration on land through biochar burial in soil	Obtaining bulk biochar; scale of (re-)forestation required to achieve globally-significant effect; use of biochar based on agricultural waste will require change in agricultural systems	Uncertain timescale and magnitude of soil storage capacity; need for major land use/ land cover changes; soil fertility effects; questions over whether biochar leads to enhanced mineralization of labile soil carbon	Possible limited duration of effect, dependent on soil conditions/type of biochar (may be stable for 100's - 1000's of years); impacts on food production; once started has to be maintained

a)ii Increasing open ocean productivity through micro- or macro-nutrient addition	Obtaining and delivering nutrients, such as iron or urea	Uncertain timescale and magnitude of carbon sequestration; ecosystem effects; possible release of climate-reactive gases	UN moratorium on such work (by Convention on Biodiversity); once started has to be maintained
a)ii Increasing ocean productivity and surface cooling through increased mixing (ocean pipes)	Design, deployment and maintenance of mixing devices	Likely to be small or zero net effect on carbon budget (CO_2 from deep water released); cooling trivial on global scale?	Assessment of cost-effectiveness; interference of mixing devices with shipping and fishing
2) Albedo modification (short wave reflection/deflection) schemes			
a) Increasing land surface albedo by physical means (paint in urban areas, plastic surface on deserts)	Production, deployment and maintenance of surface covering – large area required for global effect	Potential for urban areas; less feasible for natural surfaces. Loss of desert dust would affect ocean productivity	Public acceptability of changes to visual landscape; assessment of cost-effectiveness
a) Increasing land surface albedo by biological means (changing vegetation)	Changing crop and/or grassland albedo, without affecting yield (via GM?)	Impacts on biodiversity, productivity, hydrological cycle and regional weather; scale of change needed for global effect	Public acceptability of changes; assessment of cost-effectiveness; regional losers
b) Increased cloud albedo in lower atmosphere (e.g. using seawater spray)	Design and auto-operation of spraying devices; satellite-based verification of effect	Would effect be large enough? Need to model and monitor chemical impacts	Changes likely in regional weather patterns, with reduced rainfall downwind
c) Increased aerosols in upper atmosphere (using sulphur compounds)	Design of delivery vehicles and dispersion mechanisms; supply of sulphate; energy costs	Uncertainty in climatic effects - models suggest regional changes and overall decrease in precipitation; risk of ozone depletion and acid rain	Assessment of cost-effectiveness; public/ political acceptability likely to be low (losers as well as winners)
d) Global shading in space (using mirrors, discs or reflective mesh)	Need for novel materials; design of delivery vehicles; problem of energy-intensive start-up; opportunity for energy to be collected in space?	Actions not easily reversible, hence high reliance on models to predict climate impacts – these suggest regional changes and overall decrease in precipitation; problem of space debris.	Assessment of cost-effectiveness; public/ political acceptability likely to be low (losers as well as winners)

Table 2 Summary of current and planned research by NERC, EPSRC and other Research Councils considered relevant to geoengineering. Relevance rating: X, low; XX, medium; XXX, high. Annual cost estimates (where given) are averaged over programme lifetime and may not accurately represent current spend. *Note that figures are for the entire activity, not just the component relevant to geoengineering*. Surce-based carbon capture and storage (CCS) is not here regarded as geo-engineering.

CURRENT WORK (December 2008)

Activity	Rele-vance	Duration; annual cost	Main links to geo-engineering	Support arrangements	RC(s) providing support
Research Councils Energy Programme: www.epsrc.ac.uk/ResearchFunding/Programmes/Energy/Funding/default.htm					
• UK Energy Research Centre	X	2004-09 £2.6m pa	Energy systems and modelling	Consortium (10 institutions) led by Imperial College	EPSRC, NERC, ESRC
• Carbon management and renewables: carbon capture and storage	XX	2005-10 £3.0m pa	CCS including potential for carbon sequestration by soils	Current CCS grants include consortia, smaller projects and capacity building activities	NERC, EPSRC BBSRC
Other programmes and projects					
Tyndall Centre for Climate Change Research *Themes include constructing energy futures; integrated modelling; engineering cities; informing international climate change policy*	XX	2006-09 (Phase 2) £2.0m pa (total)	Overview; policy implications	Consortium of 6 core partners, led by UEA	NERC, EPSRC ESRC
Living with Environmental Change (LWEC) *Details in development*	X	2008 - 18	Mitigation and adaptation; socio-economics	Networking and enhanced collaborations	NERC, ESRC, EPSRC, BBSRC, MRC & AHRC
British Geological Survey (BGS) *Themes include climate change, energy, land use and development, marine geoscience*	XX	Ongoing	CCS, land use, element cycling	NERC Centre	NERC
Oceans 2025 *Themes include marine biogeochemical cycling; next generation ocean prediction*	XX	2007-12 £24.0m pa (total)	Ocean carbon uptake/release; acidification risks from CCS	Coordinated programme at 7 NERC-supported marine centres, including NOCS, PML and POL	NERC
National Centre for Atmospheric Science (NCAS) *Themes include climate science and climate change; weather, atmospheric composition, and technologies*	XX	Ongoing £9m pa	Regional and global atmospheric behaviour; climate predictions using state-of-the-art high resolution models; cloud physics; aerosol behaviour and properties	NERC Collaborative Centre involving 7 centres and facilities	NERC
Centre for Ecology and Hydrology (CEH) *Themes include land/ climate feedbacks and biogeochemical cycling*	XX	Ongoing £2-3m pa	Land surface modelling and linkage to Earth System Models to predict impacts.	Core programme of NERC Research Centre	NERC
Quantifying and Understanding the Earth System (QUEST)	XX	2003-09 £3.8m pa	Modelling climate impacts	70 grant and fellowship awards; Core Team at Bristol	NERC

Aerosol properties, processes and influences on the Earth's climate (APPRAISE)	XX	2005-11 £1.1m pa	Atmospheric dynamics and albedo	Directed programme: 7 awards at 5 institutions	NERC
Surface ocean – lower atmosphere study (UK SOLAS)	X	2003-10 £1.5m pa	Ocean carbon uptake/release; atmospheric chemistry	Directed programme: 28 awards at 14 institutions	NERC
UK contribution to VOCALS (VAMOS Ocean-Cloud-Atmosphere-Land Study)	XX	2008 -11 ~£0.3m pa	Cloud formation (via sulphate aerosol) and their albedo effect	Consortium	NERC
Participation in German-led ocean iron fertilisation experiment	XX	Jan – March 2009; ~£10k	Study of fate of Fe-enhanced primary production in Southern Ocean	National Oceanography Centre Southampton (research cruise led by AWI Bremerhaven)	NERC
Sustainable agriculture and land use	X	Ongoing	Land-based carbon sequestration	Support via Rothamsted Research, other Centres and HEI awards	BBSRC

PLANS FOR FUTURE WORK (December 2008)

Activity	Rele-vance	Duration; cost	Main links to geo-engineering	Support arrangements	RC(s) providing support
National strategy for Earth system modelling	XX	tba	Modelling climate impacts	Capacity building/start-up initiative	NERC
CCS: capture, transport, storage, whole systems and sustainability of carbon capture and storage	XX	tba	CCS	Wide ranging activities including consortia support, capacity building and start-up initiatives. Some E.ON co-support	EPSRC, NERC, ESRC
Ocean acidification	X	tba	Ocean carbon uptake/release; CCS	Large-scale research programme	NERC
Earth System Engineering IDEAS Factory (='Sandpit')	XXX	tba	Focus on geo-engineering	tbc	EPSRC
Doctoral training in CCS	XX	~£5m total	CCS	10 students pa for 5 yr	EPSRC

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