INTERGOVERNMENTAL PANEL ON climate change

WMO UNEP

IPCC Expert Meeting on Geoengineering

Lima, Peru
20-22 June 2011

Meeting Report

Edited by:
Ottmar Edenhofer, Ramón Pichs-Madruga, Youba Sokona, Christopher Field, Vicente Barros, Thomas F. Stocker, Qin Dahe, Jan Minx, Katharine Mach, Gian-Kasper Plattner, Steffen Schlömer, Gerrit Hansen, Michael Mastrandrea

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IPCC Expert Meeting on Geoengineering

Lima, Peru, 20-22 June 2011

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Preface

Geoengineering, encompassing a broad set of methods and technologies, has been an increasing focus of scientific research, and the scientific basis of geoengineering options, risks, and impacts will be assessed across the three contributions to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). In preparation of this task, Working Groups I, II, and III (WGI, WGII, and WGIII) of the IPCC held a joint Expert Meeting on Geoengineering in Lima, Peru, from 20 to 22 June 2011. The Expert Meeting provided a valuable opportunity for experts from a wide range of disciplines and across WGI, WGII, and WGIII to discuss terminology, to clarify concepts and definitions, and to consider emerging issues. Overall the meeting enabled a better understanding and coordination across the three IPCC Working Groups in the context of AR5 assessment efforts underway.

This meeting report summarizes discussions of the Expert Meeting. At its core is a summary of the synthesis session and main outcomes of the meeting. It also contains summaries of meeting discussions of geoengineering approaches and cross-cutting issues, as well as extended abstracts for the meeting's keynote and poster presentations.

We thank the Ministerio de Relationes Exteriores del Peru for hosting the meeting and providing careful arrangements. In particular, we are grateful for the extensive efforts of Professor Eduardo Calvo, Minister Augusto Arzubiaga, and Pilar Castro Barreda. The meeting could not have succeeded without the guidance of the members of the Scientific Steering Group. Finally, we thank all the participants, who contributed to constructive and fruitful dialogue. We also acknowledge the excellent work of the Technical Support Units of the three Working Groups who provided important service during the preparation and execution of the meeting, as well as in the compilation and technical edition of this report.

This successful and stimulating meeting brought together key communities to discuss topics relevant for the assessment of geoengineering. We are convinced that this meeting report will be of great value in the preparation of the AR5, and we hope that it will also provide useful information to the wider scientific community.

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Summary of the Synthesis Session

Summary of the Synthesis Session and Main Outcomes of the IPCC Expert Meeting on Geoengineering

20-22 June 2011

Lima, Peru

Authored by O. Boucher, N. Gruber and J. Blackstock

Citation:

Boucher, O., Gruber, N. and Blackstock, J., 2011, Summary of the Synthesis Session In: *IPCC Expert Meeting Report on Geoengineering.* [O. Edenhofer, C. Field, R. Pichs-Madruga, Y. Sokona, T. Stocker, V. Barros, Q. Dahe, J. Minx, K. Mach, G.-K. Plattner, S. Schlömer, G. Hansen, M. Mastrandrea (eds.)] IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam, Germany, pp.7.

The summary that follows, authored by three members of the Scientific Steering Group (SSG), characterizes the main points that were presented and discussed during the synthesis session of the IPCC Expert Meeting on Geoengineering, 20-22 June 2011, Lima, Peru. The synthesis session was prepared by the SSG and aimed to summarise the discussions that took place in plenary as well as breakout sessions. This summary reflects the authors' perceptions of meeting discussions, but may not reflect their personal views. The summary is intended for consideration by IPCC authors of the Fifth Assessment Report (AR5), but is neither endorsed nor approved by the IPCC or its Working Groups.

1. Key Terminology

A substantial amount of time in the Expert Meeting was spent in discussing terminology in and around geoengineering. This underlines the ambiguities associated with the term geoengineering and the range of opinions on the subject.

The concept of geoengineering can be traced back to the 1960s with a US report calling for research on "possibilities to deliberately bringing about countervailing climatic changes" to that of CO_2 (Marchetti, 1977). The term geoengineering itself was originally used in the 1970s by Marchetti (1977) to describe the context of the idea of injecting CO_2 into the ocean to reduce the atmospheric burden of this greenhouse gas. Since that time, the term has evolved considerably, coming to encompass a broad, and ill-defined, variety of concepts for *intentionally* modifying the Earth's climate *at the large scale* (Keith, 2000). As a result, discussions of geoengineering in both academic and public contexts have sometimes convoluted characteristics from different techniques in ways that have unhelpfully confused discussions. Nonetheless, since Paul Crutzen's 2006 editorial essay (Crutzen, 2006), scientific, policy and media attention to geoengineering concepts has grown rapidly. Several assessments have been conducted at the national level (The Royal Society, 2009; GAO, 2011; Rickels et al., 2011).

Box 1 - Background information

At the Expert Meeting, an attempt was made to provide a set of common definitions for the most important terms related to geoengineering. These definitions are intended for consideration by the author teams of the IPCC's Fifth Assessment Report (AR5). Many of the definitions below reflect the broad usage of these terms in climate science. While some terms are occasionally used interchangeably in the literature, the definitions presented here attempt to provide clear distinctions between them:

> **Geoengineering** refers to a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change. Most, but not all, methods seek to either (a) reduce the amount of absorbed solar energy in the climate system (*Solar Radiation Management*) or (b) increase net carbon sinks from the atmosphere at a scale sufficiently large to alter climate (*Carbon Dioxide Removal*). Scale and intent are of central importance. Two key characteristics of geoengineering methods of particular concern are that they use or affect the climate system (e.g., atmosphere, land or ocean) globally or regionally and/or could have substantive unintended effects that cross national boundaries. Geoengineering is different from weather modification and ecological engineering, but the boundary can be fuzzy.
>
> **Solar Radiation Management (SRM**) refers to the intentional modification of the Earth's shortwave radiative budget with the aim to reduce climate change according to a given metric (e.g., surface temperature, precipitation, regional impacts, etc). Artificial injection of stratospheric aerosols and cloud brightening are two examples of SRM techniques. Methods to modify some fast-responding elements of the longwave radiative budget (such as cirrus clouds), although not strictly speaking SRM, can be related to SRM. SRM techniques do not fall within the usual definitions of mitigation and adaptation.
>
> **Carbon Dioxide Removal (CDR)** methods refer to a set of techniques that aim to remove CO_2 directly from the atmosphere by either (1) increasing natural sinks for carbon or (2) using chemical engineering to remove the CO_2, with the intent of reducing the atmospheric CO_2 concentration. CDR methods involve the ocean, land, and technical systems, including such methods as iron fertilization, large-scale afforestation, and direct capture of CO_2 from the atmosphere using engineered chemical means. Some CDR methods fall under the category of geoengineering, while this may not be the case for others, with the distinction being based upon the magnitude, scale, and impact of the particular CDR activities. The boundary between CDR and mitigation is not clear and there could be some overlap between the two given current definitions.

It is useful in this context to refer back to the definition of mitigation and adaptation previously used by the IPCC in its Fourth Assessment Report. It should be noted that the expert meeting did not address the question of whether these definitions should be updated to differentiate them better from geoengineering.

Mitigation refers to "technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks" (IPCC, 2007: 84).

Adaptation refers to "initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist, e.g. *anticipatory* and *reactive*, *private* and *public* and *autonomous* and *planned*. Examples are raising river or coastal dikes, the substitution of more temperature-shock resistant plants for sensitive ones etc." (IPCC, 2007: 76).

Based upon the above definitions, the following schematic represents an illustration of the conceptual relationship between SRM, CDR, mitigation and adaptation, in the context of the interdependent human and climatic systems (Figure 1.1).

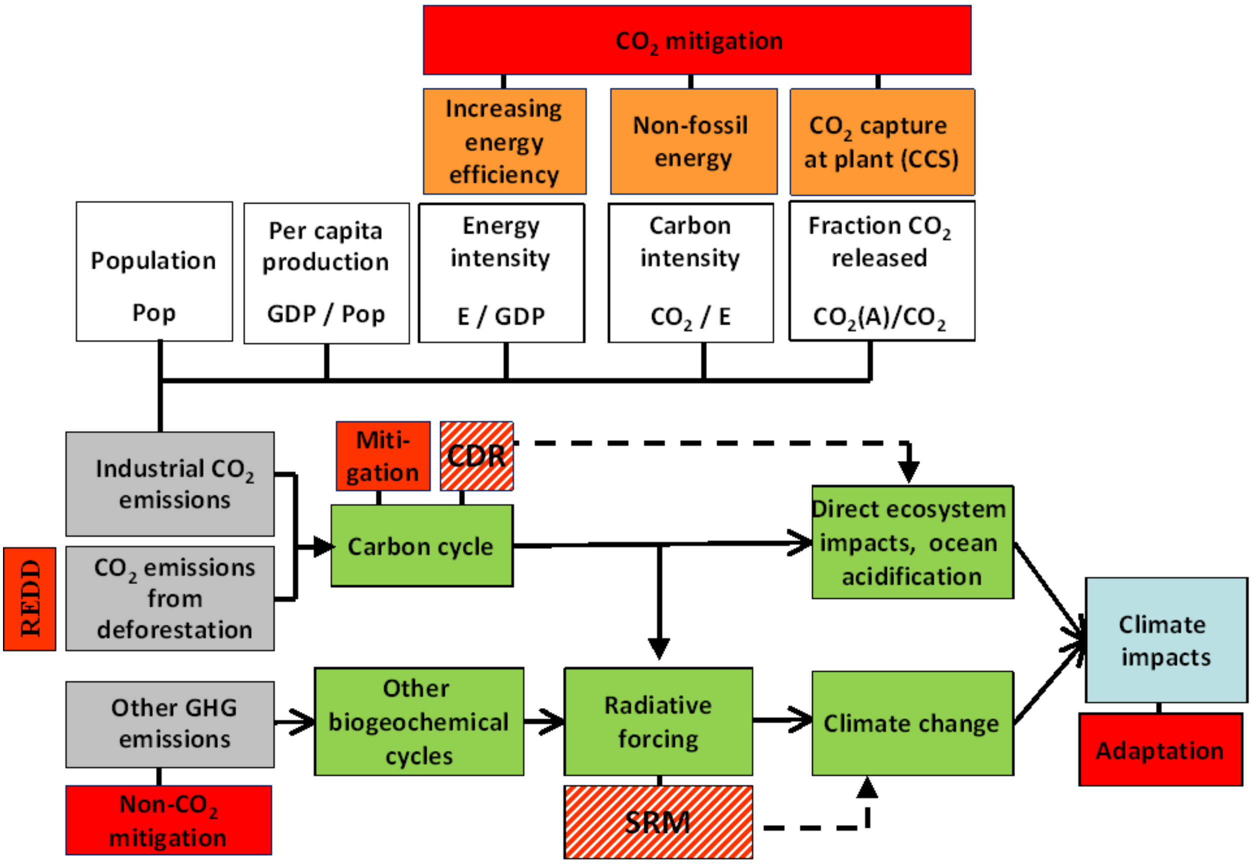

Figure 1.1: *Illustration of mitigation, adaptation, Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR) methods in relation to the interconnected human, socio-economic and climatic systems and with respect to mitigation and adaptation. The top part of the figure represents the Kaya identity. REDD stands for Reduced Emissions from Deforestation and forest Degradation. The Figure has been revised after the meeting.*

2. Emerging Issues for Consideration in the AR5

A number of points arose repeatedly in breakout and plenary sessions and were therefore highlighted during the synthesis session.

Because of the longstanding ambiguity surrounding the term geoengineering, it is suggested that in the AR5, when assessing geoengineering options, the individual methods discussed might be referred to more specifically, i.e., by CDR and SRM rather than geoengineering, or when appropriate by the specific terms, e.g., cloud brightening, stratospheric aerosols, ocean fertilization, etc. The term geoengineering could be introduced at the beginning of each WG report and the synthesis report.

- The risks and impacts of geoengineering techniques might be best assessed within the context of the risks and impacts of climate change and other responses to climate change such as mitigation and adaptation, rather than in isolation.
- CDR and SRM methods might be assessed with a common framework of criteria; for a holistic (i.e., inclusive of all potentially relevant aspects) comparison of response options, it could be valuable if the framework were also applied simultaneously to mitigation and adaptation responses. The following list of criteria is proposed for consideration by AR5 authors but is likely not to be comprehensive and would need to be carefully evaluated as part of the assessment process:
    - Effectiveness – could assess how effective the technique would be at achieving its specified goal (i.e., in removing CO_2 out of the atmosphere for CDR methods, or changing the radiative budget and/or reducing specific climate change impacts for SRM methods);
    - Feasibility – could assess the state of technological/engineering readiness for deployment of the technique (at a small scale; i.e., separate from assessing the physical or social challenges of expanding it to large-scale deployment);
    - Scalability – could combine assessments of both physical (i.e., climatic, environmental, resource-related) and social (i.e., economic, political) limits on how much and how fast deployment of the technique could be scaled up to achieve a specified goal;
    - Sustainability – could combine assessments of the reversibility of impacts and assumed longer-term commitments associated with deployment of the technique, evaluated against baseline scenarios for climate change and diverse socioeconomic pathways. Links to the precautionary principle could be considered;
    - Environmental risks – could identify and assess the physical, chemical, biological and climatic risks associated with the technique (including, but not limited to, residual climate change impacts, unintended consequences, risks inherent in the irreversibility or termination issues assessed in the sustainability criteria);
    - Costs and affordability – could combine assessments of (a) the costs of implementing and operating the technique (direct costs) with (b) the cost valuations for potential social and environmental externalities generated by the technique or its failure (indirect costs). Costs would need to be evaluated against a set of baseline mitigated and unmitigated climate scenarios;
    - Detection and attribution – could assess the extent to which both targeted and unintended consequences of the technique could be detected and attributed to its deployment (i.e., verification of CO_2 withdrawal for CDR, or identification of climatic impacts for SRM);
    - Governance challenges – could assess the legal and regulatory issues (local, national and international) that are or could be associated with the technique, along with an assessment of whether/how current institutions address these issues;
    - Ethical issues – could identify the variety of ethical issues that are or could be raised by the technique;
    - Social acceptability – could assess current knowledge of the social acceptability of the technique;
    - Uncertainty related to all of the above mentioned criteria.
- In order to ensure consistency in the treatment of geoengineering in the AR5 using a common framework, an informal group of AR5 Lead Authors from all three working groups might be formed. This might help to arrive at a 'holistic' assessment of geoengineering in the AR5.
- Once sufficient knowledge and published literature on SRM and CDR methods become available, the IPCC might want to consider a joint Special Report on Geonengineering post AR5.
- As the deployment of some geoengineering technologies could have profound long-term implications for global society, assessment of the proposed methods will need to consider timescales extending at least up to, and likely well beyond, 2100.

3. Specific Discussion Points on Solar Radiation Management Methods

As defined above, SRM refers to the intentional modification of the Earth's shortwave radiative budget with the aim of reducing climate change with respect to a given set of criteria. Specific examples include the artificial injection of stratospheric aerosols, low-level cloud brightening through the injection of sea-salt particles in the marine boundary layer, or brightening of the Earth's surface. No attempt was made to assess or further categorize these methods during the Expert Meeting; such attempts have been made elsewhere, most prominently in Royal Society (2009). A number of discussion points during the Expert Meeting were specific to SRM methods and are summarised here.

One suggestion was that the costs, benefits and risks associated with SRM techniques might be treated 'holistically' whenever possible. For assessing costs, this would require simultaneously considering both the costs of implementation and the costs of social and environmental externalities, which cover the (intended and unintended) costs of the impacts of implementing SRM. Similarly, for assessing the risks, the potential risks of implementing SRM would be evaluated alongside the potential risks of other climate change scenarios. For costs and risks, issues of residual climate change (e.g., components of climatic change left or even exacerbated after SRM implementation), expected and unintended consequences, and long-term issues of reversibility and termination would be considered.

AR5 authors might want to consider using a coherent framework for assessing SRM techniques across the IPCC Working Groups. Such a framework would require at least two components: (1) a common set of criteria for evaluation (the list provided in Section 3 could be a starting point for this); and (2) an agreement on baselines for comparisons (or at least an explicit statement of assumptions about baselines). Particularly for (2), modelling or discussions of SRM could compare scenarios with SRM against a variety of baselines – pre-industrial (i.e., a world with no climate change), present-day, or various future-climate scenarios. A holistic treatment of SRM would require examining the costs, benefits and risks of SRM in conjunction with mitigation and adaptation measures.

The expert meeting participants identified a variety of gaps in current understanding that AR5 authors will need to contend with as part of a comprehensive assessment. Those are presented here in terms of the prospective evaluation criteria suggested in Section 3. The current literature on the effectiveness, feasibility and scalability of SRM techniques is based on limited theoretical and modelling studies, with very limited empirical data (with the exception of the natural analogue of volcanic eruptions for stratospheric aerosols and ship tracks for marine cloud brightening). Knowledge gaps are more pronounced for the assessment of sustainability or environmental risks. Comparability of existing modelling studies is limited, and potential regional climate responses to SRM remain largely unexplored, but the Geoengineering Modelling Intercomparison Project (GeoMIP) is now underway (Kravitz et al., 2011). Existing literature on the costs and affordability of SRM are limited primarily to implementation (direct) costs, and even then there is limited literature for even the most prominent techniques; indirect costs and possible impacts are poorly explored, particularly in relative comparisons against ongoing climate change. There are very few studies discussing the potential for detection and attribution of SRM impacts. At present there is a small but rapidly growing body of literature on the governance challenges and ethical issues associated with SRM techniques. Literature on social acceptability and perceptions is only starting to emerge.

4. Specific Discussion Points on Carbon Dioxide Removal Methods

As defined above, CDR includes a broad set of methods involving the land, the ocean, and technological systems, all aiming to increase the rate of net removal of CO_2 from the atmosphere. One may want to expand CDR to include all greenhouse gases, such as CH_4 and N_2O, but this was not further discussed at the meeting. No assessment was undertaken at the meeting, but an attempt was made to categorize the CDR methods into a set of broad categories.

Ocean-based methods to remove CO_2 from the atmosphere fall into two broad sets, i.e., those that employ changes in the ocean's chemistry to enhance the absorption of CO_2 from the atmosphere and those that employ changes in the ocean's biological pump. The latter might be accomplished either by fertilizing the ocean with micronutrients, such as iron, or by fertilizing it with macronutrients, such as nitrate and/or phosphate.

The physically based method of direct CO_2 injection in the ocean, such as direct injection of CO_2 with subsequent dissolution or direct injection with the addition of alkalinity to neutralize the CO_2, is also commonly discussed in the framework of geoengineering and CDR. In comparison to the chemical and biological CDR methods, which directly remove CO_2 from the atmosphere and store (part of it) in the ocean, direct injection covers the storage part of the process only and therefore requires first an engineered capture process. Therefore, in order to compare this method with other CDR methods, where the capture process is inherently included, direct injection needs to be considered together with the capture process (IPCC, 2005). However, the experts at the meeting did not make a specific recommendation how exactly this should be accomplished.

Land-based methods can be categorized into those that enhance natural sinks and those that reduce natural sources, particularly by reducing terrestrial respiration. Sink-enhancing CDR methods include afforestation/reforestation, bioenergy with Carbon Capture and Storage (IPCC, 2011), fertilization of land plants, and enhanced weathering on land. Source reduction CDR methods include the production and deployment of "biochar", the application of no till and conservation agriculture, and biomass burial. This list is not exhaustive and no attempt was made at the meeting to provide a complete one.

Direct air capture by various methods is technologically closely related to the capture of CO_2 at a point emission source, but since it involves the atmosphere as a transport and storage agent, it needs to be considered as a CDR method. In order for direct air capture to work as a CDR, the captured CO_2 needs to be stored (see IPCC, 2005).

A large part of the discussion on CDR in breakout and plenary sessions centered around the question: Which CDR methods can and should be generally considered as geoengineering? Not all CDR methods automatically fall into the category of geoengineering, but at least two key characteristics separate CDR methods and particular applications that ought to be considered as geoengineering from those that ought not to be. These two criteria are scale of deployment and scale of impact, particularly with regard to transnational impacts and consequences (Figure 1.2). No conclusions were reached on the exact location of the boundary, i.e., what specific scale and what specific impact separate geoengineering from non-geoengineering methods. It was mentioned that this boundary also depends on the type of impact as well as the timescale under consideration.

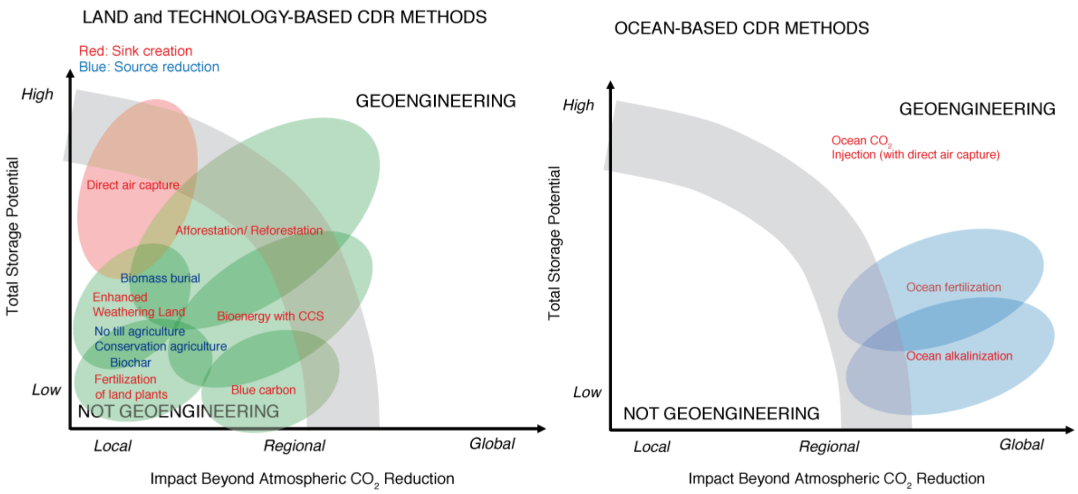

Figure 1.2: *Scale and impact are important determinants of whether a particular CDR method and specific application should be considered as geoengineering or not. Note that the specific positioning of the different methods is only illustrative and does not constitute a consensus view of the experts participating in the meeting.*

This framework also implies that a particular method per se does not fall inside or outside the realm of geoengineering, since any CDR method theoretically can fall on either side of the boundary. It is really the scale of deployment and the scale of impact that determines where a method falls.

The expert meeting participants identified the following gaps, among others, in understanding with regard to CDR. There is highly limited understanding of the relationship between the scale of deployment and the scale of impact, and there is little knowledge of the nature of the large-scale impact beyond the CO_2 benefit for most methods. Important issues are associated with the longevity of a particular method, i.e., what fraction of the removed carbon will return back to the atmosphere after a particular time. Very little is known about the economic costs of many methods, especially when deployed at the large scale. Finally, social acceptability is recognized as a potentially important regulator of the potential future application of CDR, but only a few methods have been assessed.

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Annex 1: Meeting Proposal

INTERGOVERNMENTAL PANEL ON climate change

THIRTY-SECOND SESSION OF THE IPCC

Busan, 11-14 October 2010

IPCC-XXXII/Doc. 5

(3.IX.2010)

Agenda Item: 4.2

ENGLISH ONLY

THE IPCC FIFTH ASSESSMENT REPORT (AR5)

Proposal for an IPCC Expert Meeting on Geoengineering

(Submitted by the Co-Chairs of Working Group I, II and III)

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WMO UNEP

PROPOSAL FOR AN IPCC EXPERT MEETING ON GEOENGINEERING

(Submitted by the Co-Chairs of Working Group I, II and III)

Background

Geoengineering, or the deliberate large-scale manipulation of the planetary environment, is increasingly being discussed as a potential strategy to counteract anthropogenic climate change. Prevailing uncertainty in the sensitivity of the climate system to anthropogenic forcing, inertia in both the coupled climate-carbon cycle and social systems, and the potential for irreversibilities and abrupt, nonlinear changes in the Earth system with possible significant impacts on human and natural systems call for research into possible geoengineering options to complement climate change mitigation efforts.

Geoengineering methods can be largely classified into two main groups: Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR). While both approaches aim to reduce global temperatures, they clearly differ in their modes of action, the timescales over which they are effective, their effects on temperature and other climate variables (e.g., precipitation), and other possible consequences.

SRM techniques attempt to offset the effects of increased greenhouse gas concentrations by reducing the amount of solar radiation absorbed by the Earth. This may be achieved by increasing the surface reflectivity of the planet, for example by brightening human structures, planting crops with a higher albedo, or covering deserts with reflective material. Other techniques aim to enhance marine cloud reflectivity by introducing sea salt aerosols in low clouds, mimic the effects of volcanic eruptions by injecting sulphate aerosols into the lower stratosphere, or place shields or deflectors in space to reduce the amount of incoming solar radiation.

CDR techniques aim to address the cause of climate change by removing greenhouse gases from the atmosphere. This would include advanced land use management strategies to protect or enhance land carbon sinks, and the use of biomass for both carbon sequestration (including biochar) and as a carbon neutral energy source. The removal of carbon dioxide from the atmosphere, either through the enhancement of natural weathering processes or direct capture from ambient air are further examples, as well as the enhancement of oceanic CO_2 uptake through ocean fertilisation with scarce nutrients or the enhancement of upwelling processes.

Major uncertainties exist regarding the effects of these techniques on the physical climate system and on biogeochemical cycles, their possible impacts on human and natural systems, and their effectiveness and costs. SRM, for example, could impact regional precipitation patterns while offering no solution for CO_2-induced ocean acidification. Unilateral action may have environmental side effects on other countries and regions, and may not appropriately address the global scale of the issue. Thus, geoengineering itself may constitute "dangerous anthropogenic interference with the climate system" (Article 2, UNFCCC), and consideration needs to be given to international governance frameworks.

Expert Meeting

Current discussions that suggest geoengineering as an option to support climate mitigation efforts remain rather abstract and lack comprehensive risk assessments that take into account possible adverse impacts over short and longer time frames. The understanding of the physical science basis of geoengineering is still limited and IPCC will, for the first time, assess this in several chapters of the WGI contribution to AR5. Improved scientific understanding of the impacts of geoengineering proposals on human and natural systems will be assessed by WGII. WGIII needs to take into account the possible impacts and side effects and their implications for mitigation cost in order to define the role of geoengineering within the portfolio of response options to anthropogenic climate change. Furthermore, this includes an evaluation by WGIII of options for appropriate governance mechanisms.

Objectives

The aim of the proposed expert meeting is to discuss the latest scientific basis of geoengineering, its impacts and response options, and to identify key knowledge gaps. The expert meeting would be organised by Working Group III with a cross-Working-Group focus. The following issues will be discussed in more detail:

- different geoengineering options, their scientific basis and associated uncertainties;
- associated potential risks and related knowledge gaps;
- effect of impacts and side effects on mitigation cost and the role within the portfolio of mitigation options;
- suitability of existing governance mechanisms for managing geoengineering, including social, legal and political factors;
- key knowledge gaps that could be filled in the shorter and longer terms.

Expected Outcome

The expert meeting will provide a platform for exchange and discussion among experts from the different disciplines in order to better address the important cross-cutting issue of geoengineering. This should also encourage the consistent treatment of geoengineering options across the WGs' assessments that will build the basis for the AR5 Synthesis Report.

The Expert Meeting will produce a report that could include summaries of keynote presentations, abstracts of expert contributions, reports from breakout group discussions, and a non-comprehensive bibliography of recent literature related to geoengineering.

Organization

A Scientific Steering Group will be formed with relevant experts in geoengineering from the IPCC Working Groups.

Timing: first half of 2011

Duration: 2 to 3 days

Participants: About 40 invited experts, with broad international representation. It is proposed that 25 journeys for experts from developing countries and economies in transition including Co- and Vice-Chairs from all Working Groups are allocated as part of the line item "expert meetings related to the AR5" in the IPCC Trust Fund budget for 2011. Participants will be needed with expertise in:

- WGI: clouds/aerosols & climate, carbon cycle & climate, coupled climate - carbon cycle projections
- WGII: impacts on human and natural systems
- WGIII: bottom-up modelling experts, risk analysis, integrated assessment modelling groups, governance and international cooperation.

Annex 2: Agenda

Agenda for the Joint IPCC WGI/WGII/WGIII Expert Meeting on Geoengineering

Lima, Peru, 20-22 June 2011

<u>Monday, 20 June 2011</u>

8:00 Registration

8:30 Welcome and Introduction

- Welcome Address (Local Host)
- Welcome Address (WG I, II & III Co-Chairs)

8:45 FRAMING PLENARY: Overview on Current State of Science, Geoengineering Options, Current Activities (Chair: Ramon Pichs-Madruga)

8:45-9:00 Framing Keynote F-1: The Joint Expert Meeting on Geoengineering in the Context of the IPCC's Fifth Assessment Cycle (Ottmar Edenhofer, Thomas Stocker, Christopher Field)

9:00-9:30 Framing Keynote F-2: Geoengineering: A few basic ideas to start our discussion (Granger Morgan)

9:30-10:45 Panel Reactions and Discussion (Moderator: Nicolas Gruber; Panelists: Alan Robock, Granger Morgan, Robert Scholes, Shreekant Gupta)

10:45 Coffee Break

11:15 PLENARY SESSION I: Solar Radiation Management (Chair: Thomas Stocker)

11:15-11:35 Keynote I-1: Science and Technology of Solar Radiation Management (Alan Robock)

11:35-11:55 Keynote I-2: Residual Climate Change and Unintended Consequences of Solar Radiation Management (Thomas Peter)

11:55-12:15 Keynote I-3: A Primer on the Economics of Solar Radiation Management (Scott Barrett)

12:15-12:45 Discussion

12:45 Lunch

13:45 PLENARY SESSION II: Carbon Dioxide Removal (Chair: Chris Field)

13:45-14:05 Keynote II-1: Carbon Dioxide Removal in the Oceans: Biological, Chemical, and Physical (Nicolas Gruber)

14:05-14:25 Keynote II-2: Carbon Dioxide Removal on Land: Biological and Chemical (Peter Cox)

14:25-14:45 Keynote II-3: Industrial CO_2 Removal: CO_2 Capture from Ambient Air and Geological Sequestration (James Dooley)

14:45-15:15 Discussion

15:15 Introduction to Breakout Groups (BOGs) (Ottmar Edenhofer)

15:30 Coffee Break

16:00 BREAKOUT GROUPS I: Options, Scope and Key Approaches

17:30 Poster Presentations: Short introduction of poster topics (Chair: Youba Sokona)

18:00 Poster Session

19:00 Adjourn

Reception (On-Site)

<u>Tuesday, 21 June 2011</u>

8:30 Summary of Day 1 and Introduction to Day 2 (IPCC Co-Chairs)

8:35 BOG I Reports and Plenary Discussion (Chair: Ramon Pichs-Madruga)

9:30 PLENARY SESSION III: Cross-cutting Issues: Risk, Time Scales and Governance

(Chair: Ottmar Edenhofer)

9:30-9:50 Keynote III-1: Policy, Governance and Socio-Economical Aspects of Geoengineering (Catherine Redgwell)

9:50-10:10 Keynote III-2: International Cooperation and the Governance of Geoengineering (Arunabha Ghosh)

10:10 Coffee Break

10:40 PLENARY SESSION III: Cross-cutting Issues: Risk, Time Scales and Governance (Cont'd)

(Chair: Youba Sokona)

10:40-11:00 Keynote III-3: Geoengineering in a Risk Management Framework (Granger Morgan)

11:00-11:20 Keynote III-4: The Role of Different Geoengineering Options in Long-Term Responses to Climate Change (Jason Blackstock)

11:20-12:00 Discussion

12:00 Lunch

13:00 BREAKOUT GROUPS II: Cross-cutting Issues: Risk, Time Scales and Governance

14:30 BOG II Reports and Plenary Discussion (Chair: Chris Field)

15:30 Coffee Break

16:00 BREAKOUT GROUPS III: Working Group I, II, III Perspectives

17:30 BOG III Reports and Plenary Discussion (Chair: Thomas Stocker)

18:30 Adjourn

Reception (Off-Site)

<u>Wednesday, 22 June 2011</u>

9:00 SYNTHESIS PLENARY: Synthesis of previous talks and BOG discussions (Chair: Chris Field)

9:00 Synthesis Presentation S-1: Meeting perspectives for SRM (by SSG Members) & Discussion

9:30 Synthesis Presentation S-2: Meeting perspectives for CDR (by SSG Members) & Discussion

10:00 Plenary Discussion

10:30-11:00 Coffee Break

11:00-13:00 FINAL PLENARY (Chair: Ottmar Edenhofer)

- Final discussion and approval of any recommendations to AR5 authors, including suggestions for potential glossary entries for the AR5
- Closing remarks by Co-Chairs

13:00 Lunch

14:00 Adjourn

Annex 3: Keynote Abstracts

FRAMING PLENARY: Overview on Current State of Science, Geoengineering Options, Current Activities

Chair of Session: Ramon Pichs-Madruga

Framing Keynote F-1: The Joint Expert Meeting on Geoengineering in the Context of the IPCC's Fifth Assessment Cycle
Presenters: Ottmar Edenhofer, Thomas Stocker and Christopher Field[1]*

Framing Keynote F-2: Geoengineering: A few basic ideas to start our discussion
Presenter: Granger Morgan

PLENARY SESSION I: Solar Radiation Management

Chair of Session: Thomas Stocker

Keynote Presentation I-1: Science and Technology of Solar Radiation Management
Presenter: Alan Robock

Keynote Presentation I-2: Residual Climate Change and Unintended Consequences of Solar Radiation Management
Presenter: Thomas Peter

Keynote Presentation I-3: A Primer on the Economics of Solar Radiation Management
Presenter: Scott Barrett

PLENARY SESSION II: Carbon Dioxide Removal

Chair of Session: Chris Field

Keynote Presentation II-1: Carbon Dioxide Removal in the Oceans: Biological, Chemical, and Physical
Presenter: Nicolas Gruber

Keynote Presentation II-2: Carbon Dioxide Removal on Land: Biological and Chemical
Presenter: Peter Cox

Keynote Presentation II-3: Industrial CO_2 Removal: CO_2 Capture from Ambient Air and Geological Sequestration
Presenter: James Dooley

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* The abstract for Framing Keynote F-1 is not provided in this compilation.

PLENARY SESSION III: Cross-cutting Issues: Risk, Time Scales and Governance

Chair: Ottmar Edenhofer

Keynote Presentation III-1: Policy, Governance and Socio-Economical Aspects of Geoengineering
Presenter: Catherine Redgwell

Keynote Presentation III-2: International Cooperation and the Governance of Geoengineering
Presenter: Arunabha Ghosh

PLENARY SESSION III: Cross-cutting Issues: Risk, Time Scales and Governance (Cont'd)

Chair of Session: Youba Sokona

Keynote Presentation III-3: Geoengineering in a Risk Management Framework
Presenter: Granger Morgan

Keynote Presentation III-4: The Role of Different Geoengineering Options in Long-Term Responses to Climate Change
Presenter: Jason Blackstock and Ken Caldeira

Keynote F-2: Geoengineering: A few basic ideas to start our discussion

M. Granger Morgan
Department of Engineering and Public Policy, Carnegie Mellon University, USA

There are basically three ways to change the climate. Adding greenhouse gases (GHGs) warms it. Humans have been doing this in a major way since the industrial revolution. To cool it one can reduce the concentration of GHGs. This is inherently slow, and probably pretty costly. The other thing one can do is increase the albedo (the fraction of incident sunlight that is reflected back to space). This is a very "high leverage" activity and could probably be done quickly and at relatively low cost. The first of these cooling strategies is now generally referred to as CDR, the second as SRM.

Strategies to persue CDR include: 1. Engaging in afforestation and/or reforestation; 2. Employing no-till agriculture; 3. Using biomass fuel with CCS; 4. Engaging in ocean fertilization to increase biotic up-take; 5. Enhancing natural weathering (e.g., add alkalinity to soils); and 6. Directly scrubbing from the air with engineered systems. In the talk, each is described and critiqued briefly.

Strategies to persue SRM include: 1. Adding small reflecting particles in the stratosphere; 2. Adding more clouds in the lower part of the atmosphere; 3. Placing various kinds of reflecting objects or diffraction gratings in space either near the earth or at a stable location (the L1 point) between the earth and the sun; and 4. Changing large portions of the planet's land cover from things that are dark and absorbing, such as trees, to things that are light and reflecting, such as open snow-cover or grasses. Again, in the talk, each is described and critiqued briefly.

Of the four SRM options, adding fine reflective particles to the stratosphere is the most feasible in terms of cost and effectiveness. For this reason, the balance of the talk focuses on this strategy which has the characteristic that it is fast, cheap and imperfect. The discussion focuses in particular on the ways in which SRM is imperfect. It argues that while learning more about SRM carries dangers, today the risks of not knowing more outweigh those risks.

The talk was assembled quickly after David Keith, who was originally going to present the opening keynote, got stuck in Calgary, and then Ken Caldeira, who had agreed to replace him, got stuck in Houston. The talk concludes with summary views from both of them. The author then argues that, while it is very important to do research, great caution must be exercised about doing anything more than that in the case of CDR that has large-scale ecosystem impacts, and of SRM.

Keynote I-1: Science and Technology of Solar Radiation Management

Alan Robock[1]
Philip J. Rasch[2]
[1]Department of Environmental Sciences, Rutgers University, New Brunswick, NJ, USA
[2]Atmospheric Science and Global Change Division, Pacific Northwest National Laboratory, Richland, WA, USA

In response to the global warming problem, there has been a recent renewed interest in geoengineering "solutions" involving "solar radiation management" (SRM) by injecting particles into the stratosphere, brightening clouds, brightening the surface, or blocking sunlight with satellites between the Sun and Earth. This class of geoengineering is distinct from carbon dioxide removal (CDR) strategies that counter climate change by reducing the concentration of CO2. A quite comprehensive discussion of both classes of methods can be found in a special report by the Royal Society (2009) and a volume of papers edited by Launder and Thompson (2010). The scientific issues associated with SRM will be explicitly discussed in Chapters 1 and 7 of the WGI contribution to the 5th IPCC Assessment.

Although weather and climate modification has been considered for at least a century, the idea of deliberately cooling the planet by increasing its reflectivity probably dates back to Budyko (1974), who proposed that if global warming ever became a serious threat, society could counter it with airplane flights in the stratosphere burning sulphur to make aerosols (small particles), similar to those found after a volcanic eruption. These small particles would reflect some sunlight away, increasing the planetary albedo and cooling the planet, ameliorating some (but as discussed below, not all) of the effects of increasing CO2 concentrations. Many other suggestions have been made since that time. Among them are methods to increase the reflectivity of clouds (Latham and Smith, 1990) introduce space based reflectors located at the L1 point (the orbital position where the gravitational attraction of the Earth and Sun are equal; Early, 1989); and significantly change the albedo of vegetated surfaces by replacing crops or grassland species with more reflective varieties (e.g., Lenton and Vaughan, 2009), of deserts by coating them with brighter material, or of producing bubbles in water to brighten the ocean. New ideas are being considered frequently, and this list is not comprehensive.

The various methods have been evaluated by attempting to estimate the efficacy, cost, and consequences (safety, risks, and benefits) to the planet through economic, engineering and scientific studies. These studies have used computer (economic, scientific and engineering) models to estimate the practicality, costs and outcomes of these SRM strategies. At the time of this writing, there have not been any field activities to explore implementation or testing strategies at a practical level.

While volcanic eruptions have been suggested as innocuous examples of stratospheric aerosols cooling the planet, the volcano analog actually argues that stratospheric geoengineering would produce ozone depletion and regional hydrologic responses. In this talk, I describe different proposed geoengineering designs, and then show climate model calculations that evaluate both their efficacy and their possible adverse consequences. No such systems to conduct geoengineering now exist, but a comparison of different proposed stratospheric injection schemes, using airplanes, balloons, and artillery, shows that using airplanes to put sulfur gases into the stratosphere would not be expensive. Nevertheless, it would be very difficult to create stratospheric sulfate particles with a desirable size distribution. We have just started a GeoMIP project to conduct standard stratospheric aerosol injection scenarios in the context of CMIP5, so as to examine the robustness of the few experiments conducted so far (Kravitz et al., 2011).

If there were a way to continuously inject SO2 into the lower stratosphere, it would produce global cooling, stopping melting of the ice caps, and increasing the uptake of CO2 by plants. But there are many other possible negative consequences that should be considered. These include possible changes to precipitation (e.g., monsoons), ozone depletion, a reduction in the "blueness of the sky," and impacts on solar power production. Furthermore, if SRM were employed to counter a strong greenhouse gas forcing and then stopped abruptly, the planet would warm very rapidly with serious consequences. There are other issues associated with governance and society that need to be considered (informed by the scientific topics described in this talk).

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Keynote I-2: Residual Climate Change and Unintended Consequences of Solar Radiation Management

Thomas Peter
Swiss Federal Institute of Technology (ETH), Zurich, Switzerland

This presentation will address consequences of geoengineering options based on solar radiation management (SRM) introduced in the previous keynote. It will focus on residual climate change and unintended consequences on the climate system from these technologies in the light of current uncertainties.

Using SRM methods it should in principle be feasible to balance the globally averaged radiative forcing from greenhouse gases as precisely as necessary. However, the cancellation of the global mean forcing will not lead to restoring climate change at any given location, with likely residual net impacts on regional climates.

In their report on geoengineering the Royal Society (2009) summarized aspects of residual climate change and unintended consequences of SRM techniques – besides ongoing ocean acidification – as follows:

1. Surface albedo via brightening of human settlements:
    a. Minimal environmental side-effects from materials
    b. Effects on small spatial scales, unlikely to modify weather patterns etc.
2. Surface albedo via brightening of forest canopies, grassland or deserts:
    a. Potentially major environmental and ecological effects on plant ecosystems
    b. Major environmental and ecological effects on desert ecosystems
    c. Localized and non-uniform effect on large scale, probably affecting weather patterns, rainfall etc.
3. Cloud albedo enhancement:
    a. Non-uniformity of effects may change weather patterns, in particular rainfall, on regional scales
    b. Non-uniformity may affect ocean currents
    c. Possible pollution by CCN material (if not sea-salt)
4. Stratospheric aerosol albedo enhancement:
    a. Residual regional effects, particularly on hydrological cycle (rainfall)
    b. Possible adverse effect on stratospheric ozone
    c. Possible effects on high-altitude tropospheric clouds
    d. Shift of partitioning of direct/diffuse light, potential effects on biological productivity
5. Space-based methods (mirrors etc.):
    a. Residual regional climate effects, particularly on hydrological cycle
    b. No known direct biochemical effects on environment beyond possible effects of reduced insolation

Since the publication of the Royal Society report a proposal for one additional potential geoengineering technique has been made (Evans et al., 2010; Seitz, 2011), whose unintended side effects and consequences in terms of residual climate change can presently only be speculated on:

6. Surface albedo enhancement via brightening of oceans:

    a. Reduction of light transmission to lower ocean levels with potential impact on marine ecobalance

    b. Significant ecological effects if artificial surfactants were to be used

    c. Non-uniformity of effects may change weather patterns, rainfall etc. on regional scales

    d. Induced changes in oceanic circulation and anomalous evaporation, which would in turn affect atmospheric heating and atmospheric circulation

While all these proposed techniques should be considered, techniques (3) and (4) have so far found particular interest given their potential advantages in terms of their combined effectiveness, timeliness and affordability (The Royal Society, 2009), and first quantitative comparisons have been published (e.g., Jones et al., 2011). This contribution aims at reviewing all the above techniques in terms of their regional climate effects and unintended side effects: Where do we stand? What are the uncertainties?

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Keynote I-3: A Primer on the Economics of Solar Radiation Management

Scott Barrett
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'Solar radiation management' (SRM) is a term sometimes used for engineering interventions that seek to alter the Earth's climate without affecting the atmospheric concentration of greenhouse gases. Put very crudely, the idea involves an engineering intervention that either increases the reflectivity of the Earth or that reduces the amount of incoming solar radiation before it reaches the Earth (Keith, 2000; Crutzen, 2006). Though engineering serves as a means for accomplishing the end of influencing the climate, "management" may not be the best word to describe its application. There may be sharp disagreement about the circumstances in which this engineering intervention should be considered—or even if it should be considered at all (Robock, 2008). There may also be disagreement about the desired end. (What is the ideal global climate?) The central social, political, legal, and ethical challenges posed by this technology all concern governance (Schelling, 2006; Bodansky, 1996; Barrett, 2008; Victor, 2008). The economics of this form of geoengineering is important mainly because it makes this challenge of governance acute: some forms of geoengineering are very inexpensive (Barrett, 2009).

Possible use of this form of geoengineering should be considered in the context of the other ways in which climate change, and the effects of climate change, can be influenced. Emissions of greenhouse gases can be reduced, to limit increases in atmospheric concentrations; R&D can be undertaken, to lower the costs of reducing emissions in the future; affected parties can adapt, to lower the damages (and possibly to augment the advantages) attributable to climate change; and techniques for "direct carbon removal" can be used to limit concentrations directly.

Anything that affects the climate will have global implications. Countries not involved in the effort will also be affected, for better or worse (making these interventions a global public good or a global public bad). For these reasons, countries have weak incentives individually to reduce their emissions—even though they may have great incentives collectively to do so (Barrett, 2007). This is known as the "free riding" problem. Similarly, because the benefits of R&D are derived from the likelihood that technologies embodying the R&D will be deployed for the purpose of reducing emissions, if the incentives to deploy are weak, the incentives to invest in R&D will be weak (Barrett, 2006). The incentives to adapt will be very powerful. A substantial portion of the benefits from adaptation can be captured by the parties that invest in it. Much of the rest involves the supply of local public goods (dikes being an example), which can be provided by national (or even local) governments, with no need for international cooperation. The incentives to deploy direct carbon removal are mixed. Some approaches are inexpensive, but also limited in scale. Other approaches can potentially be undertaken at a great scale, but are very expensive (Barrett, 2009).

It is sometimes said that SRM creates a "moral hazard"—since SRM can be used to lower temperature in the future, there will be incentives for countries to expend less effort in reducing emissions today (Victor et al., 2009). As Robock (2008) says, "This is the oldest and most persistent argument against geoengineering."

However, while it's true that that these incentives exist, this is an incorrect use of the term. (An example of moral hazard is the International Monetary Fund's role in offer financing to avert a financial crisis—a role that is believed to make such crises more likely to occur.) Moral hazard normally describes a situation in which there are different parties (the IMF and various government) with different interests (the IMF wants not to have to intervene, whereas the government wants to spend money more freely) and information (the IMF can't tell if the government is managing its economy well). Moral hazard results in an economic inefficiency. By contrast, while knowledge that geoengineering could be used to limit climate change in the future will likely influence emissions policy today, that effect need not be inefficient. If SRM were expected to work, and without harmful consequences, it would be desirable for countries to use it—and to ease up on their efforts to reduce emissions today.

There are other reasons why too little effort will be devoted to reducing emissions, perhaps the main one being free riding. Moreover, since the costs of deploying SRM are low, the incentives to deploy it unilaterally or minilaterally will be strong. We will tend to substitute more geoengineering for less emission reductions not because of moral hazard but because of collection action failures (Barrett, 2008).

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Keynote II-1: Carbon Dioxide Removal in the Oceans: Biological, Chemical, and Physical

Nicolas Gruber
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Over the last 250 years, the ocean has taken up more than 25% of all anthropogenic emissions (Sabine et al., 2004). While substantial, this is much less than its long-term uptake potential, which corresponds to an uptake fraction of approximately 80% of all emissions on a time-scale of ~500 years, and more than 95% on time-scales longer than 100'000 years. The former potential involves primarily the solution of CO_2 into seawater and subsequent reactions with its dissolved constituents, while the latter involves also interactions with the marine and terrestrial carbonate system. Given the large potential of the ocean carbon sink and the slowness with which this potential is being realized, it is not surprising that the idea of shortcutting the slow process of ocean uptake by injecting CO2 directly into the ocean emerged already in the late 1970s (Nordhaus, 1975; Marchetti, 1977). Recognizing that such a direct injection of CO_2 would lead to a massive decrease in oceanic pH and saturation state of the seawater with regard to mineral forms of $CaCO_3$ (ocean acidification), it was later suggested to add alkalinity in the form of limestone to the injected CO_2 to compensate (Rau and Caldeira, 1999). Even later, the direct addition of limestone to the ocean was proposed, which would not only compensate for ocean acidification, but also increase the uptake of CO_2 from the atmosphere (Harvey, 2008). An entirely different family of proposed options to use the ocean to remove CO_2 from the atmosphere emerged in the late 1980s, i.e., those that attempt to enhance the ocean's biological pump by fertilizing the ocean with limiting nutrients, in particular iron (Martin, 1990). This fertilization is meant to increase the near-surface photosynthetic fixation of CO_2 by marine algae into organic matter, part of which would escape respiration and remineralization and sink down to great depths, where it would remain sequestered from the atmosphere. This net removal of dissolved CO_2 from the surface ocean would then be compensated by uptake of CO_2 from the atmosphere, creating a net removal of CO_2 from the atmosphere. Several modification of this hypothesis have been suggested since then, including the addition of macronutrients such as phosphorus to the ocean, the enhancement of oceanic nitrogen fixation, and an increase in upper ocean mixing to provide higher levels of nutrients to surface ocean algae.

In summary, we can categorize the ocean-based methods to remove CO_2 from the atmosphere into three broad sets:

- physically-based methods: primarily direct injection of liquid CO_2 into the ocean
- chemically-based methods: primarily based on the addition of alkalinity to the ocean
- biologically-based methods: primarily based on the enhancement of the ocean's biological pump.

This plenary talk aims to provide a short introduction to each of the three main categories and will make an attempt to assess their technical potential, their effectiveness, their technical readiness, and the main benefits and risks involved. It will draw extensively on the rich literature that exists on ocean-based CO_2 removal methods. In particular, the physically-based methods have been investigated and assessed in detail in IPCC's special report on carbon capture and storage (IPCC, 2005), while the chemically and biologically-based methods have been summarized in the Royal Society Report on Geoengineering (The Royal Society, 2009).

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Keynote II-2: Carbon Dioxide Removal on Land: Biological and Chemical

Peter Cox
University of Exeter, UK

This talk will review land-based Carbon Dioxide Removal (CDR) techniques based on chemical and biological approaches. Free-air capture of CO_2 through physical processes will be covered in a subsequent talk.

The Royal Society (2009) considered CDR approaches to be relatively low risk compared to SRM geoengineering, as CDR deals with the primary cause of anthropogenic climate change and ocean acidification. Nevertheless, many of the proposed land-based CDR techniques imply land-use changes that could have consequences for regional climates and ecosystem services. Such issues cut across all three of the Working Groups of the IPCC AR5.

Chemical approaches to CDR rely on accelerating the natural processes of rock weathering, which removes CO_2 from the atmosphere on multi-millenial timescales. One land-based approach would involve spreading Olivine (Mg2SiO4) over agricultural fields to enhance weathering by one or two orders of magnitude (Schuiling and Krijgsman, 2006). Some studies suggest that the carbon sink produced would be relatively small: 0.1 to 1% of current global CO_2 emissions (Hartmann and Kempe, 2008; Hangx and Spiers, 2009). In general, **enhanced weathering** methods typically involve mining and moving a larger mass of minerals than the CO_2 captured, so they may also be expensive (The Royal Society, 2009).

Land-based biological CDR involves diverting carbon captured by plants to long-lived reservoirs. The different approaches are typically distinguished by the nature of the long-lived carbon store:

Afforestation involves planting new forests to accumulate and store carbon. Although relatively benign, in the absence of harvesting, the ultimate accumulated sink is limited by the additional carbon "carrying capacity" of the land, which is probably of the order of 150-200 GtC.

Biochar (or charcoal) can be created by thermally-decomposing biomass in a low oxygen environment. Most proposals involve adding biochar to soil to increase carbon storage and improve agricultural productivity. The potential sink by 2100 has been estimated to be significant at 5.5-9.5 GtC/yr (Lehmann et al., 2006). However, the long-term effects on land ecosystems are not well known, and there are few estimates of economic costs.

Biomass Burial is an alternative which involves burying wood in anoxic environments (e.g. deep in the soil, Zeng, 2008) where decomposition would be much slower. Estimates of the size of the sink are disputed but are likely to be limited by the cost of burial and competition for biomass with other approaches (e.g. Biochar and BECCS). Lenton (2010) estimates a potential carbon sink of less than 1 GtC/yr, and warns of the possibility of counter-productive emissions of methane from anaerobic decomposition.

Bioenergy with Carbon Sequestration (BECS) is a hybrid approach in which bioenergy crops are grown and used as fuel, and the CO_2 emissions are captured and stored. BECS could yield a large potential carbon sink (3-10.5 GtC/yr; Lenton, 2010), and might even be used to lower atmospheric CO_2. However, it has the same issues as biofuels and conventional CCS, namely potential conflicts for food production and the requirement for safe geological CO_2 storage. BECS will be considered in more detail in a subsequent talk, but is included here for comparison.

The Royal Society (2009) evaluated each of the CDR approaches based on their climate effectiveness, affordability, and safety, concluding that most were likely to be significantly more expensive than conventional CCS. A recent review by Lenton (2010) attempted to quantify the potential contribution of the various biological CDR approaches to stabilization of atmospheric CO_2 (see Figure A.3.1, which is based on the upper limits given by Lenton, 2010). These figures suggest that biochar and BECS could together contribute a carbon sink of 14 GtC/yr by 2100.

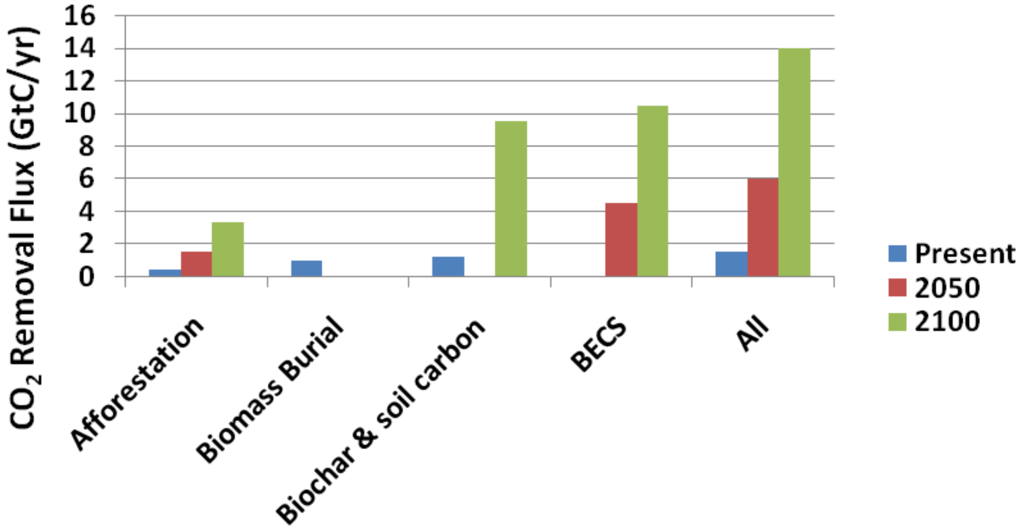

Figure A.3.1: *Potential effectiveness of land –based biological CDR (based on upper limits from Lenton, 2010).*

This talk will summarise these studies and finish by identifying some discussion points concerning the treatment of land-based CDR in the IPCC 5th Assessment Report.

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Keynote II-3: Industrial CO_2 Removal: CO_2 Capture from Ambient Air and Geological

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INTRODUCTION This abstract and its accompanying presentation, which were prepared as inputs for the IPCC's June 2011 Expert Meeting on Geoengineering, will provide an overview of two distinct industrial processes for removing carbon dioxide (CO_2) from the atmosphere as a means of addressing anthropogenic climate change. The first of these is carbon dioxide capture and storage (CCS) coupled with large-scale biomass production (hereafter referred to as bioenergy with carbon dioxide capture and storage (BECSS)). The second CCS coupled to a system that captures CO_2 from ambient air via industrial systems (hereafter referred to as direct air capture (DAC)). In both systems, the captured CO_2 would be injected into deep geologic formations so as to isolate it from the atmosphere. The technical literature is clear that both BECSS and DAC (including their necessary CCS components) are technically feasible as of today (IPCC, 2005; Keith et al., 2006; Lackner, 2009; Luckow et al., 2010; Ranjan and Herzog, 2011; The Royal Society, 2009). The technical literature on DAC and BECSS typically envisions these systems being deployed after the middle of this century and typically in "overshoot scenarios" or in scenarios that stabilize radiative forcing at very low levels (Azar et al., 2010; K. Calvin et al., 2009). What is uncertain is the relative cost of BECSS and DAC systems when compared to other emissions mitigation measures, the ultimate timing and scale of their deployment, net lifecycle emissions from these systems, and the resolution of potential site specific constraints that would impact their ultimate commercial deployment.

BECCS: Considerable concern has been expressed in the technical literature about the inherent conflict between using land to grow food to feed a growing global population and using land to grow energy crops. Concerns have been expressed in terms of: broad sustainability issues including environmental justice and equity concerns (see for example, Adger et al., 2006; Toth, 1999), whether or not there will be net reductions in greenhouse gas emissions from large scale bioenergy production and consumption (Melillo et al., 2009), whether it is possible to move the required volumes of biomass (Richard, 2010) and even in terms of technical feasibility given a changing climate that could result in lower net primary productivity over large swaths of the earth's prime agricultural areas (Lobell and Asner, 2003; Solomon et al., 2009). While not minimizing these concerns, it is important to note that most of these adverse impacts will become manifest at large levels of bioenergy production (e.g., on the order of 100s of EJ/year) and there are steps that can be taken to minimize the worst of these impacts. For example Wise et al. (2009) demonstrated that a climate policy that places an equal value on carbon emissions from the industrial sector as well as from agriculture and land use can simultaneously incentivize the large scale production of bioenergy as well as incentivize afforestation and protect carbon already stored in above ground and below ground biomass and soils. While Luckow et al (2010) make it clear that "The ability to draw on a diverse set of biomass-based feedstocks helps to reduce the pressure for drastic large-scale changes in landuse and the attendant environmental, ecological, and economic consequences those changes would unleash." However, to support BECSS on the scale of 100s of EJ/year would require large bioenergy plantations and significant international trade in bioenergy feedstocks, which could imply significant changes in key global ecosystems (see for example, Thomson et al., 2010). However by adopting technologies that would push densification, dehydration, and pelletization of the purpose grown biomass early into the harvesting process large scale international trade in biomass should be possible and thus there would not need to be a strict correspondence between where the bioenergy crops are grown and where the bioenergy crops are used and therefore where the CO_2 needs to be stored in suitable deep geologic formations (Hamelinck et al., 2005; Luckow et al., 2010). The extent to which there are continued improvements in crop productivity including efforts to enhance the efficiency of natural photosynthesis will be a significant determinant in the extent to how much bioenergy can be produced (Berndes et al., 2003; Blankenship et al., 2011; Thomson et al., 2010; Wise et al., 2009) and therefore on the cost and market potential for BECSS. According to the literature surveyed here, large scale BECSS production on this scale should be well underway at carbon permit prices less than \$100/tCO_2 (Krey and K. Riahi, 2009; Luckow et al., 2010).

DAC: There are a number of excellent recent summaries of various DAC system concepts that can provide a robust introduction to DAC technologies (IPCC, 2005; Ranjan and Herzog, 2011; Socolow et al., 2011; The Royal Society, 2009). At their most basic level, DAC systems use a chemical solvent to selectively remove CO_2 from the ambient air, that solvent is then regenerated releasing a concentrated CO_2 stream, which then is compressed most likely to a supercritical fluid and then injected into the deep subsurface and monitored for long-term permanence. Ranjan and Herzog (2011) as well as Socolow et. al., (2011) estimate that the cost of deploying DAC systems capable of removing hundreds of millions to billions of tCO_2/year from the atmosphere in the range of \$600-\$1200/tCO_2, while others have placed the cost of DAC systems within a much lower range. Keith et al., (2006) reports a cost of \$50-130tCO_2, while Lackner (2009) reports costs in the range of \$30-\$200/tCO_2. The difference in costs between these two views as to the ultimate economic feasibility of

DAC systems is remarkable and speaks to the lack of real world experience with large DAC systems. It is clear that there are significant differences in the way a number of key factors are parameterized in the DAC literature which helps to explain this large disparity in the estimated cost of DAC deployment: (1) major differences in assumptions as to the pressure drop across the entire DAC system and therefore the amount of energy needed to run the DAC system, (2) the degree to which to which the cost of separation scales inversely with the concentration of the sought after compound is in the original starting mixture, (i.e., it should be cheaper – potentially much cheaper—to separate concentrated CO_2 from a biomass gasification system than from dilute CO_2 in the ambient air), and (3) the very large physical scale of DAC systems and whether economies of scale or diseconomies of scale would dominate.

DAC systems differ from BECSS in another important respect. As carbon permit prices increase, BECSS systems produce two very valuable commodities, carbon free electricity and certified negative emissions permits (i.e., tradeable offsets for carbon emissions in other parts of the global energy and economic system). At some point, the relative value of these two commodities will change and could change to the point where the more valuable commodity is the certified negative emissions permits, but the carbon free electricity would still remain an important product from these systems. DAC systems on the other hand produce no electricity and in fact would be net (perhaps significant) energy consumers as they would need some form of energy to regenerate the solvent used to remove the CO_2 from the ambient air, run pumps, filters, compress the captured CO_2 for injection into the deep subsurface as well as many other ancillary energy loads at the DAC facility. Thus, the DAC systems produce only one product, certified negative emissions permits. The lack of a revenue stream from being able to provide carbon free electricity could be an impediment that further complicates the early commercial deployment of DAC systems.

CONCLUDING POINTS:

1. DAC and BECSS can be seen as "backstop" emissions mitigation technologies in that they should set a ceiling on the cost of CO_2 emissions abatement. Developing a better understanding of the cost to deploy these systems and the potential scale of their deployment could be a vital input into societal decisions about the relative mix of mitigation and adaptation as response strategies to anthropogenic climate change (Socolow et al., 2011).

2. As noted by Azar et al. (2010) as well as others, the critical role that BECSS systems would play is in making it potentially possible to stabilize atmospheric concentrations of CO_2 at low levels near 400 ppm. For stabilization targets that are above this threshold but yet still stringent (e.g., 450-550 ppm), BECSS could be important in significantly lowering the cost of stabilization. For example, Azar et al (2010) note that the ability to deploy BECSS on a large scale allows atmospheric concentrations of CO_2 to be stabilized at a level 50 to 100 ppm lower than what would be attainable without BECSS for roughly the same cost.

3. Large scale deployment of BECSS or DAC systems would likely increase demand for deep geologic CO_2 storage reservoirs. The total demand for geologic storage reported in the literature is a small fraction of total theoretical deep geologic storage space (Dooley and K.V. Calvin, 2010; IPCC, 2005; Krey and K. Riahi, 2009) and therefore it seems unlikely that any increased demand for geologic storage space would be a significant deployment barrier for BECSS and DAC.

4. For either large scale BECSS or DAC deployment to the point where there would be negative net global emissions for perhaps decades, there would be a need to remove more than one ton of CO_2 from the atmosphere for each ton removed by these systems as the oceans and perhaps terrestrial systems would release CO_2 stored in them until an equilibrium is reached. The magnitude, speed, and duration of these releases from the ocean are all issues that need to be better understood.

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Keynote III-1: Policy, Governance and Socio-Economical Aspects of Geoengineering

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Increasingly it is apparent that some geoengineering methods may be technically possible, though with major uncertainties regarding their effectiveness, cost and socio-economic and environmental impacts (The Royal Society, 2009). This presentation explores the regulation of geoengineering and the principles which should guide the establishment of the governance structure necessary to guide research in the short term and to ensure that any decisions ultimately taken with respect to deployment occur within an appropriate governance framework. The uncertainties and controversies surrounding geoengineering have recently been considered both nationally (UK House of Commons, 2010; U.S. House of Representatives, 2010) and internationally. In the latter context, the State parties to the 1972 London Convention and 1996 Protocol and to the 1992 Convention on Biological Diversity, have each actively debated the consistency of ocean iron fertilization activities with convention obligations, inter alia, to protect and preserve the marine environment, and in late 2010 the CBD considered the matter of geogengineering more broadly. Thus both domestically and internationally it is clear that governance of geoengineering is moving up the legal and policy agenda.

To date there has been little comprehensive assessment of the international regulation of geoengineering. Indeed, absent from the current legal landscape is a single treaty or institution addressing all aspects of geoengineering; rather, the regulatory picture is a diverse and fragmented one both at the international and national levels (Bracmort et al., 2010; Hester, 2011). Thus a major strand in the sparse legal literature addressed to geoengineering is an assessment of the extent to which existing rules may be adapted to regulate geoengineering actors and activities (e.g. Bodansky, 1996; Michaelson, 1998; Rayfuse et al., 2008; Zedalis, 2010; Redgwell, 2011; Lin, 2011).This relies on the flexible adaptation, or possible amendment, of existing treaty rules or the application of customary international law rules, seeking to employ the legal tools at hand to regulate geoengineering activities, whether field trials or potential deployment. The difficulty of drawing a sharp distinction between these in terms of the nature of the activity and its effects, especially where large-scale field trials are in question, is significant, An example of a cautious graduated approach is found in the response by the parties to the 1972 London Convention and 1996 Protocol to ocean iron fertilization to prohibit all but small-scale scientific field trials pending further development of a regulatory framework.

Assessment of existing instruments should also take into account the dynamism of the norm-generating process, particularly in the environmental context. Existing instruments may be divided between those potentially applicable to all geoengineering methods (e.g. the 1977 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques and the 1992 UN Framework Convention on Climate Change) and those potentially applicable to particular methods (e.g. the 1972 London Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter and 1996 Protocol, for ocean iron fertilization, and the 1985 Convention for the Protection of the Ozone Layer and 1987 Montreal Protocol with respect to stratospheric aerosols.)

There are a number of alternatives for geoengineering governance. The first would be the conclusion of a "bespoke" legal instrument or instruments to address geoengineering. However, a multilateral geoengineering treaty is neither likely nor desirable. It is unlikely because the appetite for law-making, particularly in the climate change context as evidenced by the Copenhagen and Cancun meetings, is low (D. Bodansky and Diringer, 2010; Werksman and Herbertson, 2010; Rajamani, 2010, 2011). It seems inconceivable that the political will would be generated for law-making on this scale and where such a degree of controversy exists. Achieving consensus on all but the lowest common denominator – if that – seems very unlikely.

Such a route is also undesirable, for two reasons. The first is that international law hardly presents a blank slate, with a plethora of potentially applicable instruments where "regime legitimacy" has been established over time. The swift response to carbon capture and storage by the parties to the global LC/LP and regional OSPAR regime is an illustration of what can be done when there is clear consensus regarding the need for international regulation, the political will to do so, and appropriate instruments to adapt. Existing instruments can, and likely will, regulate aspects of geoengineering which fall within their treaty mandate. By the same token, there are gaps, most obviously with respect to the regulation in areas beyond national jurisdiction of SRM methods. A single treaty on geoengineering is also undesirable owing to the range of methods, where they may be carried out, and by whom. There can be no "one size fits all" approach to geoengineering regulation beyond the identification of key guiding principles or concerns of general application. Amongst other things, these could inform the interpretation and application of existing instruments.

One step forward could be the adoption of guiding principles for geoengineering governance, not as a template for an international treaty instrument but as an example of potential guidance, which could be embedded in soft or hard law and used by the key geoengineering stakeholders to guide decision-making on geoengineering research in particular. These might comprise the following (Rayner, et al., 2009; Asilomar Scientific Organizing Committee, 2010):

- Principle 1: Geoengineering to be regulated as a public good
- Principle 2: Public participation in geoengineering decision-making
- Principle 3: Disclosure of geoengineering research and open publication of results
- Principle 4: Independent assessment of impacts
- Principle 5: Governance before deployment

Such guiding principles could sit well against the backdrop of a moratorium on deployment pursuant to ENMOD or a General Assembly resolution, for example. Unlike a binding legal instrument, such guidance can be adopted "instantly" through endorsement by relevant actors (UNGA resolution; UNEP guidelines; endorsement by national legislatures; professional bodies etc). Nor is the adoption of guiding principles in "soft" form and the simultaneous negotiation of binding rules mutually exclusive, with the possibility of "twin-track soft-hard" rules (Redgwell, 2011). Such principles are also adaptable to the multi-scalar multi-level – local, national and international - governance architecture needed successfully to combat climate change (Osofsky, 2008; Scott, 2011).

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Keynote III-2: International Cooperation and the Governance of Geoengineering

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The case for the international governance of geoengineering is unclear for several reasons: why governance is needed; what to govern; how widely would international governance work. This presentation asks: If geoengineering were to be governed at the international level, what would be the underlying motivations and what forms could such governance take? The purpose is two-fold: to inquire into the explicit and implicit concerns and interests that motivate countries to demand or oppose international governance; and secondly, to inquire into the functional forms that international governance could take depending on varied motivations. Not only is international cooperation on geoengineering not a given; its design and effectiveness would depend on the ultimate goals for promoting governance at the international level.

Why govern?

Demands for governing geoengineering derive from a mix of interests and ethical concerns. On interests, states are motivated by at least two competing pressures, both stemming from uncertainty over the science of geoengineering. Without further research, the state of knowledge on geoengineering will not be robust enough for policymakers to make informed decisions. An individual country might want to retain the freedom to experiment with geoengineering technologies, so that its scientific community may build an advanced knowledge base on yet unproven technologies. Viewed in this way, international rules could be considered 'status quo-ist', a constraint on a single country's freedom of manoeuvre in future. But uncertainties associated with geoengineering also mean that the actions of other countries might have unforeseen consequences. Could geoengineering offer a technological edge to some countries? Could deployment of certain techniques outside one's borders adversely affect weather patterns within one's territory? With the current state of knowledge, it is hard to answer such questions with certainty. Viewed in this way, international rules could be considered a useful tool to rein in runaway, unilateral action in an uncertain technological field. Thus, countries would favour rules that offered them maximum flexibility while keeping other countries off balance. But the demand for rules also derives from ethical concerns. Countries (and/or their citizens) could seek governance over geoengineering technologies because they oppose interference with nature, or because they want to ascertain the intent behind research into these technologies, or simply because they claim a say over actions that have international impact. Process-related concerns include: having the opportunity to participate in forums where rules might be drawn up, having the power to influence rules, and being sufficiently aware to offer informed consent or dissent. Outcome-related concerns include: capability to conduct geonengineering research and/or deployment; intentions and actions deriving from such capability; the manner in which actions are monitored and reviewed; and how disputes are adjudicated and resolved.

Why cooperate?

Even the most powerful of countries need international regimes at least under three conditions: the lack of a framework establishing legal liability for state actions; positive transaction costs; and imperfect information. The presentation will distinguish between forms of international cooperation depending on the motivations of countries demanding governance arrangements. Cooperation over scientific experiments would entail decisions about funding, building capacity, coordinating research, reviewing results, and ensuring transparency. Such cooperation could bypass national governments, at least for small scale or laboratory experiments. International cooperation gets trickier when geoengineering research is not only funded from public resources but also where intentionality is hard to identify and responsibility is hard to attribute. Even if intentions were benign, some would argue that since geoengineering is a response to climate change (an issue the burden of responsibility), the international community should have a say in why and how it is researched and deployed. Whatever the motivation, the case for international cooperation is based on: firstly, imperfect information about geoengineering activities, their intent and impact; and, secondly, the absence of a framework to establish legal liability over actions.

Which functions for what motivations?

It is unclear a priori what institutional form international cooperation would take in order to influence geoengineering activities. At least four options may be identified: one, national-level governance; two, ad hoc codes of conduct and principles developed by the scientific community; three, adapting the mandates of existing international treaties, such as the Convention on Long Range Transboundary Air Pollution, the Convention on Biological Diversity and the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques; and four, creating a new regime to govern aspects of geoengineering that other regimes or national institutions cannot handle. Each governance option has merits and demerits. In order to understand the conditions under which different options might emerge, the presentation will use a framework to identify the functions that are necessary to promote international cooperation and respond to differing motivations. Three relevant governance functions may be identified: making decisions, monitoring actions, and resolving disputes. The motivations may be broadly grouped into interest-based and ethical concerns. The former seek a balance between maintaining flexibility for oneself while constraining others' actions. Ethical concerns ask whether the processes and outcomes of geoengineering governance are considered legitimate and for whom.

Table A.3.1: The design of international governance of geoengineering will depend on functions and motivations

	Interest-based concerns		Ethical concerns	
	Maintain flexibility	Constrain others	Process legitimacy	Outcome legitimacy
Making decision	Scope of international governance limited	Scope of international governance broad	Inclusive process vs. Ease of decision-making in small groups	Equally weighted voting rules vs. Capability-driven voting
Monitoring actions	Self-reporting	Institutional reporting plus verification	Inclusiveness of review procedures	Quality and timeliness of reporting
Resolving disputes	Decentralised adjudication	Centralised adjudication plus centralised/decentralised enforcement	Ease of access to dispute settlement forums	Ability to enforce decisions

The interplay of functional demands for international cooperation and interest-based and ethical concerns offers choices for regime design (Table A.3.1). Decision-making depends on the scope of issues that would be governed internationally, who has a seat at the table, and the rules to aggregate votes and positions. Inclusive processes give countries without capacity to have a say in activities that have international consequences, but this approach competes against the efficiency of small group settings. Influence over outcomes depends on different voting rules. Monitoring actions is highly contested. Self-reporting may be preferred by sovereignty-protecting states. But regulating other's actions needs some form of institutional reporting with independent verification. Ethical concerns also drive options for monitoring depending on how broad review procedures are and whether reporting offers timely, accurate and salient information. Resolving disputes is perhaps hardest because intentions are hard to define and responsibility not attributed easily. To preserve flexibility, countries would prefer domestic courts for disputes over activities in their territories but international mechanisms for those arising elsewhere. Enforcement may be either decentralised (leaving it to countries to pursue means of influencing other) or centralised (using sanctions stemming from an international institution). For ethical concerns, barriers to entry in the formal dispute resolution arrangement could include lack of information and/or lack of resources. Outcome legitimacy depends on disputants having the ability to enforce rules against more powerful countries.

The presentation will draw upon the experience of and lessons from other international regimes and with the international coordination of research activities. By combining motivations and governance functions, the presentation suggests ways in which international cooperation might evolve depending on the balance of power, interests and ethics.

Keynote III-3: Geoengineering in a Risk Management Framework

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Conventional tools of risk analysis and decision support (including the use of failure mode and effects analysis and fault trees, combined with modern methods for assessing risk perceptions and engaging in risk communication) are entirely appropriate for use in risk management of that subset of CDR that uses engineered systems designed to scrub CO_2 from the atmosphere. After a few general preliminaries about the state of modern risk analysis and management, the talk will briefly outline strategies that can be used for risk management of engineered systems for CDR. These systems lie in region A of Figure A.3.2.

In contrast, conventional tools for risk analysis and management, and more critically tools for decision support, are only partly adequate to assess CDR that involves large-scale long-term modification of ecosystems. Many conventional tools for risk management are not adequate to make decisions related to SRM. Aspects of these strategies lie in region B of Figure A.3.2. After articulating some of the reasons for this assertion, a number of important gaps in available analytical methods will be outlined. A few alternative strategies for framing and thinking about the problem of risk management of SRM research, and possible future SRM deployment, will be suggested and discussed.

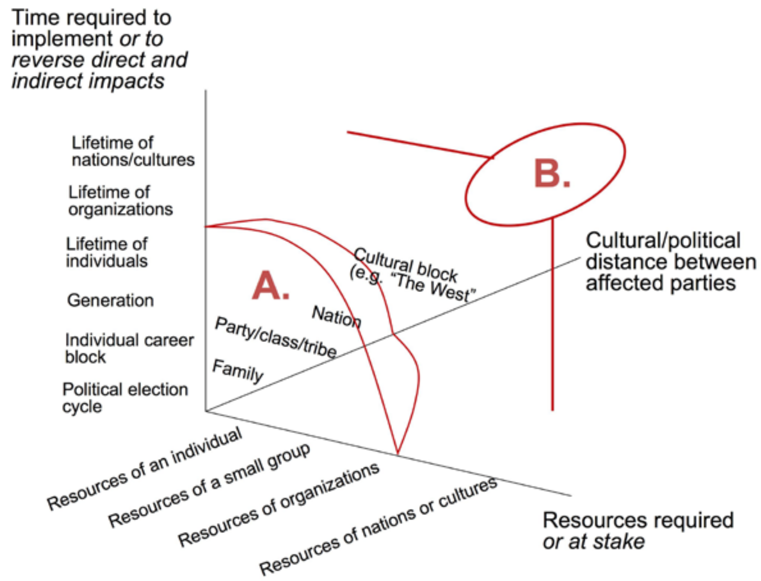

Figure A.3.2: *Conventional tools for risk analysis and risk management have been developed to address problems that fall within the space labeled A. In contrast, aspects of CDR that involves large-scale long-term modification of ecosystems, and aspect of all SRM strategies, lie in the space labeled B. Before applying conventional tools and methods for risk analysis and management in this space, one must examine carefully the underlying assumptions on which they have been based. Figure modified from Morgan et al. (1999).*

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Keynote III-4: The Role of Different Geoengineering Options in Long-Term Responses to Climate Change

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While proposed geoengineering techniques offer new potential response options to addressing climate change, the relationship between these techniques and more familiar response option – specifically mitigation and adaption – has thus far been poorly explored. Particularly over decadal time scales, different response options (or portfolios of options) are likely to generate significant differences in climatic and societal outcomes. This talk overviews some relevant technical characteristics of currently proposed geoengineering techniques, and contrasts them with the characteristics of the climate challenge and prominent mitigation and adaption response options. Because Carbon Geoengineering (also, Carbon Dioxide Removal or CDR) proposals differ dramatically from Solar Geoengineering (also Solar Radiation Management or SRM) proposals they are treated separately throughout.

The long-term nature of the anthropogenic climate change problem are associated with long-lived radiatively active substances added to the atmosphere (including CO_2; Archer et al., 2009) as well as long time scales associated with transformation of global systems of energy production and use and patterns of land use (Davis et al., 2010). Discussions focused on CO_2 may be extended to consider other anthropogenic emissions of radiatively active substances. In the IPCC AR4, the term "long term" was used to refer to the period after year 2030 (see for example IPCC AR4, Working Group III, Summary for Policy Makers, Section D; IPCC, 2007). That usage will be adopted here.

Proposed CDR techniques attempt to reverse the effects of CO_2 emissions by diminishing atmospheric CO_2 concentrations. From the perspective of the climate system, if CO_2 were removed from the atmosphere and then isolated from the atmosphere forever, this would closely approximate the effect of an avoided emission. An important issue is the amount of time that the CO_2 would remain isolated from the atmosphere. This issue of permanence of storage has been discussed within the IPCC both in reference to Carbon Capture and Storage (IPCC, 2005) and with regard to land use practices (IPCC, 2000). Permanence (or longevity) of storage is an important issue that is relevant to the potential of various CDR approaches to reduce long-term risks associated with climate change. Impermanent storage is largely equivalent to a delayed emission (Herzog et al., 2003). Delayed emission can be valuable in slowing rates, and in some cases maximum amounts, of warming. Issues of impermanence of storage are most commonly raised with respect to various biologically-oriented strategies to remove CO_2 from the atmosphere, such as ocean iron fertilization or proposals to increase organic carbon storage in plants or soils. Impermanence of storage also raises issues of intergenerational equity and transfers of responsibility. Most of these issues already have been addressed by the IPCC in other contexts. Furthermore, after removal of excess CO_2 from the atmosphere, excess CO_2 will tend to continue degassing from the oceans and land biosphere (Cao and Caldeira, 2010); thus, the long lifetime of CO_2 in these reservoirs indicates a long-term commitment to CO_2 removal if atmospheric CO_2 concentrations are to be maintained at very low levels.

If it were possible to deploy CDR techniques with permanence of capture at sufficient scales to reduce net atmospheric emissions or even draw down atmospheric concentrations, from the perspective of the climate system, this could effectively reduce anthropogenic climatic change. However, according the 2009 report of the UK Royal Society (The Royal Society, 2009) and 2011 report of the American Physical Society (Socolow et al., 2011), while there may be some relatively low-cost CDR options that can be deployed at scales that are small relative to that of global emissions, deployment at the scale of global emissions is likely to be more costly than emissions avoidance options.

SRM techniques aim to diminish the amount of climatic change by reducing the solar energy absorbed by the atmosphere, surface and/or oceans, thereby reducing global warming. Because some proposed SRM techniques (specifically stratospheric aerosols and cloud whitening) appear to offer the technical capacity to reduce globally absorbed solar radiation on the order of 1% (or more) within a few months, and for deployment costs on the order to \$1B to \$10B (McClellan et al., 2012)these techniques provide potentially fast leverage over the global climate. However, SRM techniques would not address non-climate effects increased atmospheric CO_2, such as ocean acidification (Matthews et al., 2009). Moreover, because SRM alters a different component than CO_2 of the energy flow driving the climate system (shortwave for SRM versus longwave for CO_2), the climatic conditions produced by offsetting CO_2-induced global warming with SRM would not be equivalent to climatic conditions under lower atmospheric CO_2 concentrations; differences in various climatic conditions, specifically including the hydrologic cycle, are expected. Moreover, were an SRM deployment to be terminated abruptly, rapid warming could ensue (Matthews and Caldeira, 2007; Robock et al., 2008), and thus deployment of an SRM system might be considered to pose an intergenerational transfer of this risk of sudden warming. These characteristics of SRM techniques – that they could act quickly, be cheap to deploy and by imperfectly offset anthropogenic climate change (Keith et al., 2010) – have led to varying perspectives on potential uses for SRM, ranging from being part of a "portfolio" of climate response options that seek to reduce costs of mitigation of climate change risks (Nordhaus, 1992; Wigley, 2006), to being a response reserved to address specific climate threats or climate "emergencies" (Blackstock et al., 2009; Caldeira and Keith, 2010).

Based on these characteristics, the relationship between existing geoengineering proposals and current mitigation and adaptation frameworks are explored in a preliminary way. As a starting point, the wedges framework of Socolow and Pacala (2004) and the framework for considering adaptation outlined in IPCC AR4 (IPCC AR4, Working Group II, Chapter 18; IPCC, 2007) are used to consider CDR and SRM, identifying where similar and differentiating characteristics exist. This approximate comparison demonstrates notable similarities between CDR and mitigation, while also identifying some unique characteristics of SRM that are dissimilar to both mitigation and adaptation options; specifically, SRM focuses on reducing exposure of populations and ecosystems to climatic changes, rather than their vulnerability to that change (which is the focus of adaptation). The potential climatic and societal implications of these overlaps and differences, along with the emergence of CDR and SRM techniques into mainstream climate policy discussions are explored briefly through the application of scenarios methods.

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Annex 4: Poster Abstracts

Albedo enhancement over land to counteract global warming: Impacts on hydrological cycle

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Increasing the land surface albedo via whitening the roofs and pavements in the urban area (Akbari et al., 2009; Oleson et al., 2010), covering deserts with more reflective polyethylene-aluminium to increase albedo (Gaskill, 2004) and making the color of crops lighter (Doughty et al., 2011; Ridgwell et al., 2009) are a few examples for land surface based Solar Radiation Management (SRM) schemes to counter global warming. Assuming these schemes are capable of countering global mean warming, what are the hydrological implications of large land albedo modification?

Recent modelling studies have shown that Solar Radiation Management (SRM) schemes that counteract global warming by increasing the planetary albedo uniformly (no differentiation of land versus oceans) will cause a reduction in the intensity of the global water cycle when they cancel the global mean warming exactly (Bala et al., 2009, 2008). However, precipitation and runoff over land have been shown to increase when reduction in solar insolation is applied only over the oceans by increasing the reflectivity of marine clouds (Bala et al., 2011). This most recent study implies that large scale albedo modification should lead to drying of the continental regions.

In this study, we perform idealized simulations using NCAR CAM3.1 to quantify the effect of SRM schemes that increase the albedo over land. We find that an increase in reflectivity over land that mitigates the global mean warming from a doubling of CO_2 leads to significant unmitigated warming in the southern hemisphere and cooling in the northern hemisphere since most of the land is located in northern hemisphere. Precipitation and runoff over land decrease by 13.4 and 22.3%, respectively because of a large residual sinking motion over land (see Figure A.4.1). The magnitude of hydrological changes are much larger than in the marine cloud albedo enhancement case (Bala et al., 2011) since the radiative forcing over land needed to counter global mean radiative forcing from a doubling of CO_2 is approximately twice the forcing needed over the oceans. Our results imply that albedo enhancement over oceans is superior to land albedo changes when the consequences on land hydrology are considered. Our study also has important implications for any intentional or unintentional large scale changes in land surface albedo such as deforestation/ afforestation/ reforestation, and desert and urban albedo modification.

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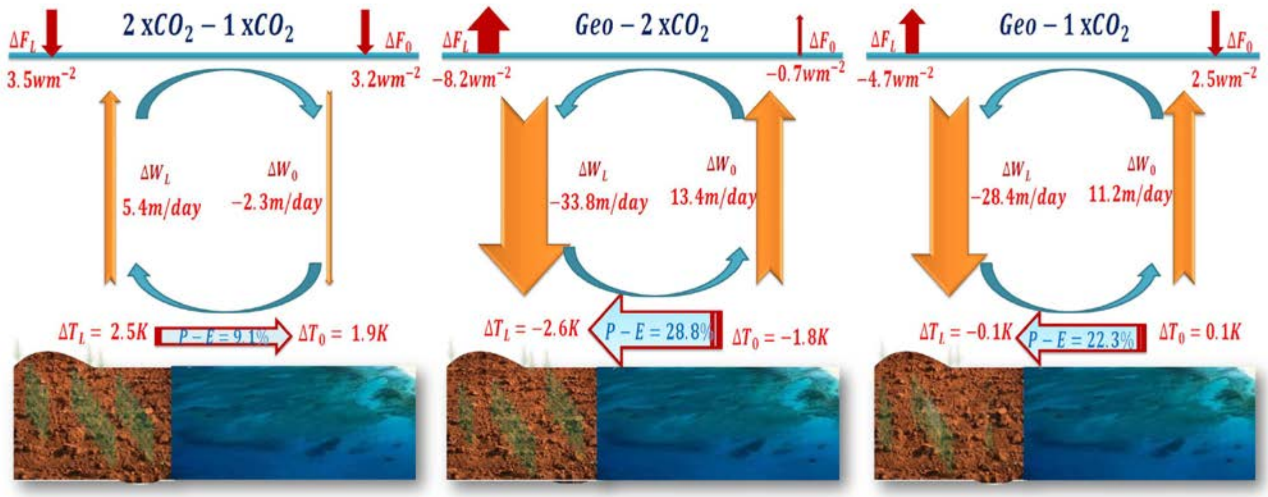

Figure A.4.1: *Schematic diagram illustrating the changes in vertical motion at 500 mb over land and oceans when CO2 is doubled (left panel, 2xCO2-1xCO2), albedo over land is enhanced (middle panel, enhanced albedo case: Geo-2xCO2) and when CO2 is doubled and land albedo is enhanced (right panel, the geoengineered case: Geo-1xCO2) cases. Radiative forcings over land and oceans in each case are shown at the top. Vertical motion in height coordinates (w, meter/day) is obtained from w = -ω/(ρg) where ω is the model simulated pressure velocity. Changes in surface temperature and precipitation minus evaporation are also shown. Strong downward motion and the consequent decline in runoff and drying over land are indicated for the enhanced land albedo and geoengineering cases.*

Categorization of policy responses to climate change with a focus on geoengineering

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Potential policy responses to anthropogenic climate change can be broadly classified into four categories: additional research into climate sciences and carbon-free or carbon-neutral sources of energy, mitigation (i.e. reduction in anthropogenic emissions of greenhouse gases), adaptation (i.e. reduction of the impacts of climate change on natural and societal systems), and geoengineering.

Geoengineering is usually defined as the intentional large-scale manipulation of some element of the Earth system, in an attempt to counteract the effects of anthropogenic climate change. It is sometimes also referred to as climate intervention, climate engineering or planetary engineering. To qualify as geoengineering, an intervention into the Earth system has to deliberately attempt to tackle climate change by a method that does not seek to reduce anthropogenic emissions of greenhouse gases or other warming agents. For instance, the emission of anthropogenic aerosols from burning fossil fuels, although responsible for a cooling effect, is not considered to be geoengineering because it is a by-product of our industrial and transportation systems rather than a deliberate action. The intervention, although it can be localized, also has to have a large-scale effect on the climate system. This clearly distinguishes geoengineering from, e.g., weather modification or other sorts of environmental engineering which attempt to modify the atmosphere or the land surface on a much smaller scale.

A number of geoengineering schemes have been proposed in the scientific literature. Their technological maturity, effectiveness, scalability, residual impacts, unintended consequences and cost vary a great deal and remain uncertain. The Royal Society report (2009) on geoengineering categorized geoengineering schemes into solar radiation management (SRM) and carbon dioxide removal (CDR) techniques. SRM schemes seek to artificially modify the solar radiation budget to cool the planet. CDR schemes seek to artificially remove carbon dioxide from the atmosphere and store it in some form. While the distinction between SRM and CDR is useful, it does not cover all potential geoengineering schemes one can think of. For instance, it has been suggested that the terrestrial radiation budget could also be artificially modified through changes in cirrus clouds and/or atmospheric water vapor in order to decrease the greenhouse effect. Carbon dioxide is not the only long-lived greenhouse gas in the atmosphere, and air removal can also be envisaged for methane (Boucher and Folberth, 2009) or other gases.

Figure A.4.2 lists a large number of approaches to climate change and attempts to refine their groupings into distinct categories. It appears that there is not always a clear division between geoengineering and adaptation or between geoengineering and conventional mitigation. For instance, it has been suggested that the Earth's albedo could be artificially increased over land by increasing the reflectivity of human dwellings (Akbari et al., 1999) or cropland (Ridgwell et al., 2009). These modifications may actually be more relevant to local and regional adaptation to climate change than geoengineering. Furthermore the frontier between geoengineering and mitigation is not very clear when it comes to biofuels. The large-scale exploitation of biofuels associated with carbon capture and storage (CCS) has the potential to remove CO_2 from the atmosphere and qualifies as a CDR scheme, even though biofuels and CCS on their own are usually considered as conventional mitigation tools.

In conclusion we argue that it is important to develop a clear terminology on policy responses to climate change, while recognizing that the frontier between these responses is not always clear-cut. We will provide in this presentation a first attempt at developing such a terminology. This will help to decide how geoengineering should fit (or not) in the portfolio of existing climate change policies. Multiple factors have to be considered when comparing these policy responses, including their technological maturity, effectiveness, scalability, timescale for implementation, risk, residual climate change, unintended consequences, degree of interference with the climate system, the policy and governance challenges they pose, and their cost.

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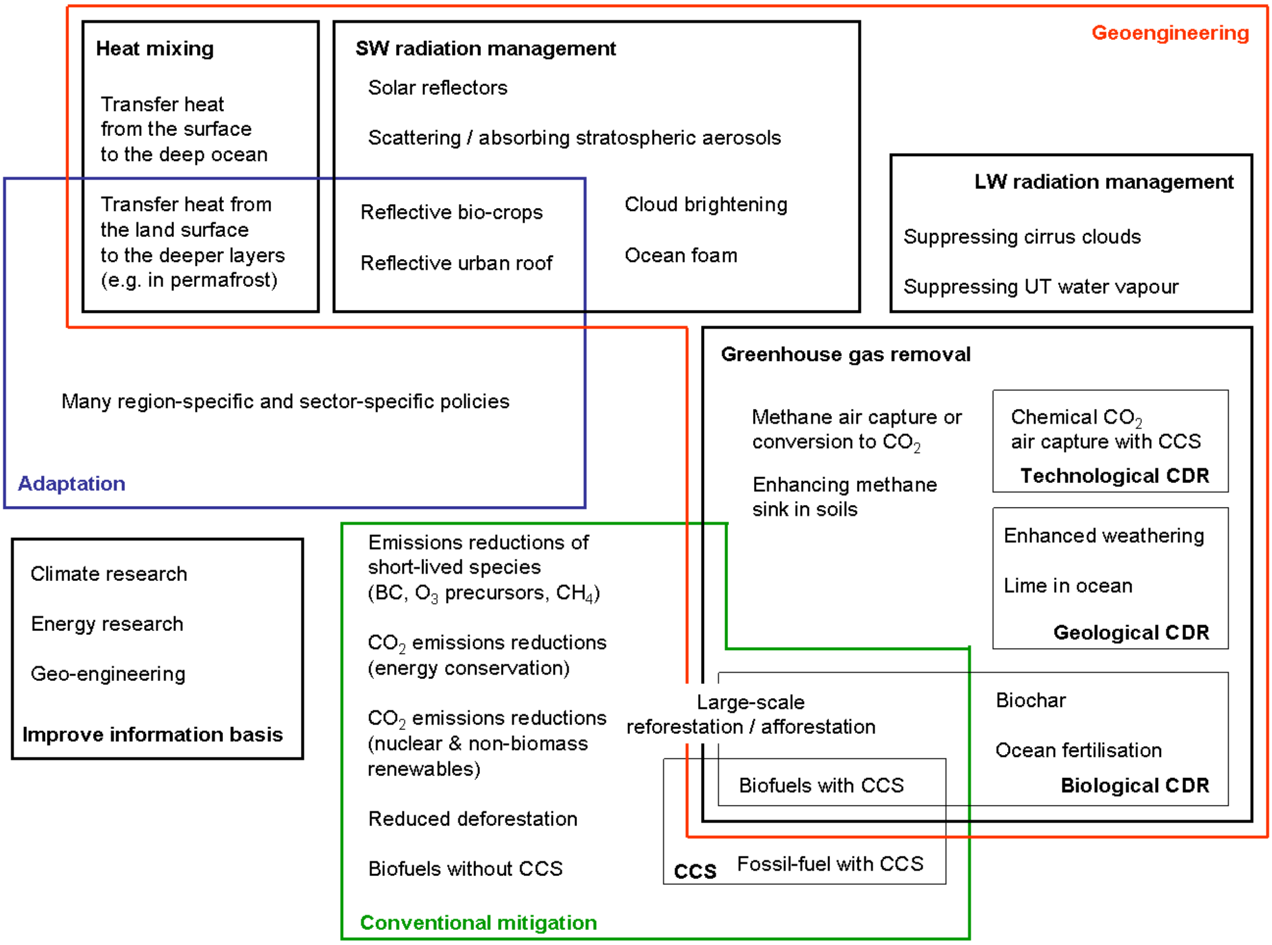

Figure A.4.2: *Categorization of existing and proposed policy responses to climate change with a focus on geoengineering techniques.*

Climate change adaptation through the development of a sensor-based early warning system for landslides

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Many poor communities in the Philippines are threatened by landslides mainly due to extreme rainfall. The frequency and scale of landslides have increased during the last decades. Given the high economic cost of relocation of communities and the use of conventional engineering mitigation methods, a low cost, sensor-based early warning system for landslides is being developed in the Philippines in order to warn communities of impending landslides. The system is composed of a sensor column array consisting of a triaxial accelerometers and soil moisture that is buried vertically underground. A modified version of the Casagrande type piezometer is also integrated into the sensor column to measure excess pore pressure. Measurements taken in each segment are accessed via the Controller Area Network (CAN) communications protocol. The sensor columns are capable of transmitting data via Short Message Service (SMS) and sending it to a base station. The sensors were initially tested on a small-scale slope model in which failure was induced through water seepage. Changes in the tilt and saturation measured by the sensors are consistent with visual observations. On November 2010, the system is being tested and was deployed in an active landslide area in Brgy. Puguis, La Trinidad, Benguet, Northern Philippines. If the prototype system is found accurate and effective, it will be deployed in other landslide-prone areas in the Philippines.

An Integrated Assessment of Geoengineering Proposals

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There is currently insufficient information to inform the emerging debate about geoengineering, this work will begin to address the gaps in our knowledge about effectiveness and side effects of geoengineering schemes. Integral to the assessment process is active and ongoing engagement with stakeholders, including science policy experts and the general public, to produce objective and informed policy-relevant science.

The Integrated Assessment of Geoengineering Proposals (IAGP) is a new four year research project that started on 1st October 2010 and is funded by the UK Engineering and Physical Sciences Research Council (EPSRC) and the Natural Environment Research Council (NERC). IAGP brings together a broad range of expertise, from climate modelling to philosophy and engineering to public perceptions to conduct an objective, policy-relevant assessment of geoengineering proposals. IAGP has the following core research objectives: to evaluate the effectiveness and side-effects of a broad range of geoengineering proposals, to evaluate the controllability of global climate using these proposals and to elicit and include stakeholder and public values into the evaluation. Key sub-objectives will be to examine in detail the public acceptability of different geoengineering solutions and to evaluate the possibility of preventing tipping points via geoengineering control.

Previous assessments of proposals (e.g. Lenton and Vaughan, 2009) have been somewhat preliminary and have been largely based on a physical science evaluation of solar radiation management techniques. For this assessment we are being more rigorous. This involves a) comparing different proposals (including solar reduction and carbon management technologies) within the same modelling framework, and b) engaging with the public and stakeholder community prior to running the climate models to help create an objective set of policy-relevant metrics to evaluate both the effectiveness and side effects of a given proposal (Corner and Pidgeon, 2010).

At this stage in the project we have run preliminary workshops with both the public and stakeholders.

The second stage will be to use these workshop findings to create a set of metric criteria for climate model evaluation. A repeat stakeholder workshop in October 2011 will decide on these metrics and climate model integrations will then start to evaluate the physical science based metrics. A further deliberative workshop towards the end of the project will feedback and interpret climate model results to stakeholders and the public. Readers are encouraged to visit the project website (www.iagp.ac.uk) to find out more about what we to keep up to date with our publications.

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Aerosols impact on dynamic of the West African monsoon: direct effects

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Aerosols play an important role in the radiative balance of the atmosphere. While sulphate aerosols are recognized as the most dominant contributor of tropospheric aerosols over and near the industrialized regions. One of the most important aerosols source in the world is West African region and is also influenced by anthropogenic aerosols from European industry (Chin and Diehl, 2005). The West African rainfall depends strongly on the activation of the monsoon circulation, which is influenced by radiative balance of the atmosphere. This fact determines the importance of this system in the agricultural activity, based on pluvial agriculture, and consequently in the economy of the region. This study examines the effect of dust and anthropogenic aerosol on dynamic of the West African monsoon using regional climate model (RegCM3) coupled with dust and anthropogenic aerosol module.

The results show the reduction of the West African rainfall under effects of cooling induced by dust and anthropogenic aerosols. This cooling reduces the meridional gradient of the moist static energy, which causes the weakening of the energy of the monsoon flux contributing for a reduction of the West African rainfall as cited by Konare et al. (2008). Also, the impact of aerosols on these systems and the precipitation was greater in the simulation with anthropogenic aerosols (Figure A.4.3, a) than simulation with dust only (Figure A.4.3, b). In general, the interaction of aerosols with radiation budget was able to influence the seasonal and the interannual variation of the West African circulation.

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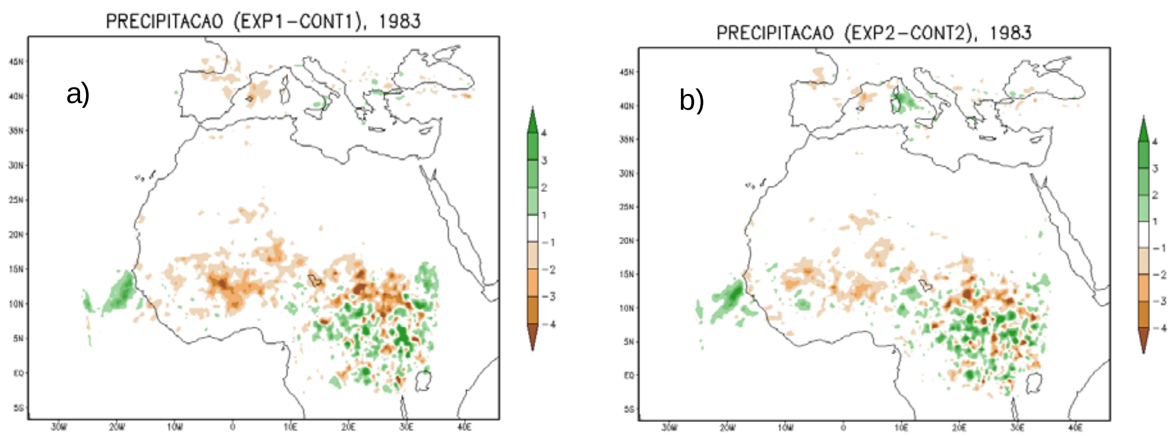

Figure A.4.3: *a) Reduction of rainfall by dust and anthropogenic aerosols, b) reduction of rainfall by only dust aerosols during the dry year*.

Sea spray geoengineering: global model simulations with explicit aerosol microphysics

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One much discussed technique for solar radiation management (SRM) is to use artificial sea spray emissions from wind powered vessels to increase the concentration of submicron sea salt particles in the marine boundary layer (Latham, 1990). It has been hypothesized that these artificially emitted aerosol particles could act as cloud condensation nuclei (CCN) and thus increase the cloud droplet number concentration (CDNC) in the marine stratocumulus clouds. This in turn would lead, at least in theory, to a higher cloud albedo and thus planetary cooling.

Using a detailed aerosol microphysics model (GLOMAP) within a global chemical transport model, we have recently shown that artificial sea spray emissions are unlikely to lead to homogeneous CDNC fields over vast oceanic areas (Korhonen et al., 2010). Our results also indicated that the relative enhancement of CDNC in low-level clouds is likely to be lower than assumed in previous climate model studies.

We have now repeated a similar set of simulations in ECHAM-HAM aerosol-climate model in order to quantify the direct and indirect effects from sea spray injections as well as to study the effect of the particle injection size on the resulting planetary cooling (Partanen et al., 2011). ECHAM-HAM includes an explicit and prognostic calculation of cloud microphysics and interaction of aerosol particles with clouds. We assume a wind-speed dependent number flux for the injected particle population and follow its transport and transformation due to microphysical processes in the atmosphere. This additional flux is assumed either over all the oceans or in three optimized regions covering 3.3% of the planet's surface area.

Applying the baseline scenario (i.e. injected particle size 250 nm) in the optimized regions, we predict a global mean radiative flux perturbation (RFP) of -0.8 Wm^{-2}. This compares well with an earlier published estimate of -0.97 Wm^{-2} which assumed a fixed prescribed CDNC of 375 cm^{-3} in the geoengineered regions (Jones et al., 2009). In our simulations the mean regional CDNC varies between 194 and 286 cm^{-3} but cloud cover increases by 2-5 percentage points. It is noteworthy that both the absolute CDNC values as well as their relative changes (74-80%) are clearly higher than predicted in an earlier study using similar emission fluxes. In the ECHAM simulations, multiples of the baseline sea spray flux cause almost a linear increase in CDNC but the RFP is clearly sublinear (global mean RFP with 5 times the baseline flux is -2.2 Wm^{-2}).

Since the three optimal geoengineering regions are characterized with persistent stratocumulus decks, inside them practically all of the radiative effect originates from aerosol indirect effects. However, the direct effect can be significant outside these regions: when all oceanic regions are seeded, the direct effect is about 65% of the aerosol indirect effects.

For a constant volume emission flux of sea spray, the size at which the individual particles are injected becomes very important. Reducing the injection size from 250 nm to 100 nm, which is typically still large enough for cloud activation in marine boundary layer, increases the global mean RFP in the run of optimized regions to -2.1 Wm^{-2}. On the other hand, injection at 500 nm has only very minor effects on CDNC due to the low number flux (13% of the baseline flux) and produces roughly the same direct forcing as the baseline simulation.

The presented work is part of an interdisciplinary project "Aerosol intervention technologies to cool the climate: costs, benefits, side effects and governance" funded by the Academy of Finland. In addition to cloud seeding with artificial sea spray emissions, the project focuses on the climate and other environmental effects stratospheric particle injections and reduction of black carbon (BC) emissions. We investigate also how the introduction of geoengineering alternatives may lead to reframing of global and national climate policies as well as how the existing legal and political frameworks will affect the pace and direction of the package of admissible alternatives.

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Biochar for Climate Change Mitigation: Prospects and Limitations

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Biochar has received significant attention as a rapid climate-change mitigation strategy. Biochar is a charcoal-type substance that shares properties with biomass-derived pyrogenic carbon which is ubiquitous in soils (E. Krull et al., 2008; Johannes Lehmann et al., 2008). In a biochar system, biomass of a wide variety of feedstocks, including wood, grass, animal manures, crop residues, and other appropriate byproducts, is pyrolysed to biochar, which is added to soil. In many applications, this conversion is used to generate usable energy from the volatile liquids and gases, such as hydrogen, bio-oil, ethanol, electricity or heat. Several anthropogenic and natural analogs can be found that allow some evaluation of biochar amendments to soils for the long term. Notably, so-called Terra Preta soils in the Amazon have provided incentive to evaluate biochar for soil improvement as these soils received biochar-type materials several thousand years ago and retained their fertility.

However, dedicated biochar research and development only started to any significant extent in 2006. The stability of biochar has been calculated to mean residence times of several hundred to a few thousand years (Johannes Lehmann et al., 2009; Zimmerman, 2010; Spokas, 2010). While the greater stability of biochar relative to the uncharred biomass is the basis for the emission reductions through utilization of biochar as a soil amendment rather than combusting it for energy to offset fossil fuels, it is not always sufficient for achieving net emission reductions. Life-cycle assessment demonstrates that projects can have positive or negative net emission balances primarily depending on the source of the feedstock (Roberts et al., 2010). In bioenergy systems, using the biochar as a soil amendment shows greater emission reductions compared to the use of combustion only if the soil productivity increases or if other greenhouse gas emissions are either offset or reduced (Roberts et al., 2010; Woolf et al., 2010; Hammond et al., 2011).

On a global scale, this may result in greater emission reductions through biochar systems than combustion for bioenergy (Figure A.4.4). The proportion of stable carbon in biochar provides about 50% of the total emission reductions of a biochar system if it is integrated in a bioenergy project. If either no bioenergy is generated or bioenergy from cookstoves with low burning efficiencies are replaced by biochar-cookstoves, the importance of biochar stability may increase to over 80% or fall below 30% (Whitman et al., 2011). The emission reductions using waste materials or crop residues as feedstocks vary between 0.7-3.8 t CO_2e t-1 feedstock (JL Gaunt and J. Lehmann, 2008; J Gaunt and Cowie, 2009; Roberts et al., 2010; Hammond et al., 2011). In a modeled cookstove system, an improved combustion stove provided similar emission reductions of 3.5 t CO_2e yr-1 per household compared to 3.69-4.3 t CO_2e yr-1 per household for an improved pyrolytic stove with biochar additions to soil (Whitman et al., 2011). Hammond et al. (2011) report life-cycle emissions abatement of 1.4-1.9 t CO_2e MWh-1 for a variety of biochar-bioenergy systems in the UK in comparison to a generation of additional emissions of 0.05-0.3 t CO_2e MWh-1 for other bioenergy systems.

The global technical potential is likely not much greater than 1 Pg CO_2-Ce yr-1 if only biomass resources are used that do not compete with food crops and other existing uses of biomass, do not require land use change or clearing of natural vegetation, and do not remove crop residues to an extent that would negatively impact soil health (Woolf et al., 2010). The economic viability largely depends on the price for the biomass feedstock, and can vary significantly between projects. In many current projects, the costs may be offset by the value of increased crop yields due to biochar, but adoption may still benefit from financial support through a price on carbon.

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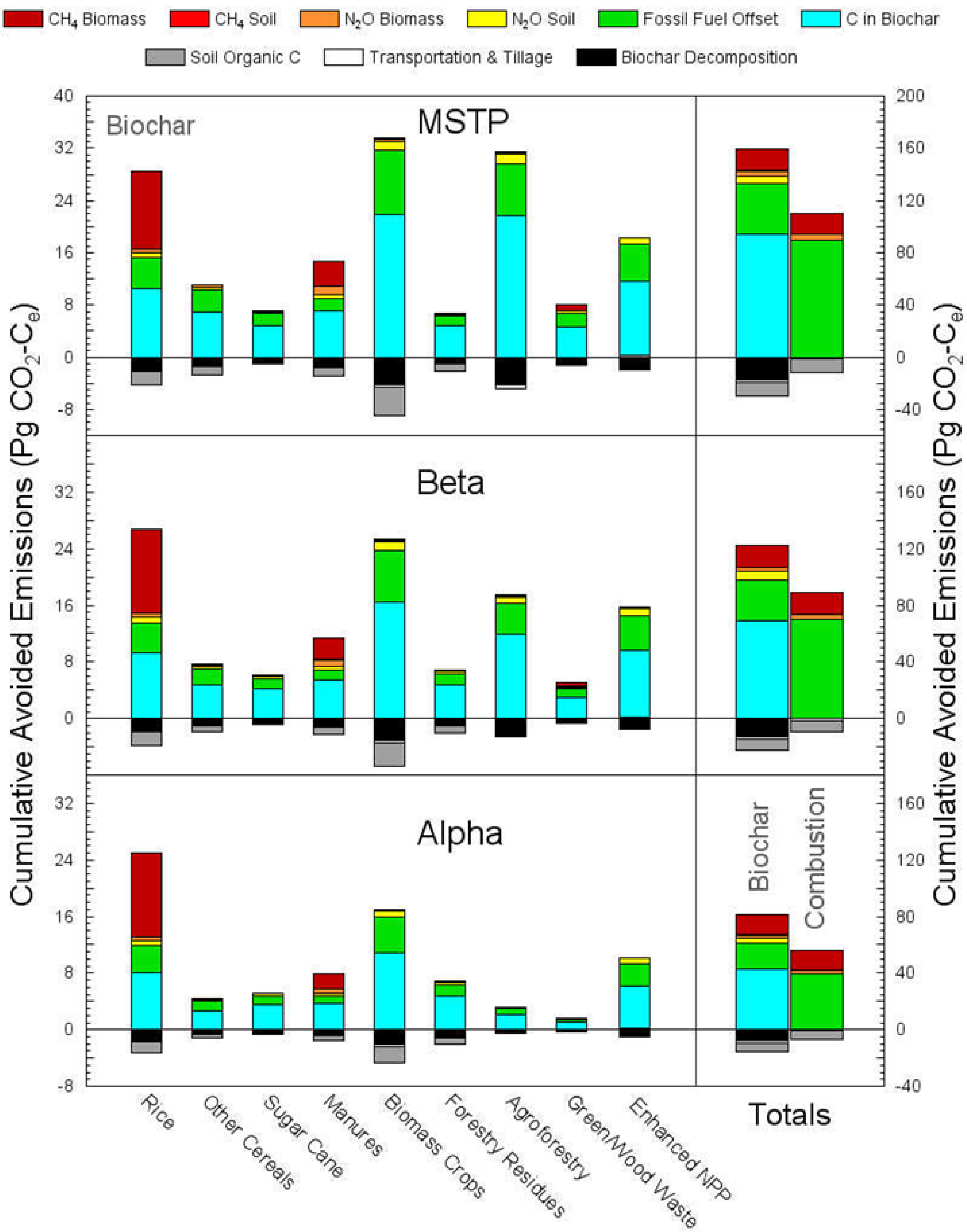

Figure A.4.4: *Cumulative avoided GHG emissions (Pg CO_2-Ce) from sustainable biochar production (Woolf et al., 2010).*

Potential Applications of Climate Engineering Technologies to Moderation of Critical Climate Change Impacts

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Although pre-geoengineering proponents in the mid-20th century argued for application of early climate engineering technologies to 'improve' what was then the prevailing climate, the more we have learned about the climate, the more we have come to understand the hubris involved in contemplating upsetting its many valuable and beneficial intercouplings. Nonetheless, society continues with little restraint to combust more and more fossil fuels, releasing many billions of tonnes of carbon dioxide (CO_2) and other greenhouse gases that are, even if unintentionally, on track to cause changes in climate far larger than what had been proposed and then dismissed as overly audacious and dangerous.

With disappointing progress in international efforts to limit global emissions and with observations indicating that climate change was intensifying more rapidly than the seemingly dire consequences that model simulations were projecting, Crutzen (2006) suggested that geoengineering might be an essential complement to mitigation and adaptation for preventing 'dangerous anthropogenic interference' with the climate system. In this context, the purpose of geoengineering, or more descriptively, climate engineering, becomes to moderate the unintended changes in climate being caused primarily by the emissions of greenhouse gases (GHGs), primarily CO_2. Thus, its intent is to keep the climate as nearly the same as it has been rather than to transform it to some supposedly 'better' state. Under this formulation, the hubris is more properly associated primarily with those who are allowing high greenhouse gas emissions to continue with little effort to reduce them than to those suggesting potential use of climate engineering technologies and approaches to maintain the current climate. While there are very likely to be unintended consequences of counterbalancing the greenhouse-gas induced changes in climate, that the climate will be nearer to the conditions that science has been carefully investigating over the past several decades may well mean that we will be able to better estimate them than the unintended consequences being created as GHG emissions carry the climate to conditions the Earth has not experienced in many millions, even tens of millions, of years. Basically, the question that needs to be considered is not whether climate engineering on its own would be beneficial or detrimental for the environment and society, but whether society and the environment would be better off working through the consequences of eventually controlling greenhouse gas emissions with or without the partial counter-balancing of at least some of the consequences using climate engineering technologies.

In addressing this question, the role of the scientific community is to, in a responsible way, come up with options, with the public and governmental decision-makers responsible for making any decision about potential application. In identifying solar radiation management options meriting investigation of the strengths and weaknesses, there has been a nearly complete jump from doing nothing to attempting to completely offset the full warming influence of a CO_2 doubling. My research has focused on conceptual exploration of the many possibilities lying between these two extremes, believing that there is a much greater likelihood that climate engineering can play an important positive role if started up on a limited scale than if there is an immediate jump to the global scale.

Recognizing that global scale climate engineering is also likely to have some noticeable unintended consequences, the proposed justification has primarily focused on its use in response to a climate emergency; that is, to invoke climate engineering only when there is clear evidence of an impending or immediately past exceedance of a threshold that would lead to runaway warming or other very significant consequence. The most discussed of the possible emergencies have been a methane burst as a result of the rapid thawing of permafrost and/or clathrates trapped in the sediments of the continental shelves, the rapid loss of ice mass from the Greenland and/or Antarctic ice sheets, collapse of the Amazon rainforest, or greatly accelerated, runaway warming. The proposed invocation of climate engineering would be rapid and strong, taking the global average temperature, for example, back to much lower levels. It seems to me there are several problems with this formulation of, essentially, holding back climate engineering until it may be too late to reverse the disastrous changes. An implicit assumption in this approach is that climate is reversible, and this is not at all clear. In addition, adaptation is likely to have spread out the range of optimal temperatures for various societal and environmental systems, such that a sudden, sharp cooling might be very disruptive.

If the goal is to keep the climate near its present value, then it seems to me it would make much more sense to initiate climate engineering as early as possible, with the intent of slowing, stopping, and then perhaps reversing the climate change that the world has experienced. With governance issues likely to take an extended period to work through before taking actions to bring global climate under control, especially as there is the possibility, or at least the fear, that actual implementation might lead to a sloughing off (or further sloughing off) of efforts to cut emissions, global-scale climate engineering seems to me unlikely to be implementable for a decade or, more likely, more. At the same time, while much of the world is not yet experiencing sufficiently severe impacts to prompt rapidly implemented sharp cuts in emissions, there are regions of the world where climate change is already exerting very disruptive impacts; these regions merit consideration of the potential for climate engineering to moderate their impacts. In addition, even if CO_2 emissions could be significantly cut immediately, warming would very likely result due to the sudden drop of the sulfate cooling offset; quite clearly, a climate engineering approach to replacing the sulfate cooling offset needs to be sought. Within this framing, a number of potentially high priority applications of climate engineering technologies appear to be worthy of aggressive research and investigation (MacCracken, 2009):

1. Reversing Arctic warming: Limiting solar absorption in the region by injection of aerosols (or aerosol precursors) into the lower stratosphere or the troposphere (brightening both clear and cloudy skies) has the potential to reduce warming in the Arctic region and down into mid-latitudes while also promoting build-up of the region's mountain glaciers and ice sheets (Caldeira and Wood, 2008; Shin et al., 2011). Increasing surface reflectivity or cloud brightening to limit heat flow into the region may also be a possibility. Limiting changes in precipitation at other latitudes may require an offsetting reduction in solar radiation over the Southern Ocean (Shin et al., 2011).

2. Moderating tropical cyclone intensification: Using cloud or ocean-bubble brightening to reduce warming in ocean and coastal water bodies would seem an approach to moderating intensification.

3. Storm track redirection: Observations indicate that storm tracks into western North America are steered, at least to some extent, by ocean temperature gradients of a few degrees, an amount that might well be achievable by region-specific cloud or ocean-bubble brightening.

4. Replacement of the sulfate offset: Loss of the sulfate offset resulting from SO_2 emissions from coal-fired power plants (so high SO_2 levels over relatively limited areas where populations are high) might be able to replaced by creation of a sulfate offset created by SO_2 emissions that would lead to a low loading of sulfate over large, low-latitude oceanic areas that are largely unoccupied.

5. Slowing of ice stream calving: If the heat promoting calving from the streams draining ice sheets is coming from warm waters entering fjords, cloud or ocean-bubble brightening and/or wave-powered vertical mixing might be useful in chilling those waters.

Given the specific beneficial and generally regional focus of these proposals, and that they may be readily terminated if problems arise, it might well be that governance issues would be easier. In my view, these much more practical and possibly near-term applications merit aggressive and early investigation.

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Cloud-resolving modeling of marine stratocumulus cloud brightening

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Marine Stratocumulus (Sc) clouds cover vast areas of the ocean surface. They play a prominent role affecting the Earth's albedo and energy budget. The possibility of mitigating some consequences of global warming by brightening these clouds (Latham, 2002) has been explored in various global modeling studies, providing important insight into some aspects of this idea. However, the inability of global models to adequately represent cloud-scale physics and dynamics due to low model resolution limits their usefulness for assessing the climate system response to cloud brightening. High-resolution cloud modeling has proven to be a useful tool for process-level understanding of aerosol-cloud-precipitation interactions. It can also provide a necessary and critical test to the assumptions and parameterizations employed by global models when exploring the geoengineering idea.

In this study (H. Wang et al., 2011), we use the high-resolution Weather Research and Forecasting (WRF) model with explicit treatment of aerosol-cloud-precipitation interactions to perform cloud-system-resolving simulations of cloud brightening. The same model configuration has been used by Wang and Feingold (2009a) to examine the transition from closed-cell Sc to open cells. The two distinct cellular structures that have starkly different reflectance patterns (also revealed by satellite imagery; e.g.,Garay et al., 2004; Wood and Hartmann, 2006), have been shown to be associated with aerosol effects on rain-production processes and dynamical feedbacks in a self-organizing system (Stevens et al., 2005; H. Wang and Feingold, 2009a; Feingold et al., 2010). More relevant to cloud brightening, however, is that once the open cells are established, they appear to be resilient to aerosol perturbations. Another key result is that gradients in aerosols and precipitation can generate mesoscale circulations that impact clouds well beyond the conventional "aerosol indirect effects" (H. Wang and Feingold, 2009b).

Based on these prior studies, we conducted experiments with four combinations of different meteorological and aerosol background conditions observed in the Northeast Pacific Sc regime. Seawater particles are injected into the model atmosphere by single, multiple or numerous sprayers. In the first two cases, sprayers are allowed to move at a speed of 5 m s-1 in the domain approximately the size of a climate model grid box, while in the latter case sprayers are uniformly distributed over the model domain. The average surface injection rate of 1.45×106 m-2 s-1 is close to that suggested by Salter et al. (2008). The injection strategy is critical in influencing the spatial distribution of the additional aerosols. Both areal coverage and local number concentration are important players in cloud brightening but neither one always emerges as dominant. For a given amount of aerosols, the two aspects need to be balanced to optimize the enhancement of cloud amount and albedo. In the cases where clouds are susceptible to aerosol perturbations, injection from single or multiple sprayers can introduce a significant heterogeneous response in the domain. The study also suggests that mesoscale circulations induced by rain suppression associated with multi-sprayers can have unforeseen influence on cloud structures and brightness depending on the distance between the sprayers, and that diurnal variations of clouds and precipitation may be important for the effective timing of seeding.

Results show that the effectiveness of cloud brightening depends strongly on meteorological and background aerosol conditions and, sometimes, the injection strategy. Suppressing rain as a means of sustaining cloud water is the most efficient way to brighten clouds in the cases considered here. Hence, it is very effective in a weakly precipitating boundary layer in which the additional aerosols can substantially weaken the precipitation. Seeding the aerosol-limited cloud in conditions preceded by heavy and/or persistent rain that has significantly depleted existing aerosols is also effective. The same amount of injected material is less effective in either strongly precipitating clouds or aerosol-rich clouds. Cloud drops grow large enough to rain out in the former case even in the presence of additional aerosols. Cloud brightening is ineffective in a relatively dry boundary layer that supports clouds of low liquid water path. In the aerosol-rich case and the dry case, the aerosol injection increases drop number concentrations but lowers supersaturation and liquid water path. As a result, the cloud experiences very weak albedo enhancement, regardless of the injection method. Detailed results have been published in Wang et al. (2011), part of which is to be presented at the meeting.

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Groundwater temperature, an indicator of climate change?

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Groundwater temperature, GWT can be considered as a conservative parameter. Changes in GWT require large energy inputs. The thermal conductivity coefficient of water is 0.6 W/m K. consequently water is a bad heat conductor. Deviations from local steady state conditions can be associated to surface changes taking into account the local geological conditions; it means the presences of geothermal sources.

Since early 80´s GWT changes have been related to global warming (Beck, 1982; Lachenbruch and Marshall, 1986). Some authors have analyzed energy feedbacks across the local and regional hydrologic cycle to get correlations between GWT and climate changes (Allen et al., 2004; Maxwell and Kollet, 2008).

There are some factors that must be taken into account when exists variations of GWT. If there are not geothermal sources or radioactive elements like Uranium that could increase temperature, then, any increase can be associated to surface temperature changes.

Soils and surface rocks can limit the heat penetration, even vegetation, making difficult a direct correlation between surface temperature and GWT, same situation can be found in urban areas (Taniguchi et al.). Rain infiltrations can decrease locally temperature of shallow aquifers. The type of aquifer rocks is one of the main factors that can facilitate heat penetration. Other aspect is the wind. Wind can cool terrain surface. Watertable variations intervene in GWT. In arid zones with limited recharge, extraction is almost greater than recharge and then watertable can go in depth some meters per year.

In Irapuato Salamanca Valley, Central Mexico, there are not feasible evidences of GWT changes (Rodriguez et al., 2006). There are not historical data records of GWT. We analyzed temperature data from 11 years that cannot be significant, not observing substantial changes. In the area there are meteorological stations with non continuous records.

It is necessary to instrument selected aquifers to have reliable data. Meteorological stations must be also recording without problems. This proposal implies a compromise from some federal institution responsible of environmental issues because it is necessary to have training personal, equipment, operation and maintenance programs and funds.

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Geoengineering and Emissions Mitigation: Policy Context

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The analysis presented in this poster considers the potential use of solar radiation management (SRM) techniques and the context in which this climate response option might be considered. As noted by others (Wigley, 2006), SRM is a viable option only if used in conjunction with emissions reductions. This is because SRM alone will not substantially reduce impacts due to ocean acidification, SRM itself will cause ancillary climate changes, and use of SRM without emissions mitigation would risk large climate changes if SRM were suddenly stopped. Only a long-term reduction in the net amount of fossil carbon dioxide entering the atmosphere can stabilize the climate system.

Scenario analysis is used to examine the context for the potential use of geoengineering. Several points are demonstrated.

- Emissions reductions, even under the most ambitious mitigation scenarios considered in the literature, cannot ensure that temperature is below a given threshold at all times if the climate sensitivity is high. Emissions reductions, however, can ultimately reduce long-term global temperature change below (or near) a 2 °C threshold value by some point in the 22nd century (or earlier if the climate sensitivity is not too high), although the scale of the necessary reductions may be large.

- The situation where the climate sensitivity is high (or, equivalently, the sensitivity of some key impact is high), is where forcing reduction through solar radiation management (SRM) techniques might be considered. SRM would need to be used in addition to emissions mitigation in order to meet stated policy goals (e.g., Cancun Agreements). SRM could potentially be used under these circumstances as a measure to reduce the magnitude of global temperature changes and associated impacts over an interim period.

- The primary determinant of the magnitude of potential SRM is the climate sensitivity. Delays in emissions reduction also increase the magnitude of the SRM that would be needed to keep global temperatures under a given threshold.

It is important to note that SRM will not exactly counter greenhouse gas forcing due to different spatial and spectral characteristics. SRM will, therefore, cause climate changes itself. The character of these changes would need to be much better understood before SRM could be deployed. It is important to examine the potential magnitude of these changes in an appropriate context. SRM used as an adjunct to emissions mitigation could be of much smaller magnitude than many of the scenarios considered in the literature (Wigley, 2006). Where scenarios in the literature have often considered SRM of sufficient magnitude to counter a CO_2 doubling, the magnitude of SRM needed if used in conjunction with emissions mitigation is generally much lower. SRM techniques are not understood well enough at present for application, and their potential use raises numerous ethical, technological, scientific, and policy issues that will need to be addressed. Because the goal of SRM is to reduce net impacts, the impacts due to the deployment of SRM measures would need to be smaller than the impacts that would have occurred without SRM. Because a deterministic understanding of all relevant impacts is unlikely to be realized, this comparison would need to be done on the basis of probabilistic and risk management paradigms. In summary, the possible use of SRM should be considered in the context of substantial, long-term emission reductions. The conditions under which SRM might be considered are the same conditions that require substantial emissions reductions in order to meet stated policy goals. SRM does not substitute for emissions reductions and it would be useful for analysis of SRM and its impacts to be done in this context. Policy measures to tie potential SRM use to long-term emission reductions could also be considered.

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Public perception of climate geoengineering in Japan as revealed in an online survey

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Public perceptions of emerging, controversial technologies play a vital role in public discourse on the path of technological development. For climate geoengineering, some studies examined the public perceptions, but efforts so far were focused only on the United Kingdom and the United States (The Royal Society, 2009; Ipsos MORI, 2010; Leiserowitz et al., 2010).

Here we present results on an online, national survey conducted in March 8-9, 2011, in Japan, to examine the public perception. Using a commercial service, we asked approximately 4000 respondents about their attitudes toward global warming and the stratospheric aerosol injection, arguably the most "promising" among various geoengineering options. Since respondents had little prior knowledge about this technology, respondents read short descriptions of climate geoengineering, which explained the basic mechanisms, possibilities of dangerous climate change as rationale for climate geoengineering, and potential side effects.

Majorities expressed cautious attitudes toward geoengineering, and show support for climate geoengineering research, although the survey questions did not distinguish between modeling, laboratory experiments, and field experiments. Survey participants chose the university researchers and international organizations as the most trusted sources for information about geoengineering, while the media and government ranked relatively low. We discuss the implications of the survey findings.

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Tropospheric sulfate burdens as a consequence of stratospheric sulfate geoengineering

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Stratospheric sulfur injection is a leading geoengineering idea to counteract climate change. Sulfate aerosols can cool the lower atmosphere by scattering and absorbing incoming shortwave radiation. The stratosphere is a more efficient location than the troposphere due to longer aerosol lifetime, but has unintended consequences such as changes to heterogeneous chemistry and ozone destruction.

Volcanoes act as natural tests to this idea; after major volcanic eruptions, reduced surface temperatures and reductions in the stratospheric ozone column are observed. However, little is known about the efficacy and consequences of continuous stratospheric sulfur injection. Simulations with prescribed size distributions have found a generally linear association between injection rate, sulfate burden, and temperature reduction (e.g. Rasch et al., 2008; Robock et al., 2008). The first microphysical aerosol simulations were conducted by Heckendorn et al. (2009) using a 2d aerosol model, and found geoengineered aerosols to grow much larger than previously assumed, resulting in a significantly lower lifetime and temperature change efficacy. All previous work has focused on the stratosphere and the earth's surface, while impacts in the middle and upper troposphere have not been well studied. We present geoengineering simulations using a 3d microphysical aerosol model fully coupled with a 3d general circulation model and full sulfur chemistry. We compare our stratospheric burden results to Heckendorn et al.(2009), and conduct a detailed analysis of the upper tropospheric sulfate burden.

We use the WACCM3/CARMA model that includes three-dimensional treatment of SO_2 and OCS surface emissions, 63-species chemistry, nucleation, growth, coagulation, and wet deposition (English et al., 2011). The model is run using 4 x 5 degrees horizontal resolution, 66 vertical levels, and 42 dry sulfuric acid aerosol bins. We use a numerically-efficient form of binary homogeneous nucleation (Zhao and Turco, 1995), and enhanced coagulation due to Van der Waal's forces (Chan and Mozurkewich, 2005). We specify four geoengineering scenarios (1, 2, 5, and 10 Tg sulfur annual injection) of SO_2 at the 50 mb level, between 4 degrees S and 4 degrees N, across all longitudes (similar to Heckendorn et al., 2009). Simulations are run for 5 years, with the 5th year analyzed.

We find the relationship between SO_2 injection rate and stratospheric mass burden is highly non-linear, with reduced efficacy at higher injection rates (Figure A.4.5). To achieve 6 Tg S burden, 10 Tg S/yr injection rate is required, which is five times more than simulations that assumed prescribed size distributions (Rasch et al., 2008), and very close to that predicted by the only other microphysical study done (Heckendorn et al., 2009). The burden discrepancy is attributed to the particles growing to larger sizes (1 micrometer radius) than previously assumed, which have faster fall velocities and shorter stratospheric lifetimes. (Additionally, larger particles are less effective at scattering shortwave radiation). Additionally, we find a significantly increased sulfate burden across large regions of the troposphere. Fully one-third of the sulfate burden is in the troposphere, with tropospheric enhancements observed in many regions, particularly the high latitude upper troposphere. For the 10 Tg simulation, we find the sulfate mass burden between the tropopause and 100 hPa below the tropopause is 30 times higher and the next 100 hPa region down is 10 times higher than the unperturbed scenario. The entire tropospheric burden is five times higher than normal. This enhancement of sulfate aerosols can have implications for tropospheric cloud properties, radiative forcing, and upper tropospheric chemistry. Additionally, increased acid deposition occurs in mid- and high- latitudes, as has been previously noted (e.g. Kravitz et al., 2009).

These results highlight numerous limitations and consequences of stratospheric sulfate geoengineering. In addition to limited efficacy, ozone destruction, and surface acid deposition that have been published previously, we find a significantly enhanced upper tropospheric sulfate burden which may alter tropospheric clouds, chemistry, and radiative forcing. We recommend geoengineering ideas to be studied in more detail before they are seriously considered as climate intervention options.

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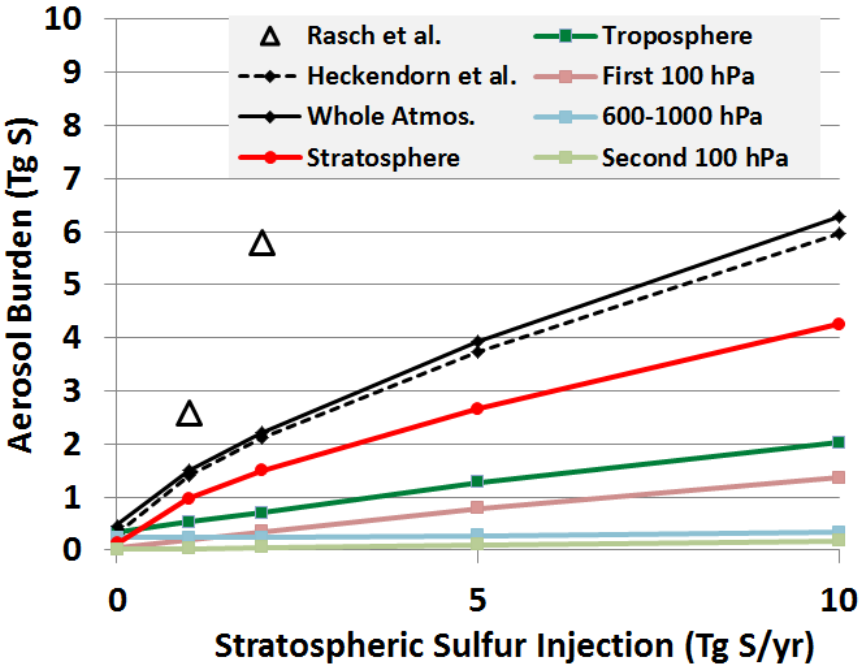

Figure A.4.5: *Aerosol burden as a function of stratospheric sulfur injection for the specified regions. "Whole Atmos." represents the whole atmosphere for a direct comparison to Heckendorn et al. and Rasch et al. Troposphere and Stratosphere burdens are found using the levels of the zonally averaged cold-point tropopause and warm-point stratopause. "First 100 hPa" represents the region spanning from the tropopause to 100 hPa below the tropopause. "Second 100 hPa" spans 100 hPa below the tropopause to 200 hPa below the tropopause. "600-1000 hPa" spans from 600 hPa to the surface.*

Understanding the potential of ocean iron fertilization to reduce atmospheric carbon dioxide.

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The reservoirs of carbon that interact on millennial time scales are those in the ocean, the atmosphere and over the top meter of the land. Of these millennial reservoirs, the ocean is by far the largest: 36 Tt as opposed to 0.7 Tt for the atmosphere and 2.3 Tt for land (Sarmiento and Gruber, 2002). By comparison, current estimates of the fossil hydrocarbon reservoir are of the order 4 Tt. Over tens of millennia, almost all of the CO_2 released into the atmosphere from fossil fuel use will enter the vast oceanic reservoir but before it does so, the enhanced atmospheric CO_2 concentrations will cause substantial environmental perturbation largely driven by greenhouse warming and ocean acidification.

Regardless of the strategy adopted for fossil fuel use over the coming decades, there will be an increase in atmospheric CO_2 followed by a much slower decrease, such that after 10,000 years, atmospheric CO_2 levels will still be substantially higher than pre-industrial levels (Archer, 2005; Solomon et al., 2009). In the context of geoengineering, the objectives of CO_2 reduction techniques are to reduce the rate of CO_2 increase and to reduce the ultimate height of the CO_2 peak so that human adaptation to environmental changes will be easier to achieve. From a carbon system perspective, because the oceans represent such a large reservoir of carbon, as well as roughly ¼ of the atmospheric CO_2 uptake, small perturbations of the system could potentially result in large changes to the carbon balance. From the oceanic geoengineering perspective, the objective of ocean carbon sequestration would be to develop ways in which the oceans can take up carbon at a faster rate than they currently do but with predictable and acceptable consequences.

The productivity of the oceans and hence their capacity to sequester CO_2 from the atmosphere is limited over large areas by the micronutrient iron. More than thirteen large scale open ocean addition experiments have been conducted to examine the effect of iron addition to the marine environment. There have also been several studies of ocean regions where there are natural supplies of iron (from islands or volcanic ash) in generally high nutrient, low chlorophyll (HNLC) regions. The conclusion from these experiments is that relief of iron stress does increase the biomass of marine phytoplankton. The effects of this biomass increase include a reduction in the concentration of CO_2 in the surface waters and potentially a local enhanced uptake of CO_2 from the atmosphere. Depending very much on the location, time of year of the experiments, and duration of the experiments, these iron additions have led to variable increases in the export of carbon from the upper ocean and sequestration of it into the deep ocean where it will be isolated from the atmosphere for decades to centuries (Boyd, 2008; Buesseler et al., 2008; Pollard et al., 2009; R. S Lampitt et al., 2010).

The experiments to date were not planned from the perspective of climate engineering and conclusions from them about the potential of this approach as a means of reducing atmospheric CO_2 concentrations have large uncertainties. The experiments have usually not been of adequate duration to determine whether sequestration occurred and have not been of sufficient areal coverage in order to reduce edge effects and to facilitate study of relationships between upper ocean processes and those at depth. In fact, few of the experiments measured carbon flux out of the surface water. Furthermore they have not been embedded in adequate coupled models of ocean physics and biogeochemistry to extrapolate results beyond the experimental area.

Few ocean iron addition experiments have addressed processes that would allow a better understanding of the unintended consequences of deliberate additions. This last point is of particular concern and has been a major feature during the recent discussion of a risk assessment framework for experimentation by the London Convention and London Protocol. There is no doubt that several consequences of ocean iron fertilization will occur beyond simply the uptake of CO_2. Some of these such as a decrease in deep water pH and in oxygen concentration are inevitable and relatively easy to predict. The potential of other unintended consequences -- such as the generation of nitrous oxide from organic matter degradation at depth, the generation of dimethyl sulfide and methane or the growth of phytoplankton which has the capability of releasing harmful toxins -- has much larger uncertainty at present. Some of these consequences are undesirable and on a large scale may be considered unacceptable.

Given the uncertainties, there is an urgent requirement to carry out more studies on ocean iron fertilization with three clear objectives

1. To develop coupled global scale computation models so that predictions can become more reliable and so that in situ experiments can be carried out efficiently and effectively

2. To carry out experiments on a sufficiently large scale and duration to determine the extent of carbon sequestration, including at what efficiencies, depths and hence time scales this would take place.

3. To explore in considerable detail the complete consequences of ocean iron fertilization, and not just the magnitude of carbon uptake from the atmosphere and sequestration in the deep ocean.

It is only when these activities have been completed that it will be possible to determine whether ocean iron fertilization has the potential to remove substantial amounts of atmospheric CO_2, whether there are harmful consequences and whether these consequences can be predicted with an uncertainty that is acceptably low.

The ISIS consortium (In Situ Iron Studies) of 13 institutions worldwide was formed in 2011 specifically to promote such studies so that informed decisions will be possible in the future. The mission statement is: "To resolve the impact of iron fertilization on marine ecosystems, to quantify its potential for removal of atmospheric carbon dioxide, and to improve our collective understanding of the changing ocean." http://isisconsortium.org/

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Annex 5: Breakout Group Reports

The program of the IPCC Expert Meeting on Geoengineering included three sets of BOG discussion sessions. In the discussions, expert participants broadly considered a range of geoengineering approaches and issues and identified both common understanding and divergent perspectives as background for author of the IPCC's Fifth Assessment Report (AR5). Three to four subgroups met in each BOG session, and the main points of each discussion are captured in the BOG reports included here. These individual BOG reports may not always be entirely consistent neither among themselves nor with respect to the overall meeting Summary of Synthesis Session (Boucher et al. 2012, this issue), instead providing snapshots of meeting discussions as context for the summary. The individual BOG reports also do not necessarily reflect the views of each BOG's Chair and Rapporteur.

Breakout Group I.1: Solar Radiation Management Options and Methods

Chair: Govindasamy Bala

Rapporteur: Piers Forster

The summary that follows, written by the Chair and Rapporteur, characterizes the main points of the BOG I.1 discussion. It may not reflect the personal views of the BOG's Chair and Rapporteur. The summary is intended for consideration by IPCC authors of the Fifth Assessment Report (AR5), but is neither endorsed nor approved by the IPCC or its Working Groups. Participants in the BOG considered a series of questions related to geoengineering research, developed by the meeting's Scientific Steering Group.

Questions suggested for discussion:

- What are the most important Solar Radiation Management approaches that IPCC authors might want to consider in the AR5?
- What are the most important aspects of these approaches to evaluate (e.g., physical impacts, time scales, system boundaries, spatial scales, direct/private costs)?
- Can the most important aspects of these issues be supported by reference to the peer-reviewed literature, ideally drawing from multiple lines of independent evidence? What is the available evidence and what are relevant references?

Introduction

This BOG discussed Solar Radiation Management (SRM) focusing on determining techniques IPCC authors might consider, overall framework and terminology that could be employed, and ways different impacts could be assessed.

Terminology

The group briefly discussed terminology. The group felt comfortable with "geoengineering" as a term describing a variety of mechanisms that deliberately affect climate at a large scale. The group discussed the boundaries of this term when impacts of a given technique are more regional than global. However, the group did not see the necessity of forcing an exact definition; a loose definition may serve the community.

As some proposed techniques, such as cirrus thinning, affect long wave radiation, the term SRM was discussed. The BOG suggested that the term "Radiation Management" may be more appropriate.

Scope

Much discussion focused on what was and was not in the scope of approaches that IPCC authors might want to consider in the AR5. Generally it was felt that the IPCC's AR5 reports should be as comprehensive as possible with regard to SRM, but focused on the most plausible schemes that are supported by the literature. Extensive discussion of speculative schemes or those with little potential of either deployment and/or impact would be less useful for policymakers.

Approaches supported by literature that the IPCC could consider are: space mirrors/generic total solar irradiance (TSI) experiments; stratospheric aerosol techniques via injection of gases, particles and/or special particles; cloud whitening, especially marine stratocumulus; direct tropospheric aerosol effects from sea-salt or sulphate; reducing cirrus amount or thickness; increasing crop albedo, land-surface albedo, or ocean surface albedo (e.g., ocean bubbles or painting roofs white). It was felt that within these techniques, stratospheric aerosol and cloud whitening had more extensive literature.

Some suggested assessment of ideas that, although small on the global scale, may be relevant for regional adaptation and mitigation, such as the possible role of urban surface albedo enhancement in urban heat island mitigation.

Several other possible techniques such as hurricane suppression, modifying storm track position and protecting glaciers were also discussed. Some participants thought that these ideas were too small scale and may be better considered on the scale of adaptation, but they could also be assessed by the IPCC where literature is available.

Framing

The group felt that it was important to consider frameworks for assessing geoengineering, such as in the wider context of mitigation and climate change adaptation. Choice of baseline for comparing techniques was repeatedly discussed. The group acknowledged that publications have different baselines and this could make assessment of the literature difficult. Activities such as the Geoengineering Model Intercomparison Project (GEOMIP) could be useful as baselines are comparable (Kravitz u. a. 2011).

BOG participants discussed value judgments in assessing geoengineering techniques. Words such as "good" and "bad" or even "effectiveness" and "side-effects" can be awkward when there are winners and losers both from geoengineering and mitigation. Authors should try to be explicit when value judgments and/or assumptions are made.

The BOG discussed the advantages of the radiative forcing metric. It also considered the importance of assessing other aspects of the physical climate, as not all radiative forcings are created equal: there are regional effects and hydrological cycle effects, and radiative forcings can have different efficacies for even the globally averaged surface temperature.

Other framing issues considered were the timescale of deployment, the testability of techniques, their scalability, any termination effects from turning schemes off, and the timescales of such effects. How SRM could influence CO_2 was also considered, as were the costs that might be included in assessments.

Overall there was a general focus on Working Group I issues. Due to lack of time and the direction of the conversation several issues particularly surrounding Working Group II and III issues were not covered in detail.

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Breakout Group I.2: Solar Radiation Management Options and Methods

Chair: Olivier Boucher

Rapporteur: Michael Prather

The summary that follows, written by the Chair and Rapporteur, characterizes the main points of the BOG I.2 discussion. It may not reflect the personal views of the BOG's Chair and Rapporteur. The summary is intended for consideration by IPCC authors of the Fifth Assessment Report (AR5), but is neither endorsed nor approved by the IPCC or its Working Groups. Participants in the BOG considered a series of questions related to geoengineering research, developed by the meeting's Scientific Steering Group.

Questions suggested for discussion

- What are the most important Solar Radiation Management approaches that IPCC authors might want to consider in AR5?
- What are the most important aspects of these approaches to evaluate (e.g., physical impacts, time scales, system boundaries, spatial scales, direct/private costs)?
- Can the most important aspects of these issues be supported by reference to the peer-reviewed literature, ideally drawing from multiple lines of independent evidence? What is the available evidence and what are relevant references?

Introduction

The BOG's efforts to directly answer the above questions led to better defining an approach to answering such questions, an approach that could be shared by all three Working Groups. Participants in the discussion did not feel that this BOG could make the scientific assessment asked for in these questions, but recognized that AR5 authors must do so.

Terminology

Should IPCC authors change the terms? Probably not, but it would be beneficial to explain the limitations and multiple meanings of "geoengineering" as well as "Solar Radiation Management" (SRM). Also, authors may wish to be careful in the nomenclature regarding inadvertent or adverse effects; "indirect effects" can be used to cover both climate system issues (e.g., pertaining to the ozone, oceans, ecosystems) and socially related issues (e.g., costs, waste products, atmospheric visibility/astronomy).

Literature

The group discussed keeping the IPCC AR5 focused on assessment of the geoengineering literature, but also on scientific literature relating to processes invoked in SRM and on the scientific basis of the proposed geoengineering methodology.

Overall Approach:

AR5 authors may consider inclusion of the following topics:

- indirect, non-climate impacts
- energy inputs
- uncertainty in predicting aerosol-cloud response
- uncertainty in stratospheric aerosols' role in circulation and ozone

Regional SRM – regional climate change

There are limitations in current ability to predict regional climate change patterns from global mean forcing over several decades (e.g., from greenhouse gases), and hence the ability to project local, regional responses to local SRM (e.g., associated with roofs or agriculture) is also limited, with corresponding consequences for assessment possible at this time.

Verification

Verification of an SRM's impact on climate forcing may be through a set of simple metrics relating to reflectivity, rather than the much more difficult task of measuring a change in radiative forcing. Given surprises of non-linearity (e.g., as associated with Mt. Pinatubo) and indirect effects (e.g., as associated with anoxic oceans), there needs to be scientific verification that a geoengineering action actually has the pre-calculated results. The AR5 might assess the current state of scientific understanding regarding such verification.

Extent of AR5

Do IPCC authors focus on specific SRM topics or cover all equally? A table with similar format across all the Working Groups could help guarantee that all reasonable, published approaches are included, with assessments focused on approaches with more mature analyses and literature.

Proposal:

A table on geoengineering that cuts across the Working Groups and could be combined for the Synthesis Report. All Working Groups could use the same format, with the same rows (SRM and CDR proposals) but with different columns.

Approaches: (sectioned, with multiple rows, to include SRM and CDR)

Major SRM sections are:

- Space-based reduction in incident sunlight
- Stratospheric aerosols (e.g., sulfate, others, engineered)
- Cirrus modification (e.g., ice nuclei)
- Cloud brightening (e.g., marine stratus)
- Surface albedo change (e.g., no roofs, deserts, crops, ocean bubbles)

Columns: (columns specific to each Working Group)

- Realizable potential radiative forcing (possible global radiative forcing, also considering economic/social limitations)
- Scalability – in terms of climate and indirect environmental effects (Working Group 1 and 2), e.g., scalable from pilot to climate-effective implementation?; in terms of economic and social costs (Working Group 3)
- Indirect effects – in terms of the climate system (Working Group 1 and 2); in terms of social costs (Working Group 3)
- Potential for unpredictable effects
- Sustainability / Ability to be corrected (scientific or socio-economic)
- Affordability / Costs
- Verification of climate impacts
- Governance / Challenges (including ability to be invoked by individuals, impacts beyond boundaries, timescales of response)
- Subsections on scientific understanding and confidence level

Breakout Group I.3: Carbon Dioxide Removal Options and Methods

Chair: Peter Haugan

Rapporteur: Johannes Lehmann

The summary that follows, written by the Chair and Rapporteur, characterizes the main points of the BOG I.3 discussion. It may not reflect the personal views of the BOG's Chair and Rapporteur. The summary is intended for consideration by IPCC authors of the Fifth Assessment Report (AR5), but is neither endorsed nor approved by the IPCC or its Working Groups. Participants in the BOG considered a series of questions related to geoengineering research, developed by the meeting's Scientific Steering Group.

Questions suggested for discussion:

- What are the most important Carbon Dioxide Removal approaches that IPCC authors might want to consider in the AR5?
- What are the most important aspects of these approaches to evaluate (e.g., physical impacts, time scales, system boundaries, spatial scales, direct/private costs)?
- Can the most important aspects of these issues be supported by reference to the peer-reviewed literature, ideally drawing from multiple lines of independent evidence? What is the available evidence and what are relevant references?

Introduction

This BOG's discussion concentrated on identifying major Carbon Dioxide Removal (CDR) approaches that might be considered in the AR5, evaluating issues relevant to development and implementation of the approaches, and considering the peer-reviewed literature on development aspects. In addition, the group spent time discussing the terminology of geoengineering.

What are the most important Carbon Dioxide Removal approaches that IPCC authors might want to consider in the AR5?

The group wrestled with whether the terms "geoengineering" and even "Carbon Dioxide Removal" are appropriate organizing principles for associated technologies within the context of the IPCC or national debates. While the choice of terminology may at this juncture be unavoidable for multiple reasons (historical development, risk of "white-washing", etc.), the organizing principle may benefit from rethinking.

The unifying characteristic of currently grouped CDR approaches is creation of a storage issue. This can be used as a high-level organizing principle to distinguish with Solar Radiation Management (SRM). Other organizing principles worth considering include the following:

- Transboundary processes?
- Emissions reductions versus sink creation?
- Size of sink?
- Biological, physical, chemical?
- Local benefit as additional driver or control? (e.g., soil fertility in case of conservation agriculture, tillage, or biochar; or local energy needs in case of bioenergy in combination with Carbon Capture and Storage (CCS))

The group proposed a range of approaches without making a priority list:

- Afforestation/reforestation
- Improved forest management
- Sequestration in buildings
- Biomass burial
- No till agriculture
- Biochar
- Conservation agriculture
- Fertilization of land plants
- Creation of wetlands
- Bioenergy with CCS
- Ocean storage (biological, chemical, physical):
  - Fertilization
  - Algae farming and burial
  - Blue carbon (mangrove, kelp farming)
  - Modifying ocean upwelling
  - Direct CO_2 injection
  - Weathering
  - Ocean pipes
- Carbon absorbing cement
- Direct air capture of CO_2

Figure A.5.1 provides an example for applying the organizing principles discussed above to more appropriately shape the discussion about CDR:

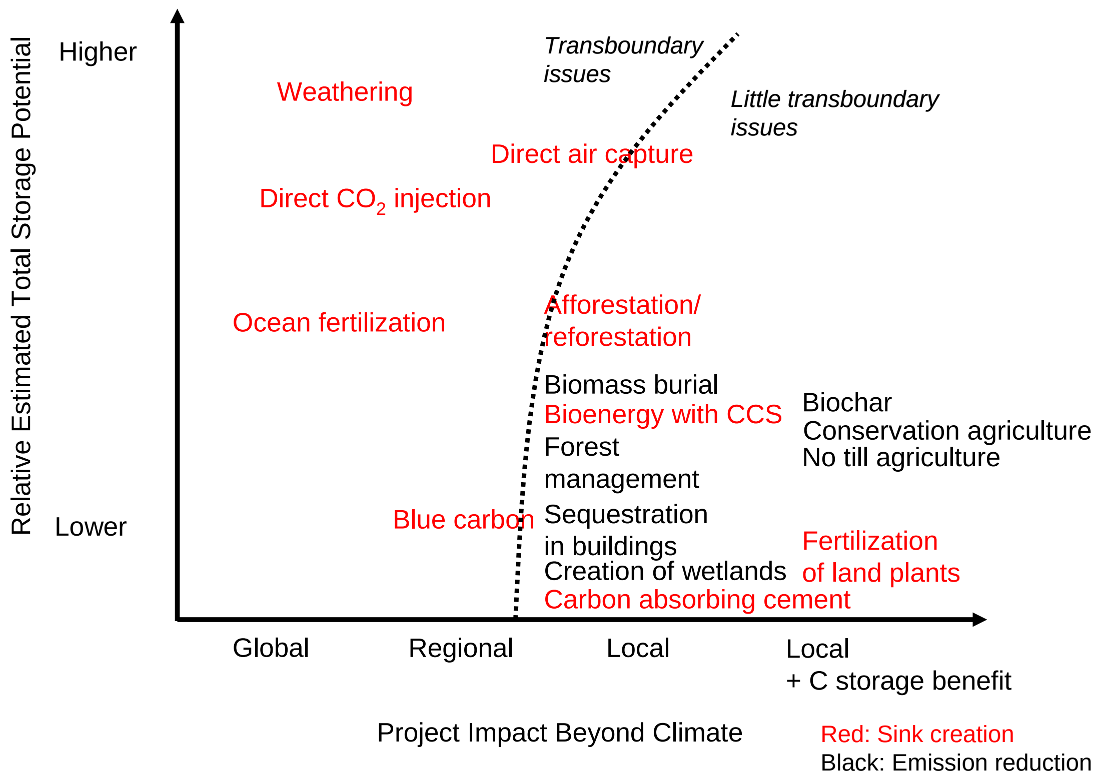

Figure A.5.1: *The relative estimated total storage potential for emission reduction and sink creation projects at different scales.*

What are the most important aspects of these approaches to evaluate?

The group's discussion included the following aspects:

- Feasibility (technical, risks)
- Effectiveness (time to maximum deployment, maximum rate of CDR (Gt C/yr); maximum integrated storage potential (Gt))
- Side effects (physical, biological, risks, local and global scale)
- Efficiency (direct cost, social costs, including side effects)
- Legal and social acceptability
- Regulation (economic incentives, command and control)
- Monitoring and Verification
- Ethics (long time scales)

The BOG noted that it is important to distinguish whether research or deployment is to be evaluated.

Can the most important aspects of these issues be supported by reference to the peer-reviewed literature?

The group discussed whether relevant criteria can be assessed using the available peer-reviewed literature (Y/N). The judgment is subjective rather than based on the number of publications in the peer-reviewed literature, also recognizing that publication activity is not necessarily an indicator of the ability to draw conclusion.

Table A.5.1: Criteria for Carbon Dioxide Removal Approaches

	Weathering (land and ocean)	Ocean fertilization, biological	Afforestation/ reforestation	No-tillage	Biochar	Direct capture
Feasibility	Y	Y	Y	Y	Y	Y
Effectiveness	N	Y	Y	Y	Y	Y
Side effects	N	N	Y	Y	N	Y
Efficiency	N	N	Y	Y	N	Y
Social/legal acceptability	N	N (Y for legal)	Y	Y	Y	Y
Regulation	N	N	Y	Y	N	N
Monitoring & Verification	N	N	Y	Y	Y	Y
Ethics	N	N	Y	Y	N	N

Breakout Group I.4: Carbon Dioxide Removal Options and Methods

Chair: Dieter Wolf-Gladrow

Rapporteur: Robert Scholes

The summary that follows, written by the Chair and Rapporteur, characterizes the main points of the BOG I.4 discussion. It may not reflect the personal views of the BOG's Chair and Rapporteur. The summary is intended for consideration by IPCC authors of the Fifth Assessment Report (AR5), but is neither endorsed nor approved by the IPCC or its Working Groups. Participants in the BOG considered a series of questions related to geoengineering research, developed by the meeting's Scientific Steering Group.

Questions suggested for discussion:

- What are the most important Carbon Dioxide Removal approaches that IPCC authors might want to consider in the AR5?
- What are the most important aspects of these approaches to evaluate (e.g., physical impacts, time scales, system boundaries, spatial scales, direct/private costs)?
- Can the most important aspects of these issues be supported by reference to the peer-reviewed literature, ideally drawing from multiple lines of independent evidence? What is the available evidence and what are relevant references?

Introduction

The BOG discussed the characteristic features of geoengineering in terms of Carbon Dioxide Removal (CDR) options and methods. Considerations also included direct and indirect consequences over a range of temporal and spatial scales, associated with economic considerations as well as risks and uncertainties. Important CDR approaches for land and ocean were listed. The group discussed criteria for assessing geoengineering methods and considered review papers, recent development papers and classical papers. The group was of the opinion that current knowledge and peer-reviewed literature is not sufficient to assess all important issues of geoengineering.

Definition of geoengineering

The BOG discussed that it could be useful to prioritize the IPCC AR5 geoengineering discussion by focusing on those actions with potentially large consequences and technologies that are relatively poorly understood. However, it was also recognized that the technologies fall on a continuum of scale and risk, and any delimitation is necessarily arbitrary. Rather than getting stuck in an endless debate about what is and is not geoengineering, the group suggested, for the purposes of the IPCC and in the immediate term, a core definition (based on Schneider (2001), Royal Society (2009) and the CBD definition):

'Geoengineering' consists of actions taken with the intent of controlling the global climate.

And then reducing the scope by specific exclusions. Some of the key criteria for including or excluding topics are:

1. ***Scale*** – this is 'climate scale' rather than 'geographical scale'
2. ***Consequence*** – are there potentially significant or poorly understood undesired impacts on either the climate system or on other issues of concern, such as biodiversity?
3. ***Reversibility*** – is it easy to return to the pre-action state, and will rapid climate change result from discontinuation of the activity?

4. ***International scope*** - Does the action take place and have its undesired impacts solely within the sovereign territory of the party taking the action, or does it unavoidably affect other countries or the global commons (e.g., atmosphere or open oceans)?

On one or more of these bases, some approaches (e.g., afforestation, energy technologies such as bioenergy) can be excluded from immediate global assessment (or relegated to a second tier, where they are noted but not assessed in depth), though they may need comprehensive local assessment (e.g., a national environmental impact assessment for action on Carbon Capture and Storage), potentially with global assessment at a later stage.

Technologies for potential consideration in the AR5

Predominantly land-based actions

1. Enhanced weathering of silicates. Mining and finely grinding silicate minerals and dispersing them widely over terrestrial or marine ecosystems or incorporating them into agricultural soils. Among the key impacts are the massive scale of mining and transport needed.
   a. Calcium silicates: $CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$
   b. Olivine: $MgSiO_4 + 4\ CO_2 + 4\ H_2O \rightarrow Mg^{2+} + 4\ HCO_3- + Si(OH)_4$
2. Biochar production through pyrolysis of biomass in a reduced-oxygen environment to the point where it becomes very resistant to decomposition (half life > 1000 years) and its subsequent incorporation in agricultural soils as an amendment
3. Bioenergy production coupled with Carbon Capture and Storage (CCS)
4. Direct Air Capture followed by CCS
5. Land use change and management, including but not restricted to afforestation and reforestation
6. Biomass harvest and burial in anoxic environments, such as deep oceans, lakes or bogs

Predominantly ocean-based actions

1. Deep or intermediate injection of CO_2 in oceans as CO_2 or as hydrates
2. Fertilisation of the oceans with iron or other nutrients
3. Addition of alkalinity to the ocean, alone or in conjunction with CO_2 injection
   a. Adding finely crushed $CaCO_3$ directly
   b. Converting $CaCO_3$ to CaO (added to ocean) and CO_2 (put into CCS)
   c. Actions involving silicates (see land discussion)
   d. Cooling and fertilising of surface ocean by pumping up deep water

Overview of possible criteria for assessment

1. Potential magnitude (Pg C) and rate (Pg C/yr) of removal associated with technology
   a. Technical (upper) vs realisable/realistic/market potentials
2. Timescales of
   a. deployment (technology readiness, time to build infrastructure),
   b. operation (for how long will this need to occur)
   c. reversion of atmospheric CO_2 if you stop doing it ('relaxation time')
   d. time-lag between doing it and seeing benefits (over what timescale do you assess the effects?)

3. Scale:
    a. Geographic extent of activity and its intended and unintended consequences
    b. What is the minimum unit size (not geographical, but in terms of Pg C/yr) to be viable and what is the potential for starting small and benefitting from learning curves?
    c. How does the technology scale? Is there a maximum size, a diminishing effectiveness with size or increasing effectiveness with size (economies/diseconomies of scale)?
    d. Where is the technology currently with respect to scale: laboratory-, pilot-, or full-scale?
4. Net consequences for the climate system
    a. temperature, precipitation, radiation (amount and the split between diffuse and direct radiation), CO_2^{atm}
    b. effects on climate variability (including diurnal and seasonal variation) and extremes
    c. regional differences in outcomes
    d. full Life Cycle Analysis including all relevant direct and indirect environmental impacts
5. Impacts, including benefits, on systems other than the climate system, whether intended or unintended
    a. Global to regional-scale impacts, e.g., on ocean acidification, food production (including fisheries), or biodiversity
    b. regional to local impacts, e.g., on ecosystem services, pollution, and land changes due to mining and infrastructure
6. Costs (including economic benefits)
    a. Include both financial (private) costs and full (public) costs.
    b. Differentiate between the entry cost versus the final costs for large-scale implementation.

The group noted the patchiness of the literature on costs, which is very sparse for some technologies.

7. Social acceptability
8. Risk of rapid leakage of CO_2, either by unforeseen failures or following discontinuation of action
9. Verification
    a. Can the claimed level of the activity be verified?
    b. Is it having the claimed and intended climate effect (attribution)?
    c. Can the associated impacts be monitored and attributed?
10. Legal issues
    a. conflict with existing treaties
    b. sovereignty
    c. equity
    d. Liability, responsibility
11. Current level of scientific knowledge/uncertainty, and what is it based on?
    a. Theory, simulation studies, small scale experimentation, or realistic-scale tests?

References

Schneider S.H., 2001: Earth systems engineering and management. *Nature* **409**, 417–421.

The Royal Society, 2009: *Geoengineering the climate: Science, governance and uncertainty*. Royal Society, London, UK. 82 pp., (ISBN: 9780854037735).

Breakout Group II.1: Solar Radiation Management Issues and Risks

Chair: Jason Blackstock

Rapporteur: Hannele Korhonen

The summary that follows, written by the Chair and Rapporteur, characterizes the main points of the BOG II.1 discussion. It may not reflect the personal views of the BOG's Chair and Rapporteur. The summary is intended for consideration by IPCC authors of the Fifth Assessment Report (AR5), but is neither endorsed nor approved by the IPCC or its Working Groups. Participants in the BOG considered a series of questions related to geoengineering research, developed by the meeting's Scientific Steering Group.

Questions suggested for discussions:

- What are the most important issues or dimensions related to Solar Radiation Management that IPCC authors might want to consider in the AR5 (e.g., governance issues, physical science issues, etc.)?
- What are the most important aspects of these issues to evaluate (e.g., unintended side effects, risks and uncertainties, indirect/social costs, legal and governance issues)?
- Can the most important aspects of these issues be supported by reference to the peer-reviewed literature, ideally drawing from multiple lines of independent evidence? What is the available evidence and what are relevant references?

Introduction

This BOG focused on the physical science related to Solar Radiation Management (SRM), governance and ethics issues that IPCC authors might wish to consider in the upcoming AR5. The group also discussed the extent of peer-reviewed literature available to evaluate each of these issues.

General points

It was stressed that all impacts of and uncertainties related to SRM should be evaluated in the context of not doing SRM. Even in a world without SRM, continuing greenhouse gas emissions mean that there is potential for new climatic conditions that could have severe or unexpected impacts on the environment and society.

The economics of SRM and the current knowledge on technological and engineering aspects were flagged as important issues that could be considered in the AR5, but questions were raised about which Working Groups and chapters this information would be assessed in. Concerns were raised that this information might fall between the cracks of existing Working Group and chapter outlines.

Physical science issues

The group noted that it may not be useful to make a distinction between intended and unintended consequences of SRM.

It was suggested that there is a reasonable amount of literature available from climate models related to global and regional precipitation and temperature effects from stratospheric aerosol injections and cloud whitening, as well as related to ozone loss from stratospheric injections. Constraining the physical effects can be done, for example, by looking at analogues (volcanic eruptions), model intercomparisons, etc.

For other SRM methods (e.g., cirrus clouds, space mirrors), the literature on physical impacts is very scarce.

There are a couple of publications available discussing sector-relevant issues, such as run-off, soil moisture, evaporation, diffuse radiation and UV flux. The group noted that these effects may be the most interesting to policy makers and the general public, although publications are limited.

There is no SRM-specific literature related to the potential for detection and attribution of SRM impacts against background climate change (signal-to-noise). However, some literature related to, for example, volcanic eruptions and "fingerprinting" climatic impacts can be relevant here.

Other important physical issues that might be discussed include ocean acidification, the termination problem, and the effect of SRM on atmospheric CO_2 concentration (e.g., by carbon uptake by vegetation in a cooler world with more diffuse radiation).

It was also mentioned that a thorough assessment of science in Working Group 1 will help the work of the authors of the other two Working Groups.

Social and governance issues

There is a range of peer-reviewed literature, in addition to the Royal Society report (Royal Society, 2009), that addresses the social and governance issues of SRM. However, most of this literature discusses the issues on a global, not regional scale.

It was suggested that, overall, SRM might be further discussed as a part of the IPCC AR5[2]. Legal and governance considerations and needs may evolve with new research and knowledge as well as with future climate conditions.

The group felt that IPCC authors might include both the governance of research and governance of implementation. It was also acknowledged that it can often be difficult to draw a line between research and deployment of SRM. However, it might be helpful to distinguish between the different levels of research (computer simulations, lab experiments, small scale tests with very little impacts, large scale tests). Although there is fear that successful small scale outdoor experiments could automatically lead to full scale deployment, many group members felt that this is unlikely without first going through a thorough investigation of large scale impacts.

The group also discussed the potential uses of SRM. Almost all the research thus far has focused on counteracting the effects of climate change that is, keeping the climate roughly where it is. However, SRM could also be used to meet more specific goals, for example, to optimize agricultural production or to preserve Arctic sea ice. There is currently no literature focusing specifically on this issue, although some papers address it to some extent.

It was also discussed that equity considerations need to be balanced. Also, an important governance issue is whether one country or a small coalition of countries can decide to implement SRM or whether a broader consensus is required.

Ethics

There is some literature either published or coming out soon on ethical questions of SRM. These issues may also be considered by IPCC authors.

References

The Royal Society, 2009: *Geoengineering the climate: Science, governance and uncertainty*. Royal Society, London, UK. 82 pp., (ISBN: 9780854037735).

[2] Note of the editors: No final attempt was made to place geoengineering within the range of human responses to climate change, including mitigation and adaption. This issue will need to be addressed in the context of the AR5.

Breakout Group II.2: Solar Radiation Management Issues and Risks

Chair: Catherine Redgwell

Rapporteur: Clarisse Kehler-Siebert

The summary that follows, written by the Chair and Rapporteur, characterizes the main points of the BOG II.2 discussion. It may not reflect the personal views of the BOG's Chair and Rapporteur. The summary is intended for consideration by IPCC authors of the Fifth Assessment Report (AR5), but is neither endorsed nor approved by the IPCC or its Working Groups. Participants in the BOG considered a series of questions related to geoengineering research, developed by the meeting's Scientific Steering Group.

Questions suggested for discussions:

- What are the most important issues or dimensions related to Solar Radiation Management that IPCC authors might want to consider in the AR5 (e.g., governance issues, physical science issues, etc.)?
- What are the most important aspects of these issues to evaluate (e.g., unintended side effects, risks and uncertainties, indirect/social costs, legal and governance issues)?
- Can the most important aspects of these issues be supported by reference to the peer-reviewed literature, ideally drawing from multiple lines of independent evidence? What is the available evidence and what are relevant references?

Introduction

This BOG discussion focused predominantly on Solar Radiation Management (SRM) issues that might be considered in the IPCC AR5 and their means of evaluation—that is, responding to the first two questions above. The final question regarding sources was addressed only cursorily.

What are the most important issues or dimensions related to Solar Radiation Management (SRM) that IPCC authors might want to consider in the AR5 (e.g., governance issues, physical science issues, etc.)?

The difficulty of assessing regional impact was identified as an issue that might be considered by AR5 authors. BOG participants proposed that assessing regional impacts of SRM is a governance issue (as opposed to a (purely) physical science issue). Work published today that *does* provide insight on regional impacts of global scale SRM is tentative. BOG participants proposed that while it would not be imprudent to trust extant predictions, there is also significant agreement that optimal forcing for one region would not be optimal for another region. It was proposed that the regional issues could be dealt with in various parts of AR5, including within Working Group I, and/or in the Working Group III chapter on national-international linkage (Chapter 13).

The detection and attribution of cause and effect was also identified by the BOG as a complex issue. From a scientific standpoint, it is difficult to attribute cause and effect in context of SRM. Thus, AR5 authors might consider the question of how well are we able to detect and attribute cause and effect for SRM. Furthermore, legal dimensions are also germane and complex. The question was also raised, but unanswered, as to whether IPCC AR5 authors should address liability and compensation. Finally, it was proposed that AR5 authors might question the increased complexity black carbon causes for this question of cause and effect.

IPCC AR5 authors may wish to consider how SRM is linked to current metrics in climate change. There is no metric to put these in the same framework—this was considered by some BOG participants as a gap in the literature. Still considering SRM and climate change, another issue for AR5 authors to consider is the flagging of risk (climate change) v. risk (SRM) to the 'external' world. Furthermore, the question of parallel treatment of issues was discussed: if looking at ethics and SRM, for example, parallel treatment might be considered for ethics of climate change generally. This led to several questions about IPCC assessment of questions of ethics.

The BOG also suggested that AR5 authors might pose the question, 'What are the governance gaps?' When considering governance, a distinction can be made between research and deployment. Some BOG participants believe that this distinction requires defining 'small scale'. The linkages to other processes might also be considered, for instance linking SRM and mitigation, or linking SRM to adaptation and development. Equity in governance is another consideration.

IPCC AR5 authors might also consider noting the outcome of a workshop of the Solar Radiation Management Governance Initiative (SRMGI), which articulated a need for an independent overseeing advisory board or committee which is independent and not purely scientific (SRGMI, 2011). A final question discussed by the BOG which might be considered by AR5 authors is whether there is something special about SRM that makes it 'international'. This may depend on the motivation of the actor. A need to assess technical impacts of SRM was also contemplated.

What are the most important aspects of these issues to evaluate (e.g., unintended side effects, risks and uncertainties, indirect/social costs, legal and governance issues)?

This question was to some extent addressed in the discussion summarized above. In addition, BOG participants emphasized that governance may not be 'one size fits all'. This is particularly true as concerns scale—it is important to be able to distinguish *de minimis* up to full-scale deployment. Another important distinction is between indirect and direct social cost, and unintended side effects.

Can the most important aspects of these issues be supported by reference to the peer-reviewed literature, ideally drawing from multiple lines of independent evidence? What is the available evidence and what are relevant references?

It was acknowledged that only the broadest outlines of the aspects discussed above are supported by the literature. For this reason, it might be relevant for AR5 authors to consider pertinent, analogous literature, and not just geoengineering literature—e.g. ethics and governance, but also other physical sciences. Some issues raised are quite absent from the literature—e.g., the metrics of SRM and climate change, as mentioned above.

References

Solar Radiation Management Governance Initiative, 2011: Solar radiation management: the governance of research. Environmental Defense Fund, The Royal Society, TWAS.

Breakout Group II.3 and 4: Carbon Dioxide Removal Issues and Risks

Chair: Gernot Klepper

Rapporteur: Shreekant Gupta

The summary that follows, written by the Chair and Rapporteur, characterizes the main points of the BOG II.3/4 discussion. It may not reflect the personal views of the BOG's Chair and Rapporteur. The summary is intended for consideration by IPCC authors of the Fifth Assessment Report (AR5), but is neither endorsed nor approved by the IPCC or its Working Groups. Participants in the BOG considered a series of questions related to geoengineering research, developed by the meeting's Scientific Steering Group.

Questions that might be addressed in this BOG include:

- What are the most important issues or dimensions related to Carbon Dioxide Removal that IPCC authors might want to consider in the AR5 (e.g., governance issues, physical science issues, etc.)?
- What are the most important aspects of these issues to evaluate (e.g., unintended side effects, risks and uncertainties, indirect/social costs, legal and governance issues)?
- Can the most important aspects of these issues be supported by reference to the peer-reviewed literature, ideally drawing from multiple lines of independent evidence? What is the available evidence and what are relevant references?

Introduction

The BOG decided to take an integrated view on approaches that could be taken for assessing certain Carbon Dioxide Removal (CDR) technologies. It went on to discuss priorities within these assessments and made suggestions to the authors of AR5 regarding potential points of focus. The time did not permit discussion of whether currently available literature could provide support for the assessment of the many CDR-technologies.

Potential focus of CDR assessments

The group looked at the matrix below, which lists a number of criteria that could be applied when different CDR options are assessed. This matrix refers both to the evaluation of research on CDR and to its deployment. The CDR options listed are not complete and should be further disaggregated. The naming of the criteria also should be interpreted as an abbreviation for a more elaborate definition.

Table A.5.2: Criteria for Carbon Dioxide Removal Approaches

	Ocean uptake, biological	Ocean uptake, chemical	Afforestation; Reforestation	Biochar; Bio-Storage	Air Capture	Weathering on land
Ethical Arguments						
Feasibility						
Effectiveness						
Side-effects						
Efficiency ("Social cost", including side-effects)						
Regulation (legal aspects)						
Regulation (policies and instruments)						
Monitoring / Verification						
Social Acceptability						

The group discussed the value of the criteria shown in the matrix in evaluating CDR technologies. There was also a suggestion not only to consider the economic efficiency of CDR options but also to recognize explicitly the distributional impacts of certain CDR options, across societal groups as well as across nations or regions.

Suggestions for AR5

It was agreed to discuss the evaluation criteria in a generic manner (CDR broadly rather than specific approaches) and to focus on the societal aspects (e.g., regulation, acceptability, etc.). Points raised include the following:

- AR5 authors may wish to note that published papers almost always refer to operating costs. They often ignore investment and research and development costs. Often, the market effects of rising prices for large-scale purchases for geoengineering activities are neglected, and in addition, the external costs of side-effects are not taken into account. It was highlighted that an assessment of CDR (and also of Solar Radiation Management (SRM)) may need to go beyond operating costs and look at the 'full' economic cost (a term that should be well defined) for each of the CDR approaches.
- One of the important aspects of an assessment of CDR is the choice of a reference case. There are many possible reference scenarios against which a certain CDR option can be evaluated. It was emphasized that the choice of a reference scenario by itself is a normative decision and has an important influence on the evaluation of a CDR option. It was suggested that several scenarios be used as a reference and that the difference in the results communicated.
- The issue of vulnerability or resilience in the context of implementing CDR options was raised. This is an important issue when certain vulnerable social groups might be affected by CDR. The evaluation of CDR might be considered within the particular external conditions of the region in which it will be applied. The example of afforestation was given.

- AR5 authors might also wish to consider assessment of research on the social acceptability of CDR, in terms of research on CDR and later deployment).

Breakout Group III.1: Solar Radiation Management in the Working Group Contributions to the IPCC AR5

Chair: Scott Barrett

Rapporteur: Naomi Vaughan

The summary that follows, written by the Chair and Rapporteur, characterizes the main points of the BOG III.1 discussion. It may not reflect the personal views of the BOG's Chair and Rapporteur. The summary is intended for consideration by IPCC authors of the Fifth Assessment Report (AR5), but is neither endorsed nor approved by the IPCC or its Working Groups. Participants in the BOG considered a series of questions related to geoengineering research, developed by the meeting's Scientific Steering Group.

Questions suggested for discussion:

- Where might each of the important Solar Radiation Management approaches and issues be evaluated within the IPCC AR5 (i.e., in which Working Group contribution and in which chapters)?
- Where might it be best to cover cross-cutting issues that do not neatly fall within one chapter or one Working Group's contribution?
- Are there some aspects of SRM that require expertise that is missing from the author teams of Working Group I, II and III? Are there other things the author teams can do to improve their ability to develop a high quality assessment?
- What geoengineering-related glossary terms might the AR5 include? For those terms, what might the corresponding entries be?

Introduction

The discussions in this BOG focused on where important Solar Radiation Management (SRM) approaches and issues might be evaluated within the IPCC's AR5 and where certain cross-cutting issues might be best covered. The discussions addressed the first two questions listed above but did not cover the last two questions.

Where should SRM be covered in the AR5?

BOG participants suggested that SRM should be covered in all Working Groups and treated consistently across them. Participants thought that the flow chart presented in plenary by one of the keynote speakers could be a useful framework for all Working Groups to reference (see Figure A.5.2). However, it was noted that in the framework all SRM proposals were grouped together and had an influence on 'radiative forcing'; a possible alternative is to have an influence on 'impacts'.

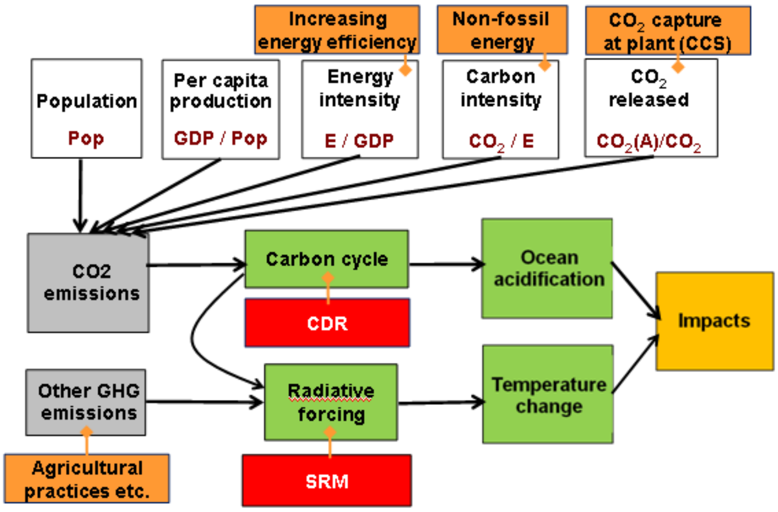

Figure A.5.2: *Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR) methods in relation to the interconnected human, socio-economic and climatic systems and with respect to mitigation and adaptation. The Figure has been extracted from Figure 1.1.*

Working Group I - The Physical Science Basis

At the time of the expert meeting geoengineering was suggested as a topic in the following chapters of the Working Group I contribution to the AR5: Chapter 1: Introduction – Introduction to geoengineering (SRM and Carbon Dioxide Removal (CDR)); Chapter 6: Biogeochemistry – CDR; Chapter 7: Radiative forcing – SRM (cloud and aerosols), including sections on idealized experiments and one Frequently Asked Question on geoengineering; Chapter 11: Near term climate change projections and predictability including the outputs of the Geoengineering Model Intercomparison Project (GEOMIP) (see Kravitz et al., 2011).

Working Group II – Impacts, adaptation and vulnerabilities

The BOG suggested inclusion of SRM in Chapter 10: Key economic sectors and services. Suggestions of further possible chapters in which SRM may be considered include: Chapter 16: Adaptation opportunities, constraints and limits; Chapter 17: Economics of adaptation; Chapter 19: Emergent risks and key vulnerabilities; Chapter 20: Climate-resilient pathways: adaptation, mitigation and sustainable development. The impacts of SRM could be considered in the impact chapters (Chapter 3: Freshwater resources; Chapter 4: Terrestrial and inland water systems; Chapter 5: Coastal systems and low-lying areas; Chapter 6: Ocean systems; Chapter 7: Food production systems and food security. It was also suggested that Chapter 19 may be a suitable place to discuss the impacts of SRM, as SRM may be considered an emergent risk itself in addition to potential use to mitigate or lessen climate-change-related risks.

Working Group III Mitigation of climate change

According to the current plan for Working Group III, SRM is only suggested for inclusion in Chapter 5: Drivers, trends and mitigation, within the topic, 'Carbon and radiation management and other geoengineering options including environmental risks'. Suggestions for other chapters where SRM literature may be relevant were: Chapter 1: Introduction; Chapter 2: Integrated risk and uncertainty assessment of climate change response policies; Chapter 3: Social, economic and ethical concepts and methods; Chapter 4: Sustainable development and equity; Chapter 13: International cooperation: agreements and instruments; Chapter 14: Regional development and cooperation; and Chapter 16: cross-cutting investment and finance issues. Discussion then considered whether SRM fits into the Working Group III contribution to the AR5 given the title of the Working Group states 'mitigation' and the IPCC definition of mitigation does not include SRM activity (see Section 2 of this report).

Locally or regionally targeted SRM

It was suggested that localized and/or regionally focused impact remediation with targeted SRM may also be considered; for example, there is some literature on the use of SRM to cool the Arctic. It was unclear where in the AR5 this type of focused regional intervention could be covered, that is, would it require a separate category or fall under the definition of SRM? (N.B. geoengineering is usually defined as having large-scale or global impact).

Overlaps

There was a brief discussion about potential overlap of topics such as economics, between Working Groups II and III. It was suggested that ethical questions may be discussed in Working Group II as well as III.

Definitions of Mitigation and Adaptation

There was discussion about the IPCC definition of 'mitigation', whether it refers to emissions reductions or whether it is a more general term. The IPCC Working Group III AR4 definition is:

"Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to Climate Change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks."

Although a dictionary definition of the word mitigation would generally mean reducing the impacts of something, it has come to be used by the IPCC to refer to emissions reductions and sink enhancement. Therefore CDR may fall under this definition but not SRM, even though ordinary usage of the word mitigation may include SRM. It was suggested that the IPCC definition of mitigation should not be changed to include SRM, not least because SRM does not affect atmospheric concentrations of greenhouse gases. This then led on to a discussion about whether SRM is a form of adaptation. The IPCC Working Group III AR4 definition of adaptation is:

"Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist, e.g. anticipatory and reactive, private and public and autonomous and planned. Examples are raising river or coastal dikes, the substitution of more temperature-shock resistant plants for sensitive ones, etc."

Although SRM could be considered a type of adaptation (to climate change) it was suggested that SRM should be distinguished from adaptation in the AR5.

Baselines and reference scenarios

Identifying the baselines or reference cases used in SRM literature is important but can be difficult. For Working Group I, the GEOMIP modelling experiments are an example where consistent baselines are used. However, much of the modelling work on SRM uses a variety of baselines and reference scenarios (such as $2xCO_2$, $4xCO_2$, ramping up or not). For Working Group II it is likely to be difficult to find a consistent baseline or reference case across the literature. Similarly, for Working Group III (e.g., governance, economics, risk and ethics) the relevance of baselines may need to be discussed even if the literature is not entirely explicit or consistent. Across all Working Groups, analysis of SRM may need to compare scenarios, such as with or without SRM. A suggestion was made to consider the impacts of SRM with reference to different Representative Concentration Pathways (RCPs), that is, would SRM cause a shift from one set of RCP impacts to another, and what novel impacts would be caused by SRM? It was concluded that it is very important to be transparent about the reference cases and baseline assumptions.

References

Kravitz B., Alan Robock, O. Boucher, H. Schmidt, K.E. Taylor, G. Stenchikov, and M. Schulz, 2011: The Geoengineering Model Intercomparison Project (GeoMIP). *Atmospheric Science Letters* **12**, 162–167. (DOI: 10.1002/asl.316).

Breakout Group III.2: Solar Radiation Management in the Working Group Contributions to the IPCC AR5

Chair: Don Wuebbles

Rapporteur: Thomas Leisner

The summary that follows, written by the Chair and Rapporteur, characterizes the main points of the BOG III.2 discussion. It may not reflect the personal views of the BOG's Chair and Rapporteur. The summary is intended for consideration by IPCC authors of the Fifth Assessment Report (AR5), but is neither endorsed nor approved by the IPCC or its Working Groups. Participants in the BOG considered a series of questions related to geoengineering research, developed by the meeting's Scientific Steering Group.

Questions suggested for discussion:

- Where might each of the important Solar Radiation Management approaches and issues be evaluated within the IPCC AR5 (i.e., in which Working Group contribution and in which chapters)?
- Where might it be best to cover cross-cutting issues that do not neatly fall within one chapter or one Working Group's contribution?
- Are there some aspects of Solar Radiation Management that require expertise that is missing from the author teams of Working Group I, II and III? Are there other things the author teams can do to improve their ability to develop a high quality assessment?
- What geoengineering-related glossary terms might the AR5 include? For those terms, what might the corresponding entries be?

Introduction

The group felt that it will be important to ensure a coherent coverage of geoengineering throughout the AR5 and that the crosscutting issues would benefit from consistent treatment in the respective chapters. This includes terminology as well as specific examples or measures of Solar Radiation Management (SRM) that might be discussed. Therefore, the group focussed mainly on questions one and two and to a lesser extent on questions three and four.

Where might each of the most important SRM approaches and issues be evaluated within the IPCC AR5 (i.e., in which Working Group contribution and in which chapters)?

The AR5 chapters where geoengineering should be mentioned have been considered by authors already, particularly in Working Group I, and the group highlighted the importance of mentioning SRM in all relevant chapters. The BOG suggested that a common table template could be used throughout the chapters, with the columns reflecting the various SRM approaches and the rows corresponding to the issues being addressed (see BOG Report I.2). The columns could be the same throughout AR5, but the rows could be specific to the relevant IPCC Working Group or chapter. Some suggestions for approaches and issues to be considered were worked out in a previous BOG and are summarized below. For in depth discussion of specific issues, the AR5 lead authors might want to concentrate some discussion especially on the same specific SRM approach (e.g., some variant of stratospheric aerosol injection) to achieve consistency throughout the report.

Where might it be best to cover cross-cutting issues that do not neatly fall within one chapter or one Working Group's contribution?

Crosscutting issues such as geoengineering benefit from consideration throughout the three Working Groups and in the synthesis report. The group discussed that a crosscutting committee could be formed to establish continuous communication among the IPCC Working Groups on geoengineering issues.

In the BOG, several specific issues that need a special emphasis in cross-cutting coverage were discussed more in detail. Key suggestions were:

- Cost issues: Authors could analyse, potentially with an integrated approach, cost estimates, including even for direct costs the time scale dimension to cost. Scalability: Are effects and side effects linear? Many aspects may be nonlinear (for example, feedbacks on stratospheric dynamics from sulphate injections need to be better represented).

- Technology: Working Group 1 may address the requirements for the technology to be effective, while Working Group 3 may discuss specific technologies and the costs (there is no obvious chapter for that in Working Group 3 – maybe Chapter 5?). It was an unresolved question in the BOG whether SRM approaches should be considered under adaptation technologies or technologies for adaptation in Working Group 2.

Are there some aspects of SRM that require expertise that is missing from the author teams of Working Group I, II and III? Are there other things the author teams can do to improve their ability to develop a high quality assessment?

The BOG felt that there is no obvious missing expertise amongst the lead authors. For specific questions that may need further consideration, it is advisable to involve others as contributing authors.

What geoengineering-related glossary terms might the AR5 include? For those terms, what might the corresponding entries be?

The BOG suggested that the major row and column items of the overarching table be present in the AR5 glossaries. The BOG also thought that the glossaries should be made as early as possible, with an emphasis on consistency throughout the Working Groups. The group discussed that, where possible and appropriate, the glossary should reflect definitions made in earlier reports.

Breakout Group III.3 and 4: Carbon Dioxide Removal in the Working Group Contributions to the IPCC AR5

Chair: Peter Cox

Rapporteur: Masahiro Sugiyama

The summary that follows, written by the Chair and Rapporteur, characterizes the main points of the BOG III.3/4 discussion. It may not reflect the personal views of the BOG's Chair and Rapporteur. The summary is intended for consideration by IPCC authors of the Fifth Assessment Report (AR5), but is neither endorsed nor approved by the IPCC or its Working Groups. Participants in the BOG considered a series of questions related to geoengineering research, developed by the meeting's Scientific Steering Group.

Questions suggested for discussion:

- Where might each of the most important Carbon Dioxide Removal approaches and issues be evaluated within the IPCC Fifth Assessment Report (i.e., in which Working Group contribution and in which chapters)?
- Where might it be best to cover cross-cutting issues that do not neatly fall within one chapter or one Working Group's contribution?
- Are there some aspects of Carbon Dioxide Removal that require expertise that is missing from the author teams of Working Group I, II and III? Are there other things the author teams can do to improve their ability to develop a high quality assessment?
- What geoengineering-related glossary terms might the AR5 include? For those terms, what might the corresponding entries be?

Introduction

This BOG first discussed issues surrounding terminology and the definition of "geoengineering", and spent most of the remaining time addressing the first two questions above, that is, where and how Carbon Dioxide Removal (CDR) geoengineering approaches should be covered in the IPCC AR5. The group did not have sufficient time to address expertise missing from the IPCC lead-author teams.

Terminology and definition of geoengineering

There was a good deal of discussion concerning the use of the term "geoengineering" for CDR techniques. Some members of the group felt that relabeling existing climate mitigation techniques, such as reforestation, as "geoengineering" could create confusion. Others felt suggested small-scale local actions (e.g., biochar) may be less relevant in the context of the IPCC. The group made the following suggestions for consideration by AR5 authors:

- Authors could mention geoengineering early in the AR5 Working Group contributions in order to guide policymakers, but then avoid the term "geoengineering" as much as possible afterwards, instead referring to specific techniques or "Solar Radiation Management" (SRM) and "Carbon Dioxide Removal" where necessary.
- It would be beneficial for authors to aim to use consistent terminology across the IPCC AR5. The group realized that some of the Working Group chapters have geoengineering in their section titles, and could use terminology that is consistent across the IPCC AR5.
- Authors may wish to avoid over-generalizations such as "SRM is cheap, fast, and imperfect", and instead refer to the characteristics of specific proposals, as these differ markedly even within the broad SRM and CDR categories.

- Authors may also want to avoid singling out geoengineering by imposing special criteria that are not equally applied to conventional mitigation. For example, it has been noted that CDR has a rebound effect (decreasing atmospheric CO_2 would reduce ocean CO_2 uptake), but this also applies to conventional mitigation.

With regard to consideration of CDR techniques in the IPCC AR5, the group then considered tightening the definition of CDR. Elements suggested for consideration by authors in the IPCC AR5 were the potential for techniques to:

1. significantly cool global climate (e.g., by removing greater than 1 GtC/yr of CO_2)

and/or

2. lead to significant trans-boundary impacts, other than the intended impacts of lowering global atmospheric CO_2.

A refined CDR definition might exclude some techniques from consideration as geoengineering in the IPCC AR5 on the basis of scale (e.g., ocean pipes), or the relative absence of non-CO_2 trans-boundary effects (e.g., no-tillage agriculture).

The figure proposed by BOG I.3 (Figure A.5.1) was thought to be useful to conceptualize these aspects of CDR approaches. On the basis of these criteria, CDR techniques that are on the left side of the dotted line could be the priorities for assessment in the IPCC AR5.

Treatment of various aspects of CDR across IPCC AR5 Working Groups

The BOG discussed which chapter/section of the IPCC AR5 might treat each aspect of CDR, with Table 1 produced as a first attempt at suggestions. The BOG also suggested that the following chapters may cover CDR in a broad sense: for Working Group 1, Chapter 6 (carbon and other biogeochemical cycles); for Working Group 2, Chapter 20 (climate-resilient pathways); for Working Group 3, Chapter 2 (risk, framework), Chapter 13 (international governance), Chapter 14 (national policy).

As the table shows, the treatment of CDR (and geoengineering in general) could be distributed throughout the contributions of the three IPCC AR5 Working Groups. This implies a challenge to present a coherent analysis of CDR. The group felt that the IPCC could consider the following options to meet this challenge: (a) A Technical Report or Special Report (but this would entail significant work and could only be undertaken after the IPCC AR5 process had been completed); and (b) a topic or box in the synthesis report that brings together the assessment of CDR from across the three Working Group reports.

Other suggestions

The group recommended that the expert meeting participants should serve as reviewers of the relevant chapters of the IPCC AR5, to help ensure consistent treatment of geoengineering across the different IPCC Working Groups.

Table A.5.3: *A possible allocation of various aspects of CDR options across the IPCC AR5 Working Groups (WGs), as discussed in BOG III.3 and 4.*

	Weathering (land & ocean)	Ocean fertilization, biological	Afforestation/ reforestation	Biochar	Direct air capture	Direct CO_2 Injection into the ocean
Feasibility	WG1&3	WG1	WG1&3	WG3	WG3	WG1
Effectiveness	WG1	WG1	WG1	WG1	WG1	WG1
Side effects	WG1/2	WG1/2	WG1/2	WG1/2	WG1/2	WG1/2
Costs, including social cost	WG3	WG3	WG3	WG3	WG3	WG3
Legal issue	WG3	WG3	WG3	WG3	WG3	WG3
Social acceptability	WG3	WG3	WG3	WG3	WG3	WG3
Regulation	WG3 Ch13-15	WG3 Ch13-15	WG3 Ch13-15	WG3 Ch13-15	WG3 Ch13-15	WG3 Ch13-15
Monitoring & Verification (*)	WG1/3 Ch13-15	WG1/3 Ch13-15	WG3 Ch13-15	WG3 Ch13-15	WG1/3 Ch13-15	WG1/3 Ch13-15
Ethics	WG3	WG3	WG3	WG3	WG3	WG3

*As for monitoring and verification, detectability should be discussed in Working Group 1.

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