

The European Transdisciplinary Assessment of Climate Engineering (EuTRACE)

**Removing Greenhouse Gases from the
Atmosphere and Reflecting Sunlight
away from Earth**

Editors: Stefan Schäfer, Mark Lawrence, Harald Stelzer,
Wanda Born, Sean Low



Editors:

Stefan Schäfer, Mark Lawrence, Harald Stelzer, Wanda Born, Sean Low

Lead authors:

Paola Adriázola, Gregor Betz, Olivier Boucher, Stuart Haszeldine, Jim Haywood, Peter Irvine, Jon-Egill Kristjansson, Mark Lawrence, Tim Lenton, Helene Muri, Andreas Oschlies, Alexander Proelss, Tim Rayner, Wilfried Rickels, Lena Ruthner, Stefan Schäfer, Jürgen Scheffran, Hauke Schmidt, Vivian Scott, Harald Stelzer, Naomi Vaughan, Matt Watson

Contributing authors:

Asbjørn Aaheim, Alexander Carius, Patrick Devine-Right, Anne Therese Gullberg, Katherine Houghton, Rodrigo Ibarrola, Jasmin S. A. Link, Achim Maas, Lukas Meyer, Michael Schulz, Simon Shackley, Dennis Tänzler

Project advisory board:

Bidisha Banerjee, Ken Caldeira, Mike Childs, Harald Ginzky, Kristina Gjerde, Timo Goeschl, Clive Hamilton, Friederike Herrmann, David Keith, Tim Kruger, Doug Parr, Katherine Redgwell, Alan Robock, David Santillo, Pablo Suarez

Project coordinator:

Mark Lawrence

The EuTRACE project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 306993. It brought together a consortium of 14 partner institutions that worked together to compile this assessment report. Consortium members represented various disciplines with expertise on the topic of climate engineering. The views expressed in this report are not necessarily representative of the views of the institutions at which the authors are employed.

Citation: Schäfer, S.; Lawrence, M.; Stelzer, H.; Born, W.; Low, S.; Aaheim, A.; Adriázola, P.; Betz, G.; Boucher, O.; Carius, A.; Devine-Right, P.; Gullberg, A. T.; Haszeldine, S.; Haywood, J.; Houghton, K.; Ibarrola, R.; Irvine, P.; Kristjansson, J.-E.; Lenton, T.; Link, J. S. A.; Maas, A.; Meyer, L.; Muri, H.; Oschlies, A.; Proelß, A.; Rayner, T.; Rickels, W.; Ruthner, L.; Scheffran, J.; Schmidt, H.; Schulz, M.; Scott, V.; Shackley, S.; Tänzler, D.; Watson, M.; Vaughan, N. (2015) *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth*. Funded by the European Union's Seventh Framework Programme under Grant Agreement 306993.

EuTRACE is a joint project of



Contents

Preface	12
Executive Summary	13
<hr/>	
1 Introduction	16
1.1 The context: climate change	16
1.2 Engineering the climate as a proposed response to climate change	18
1.3 Understanding climate engineering: the role of scenarios and numerical climate modelling	22
1.4 Historical context and overview of this report	25
 2 Characteristics of techniques to remove greenhouse gases or to modify planetary albedo	 27
2.1 Greenhouse gas removal	27
2.1.1 Afforestation	28
2.1.2 Biomass energy with carbon capture and storage (BECCS)	28
2.1.3 Biochar	31
2.1.4 Additional biomass-based processes: non-forest, burial, use in construction, and algal CO ₂ capture	32
2.1.5 Direct air capture	32
2.1.6 Enhanced weathering and increased ocean alkalinity	33
2.1.7 Ocean fertilisation, including ocean iron fertilisation (OIF)	34
2.1.8 Enhancing physical oceanic carbon uptake through artificial upwelling	36
2.1.9 Cross-cutting issues and uncertainties	37
2.1.9.1 Lifecycle assessment of greenhouse gas removal processes	37
2.1.9.2 CO ₂ storage availability and timescale	38
2.2 Albedo modification and related techniques	40
2.2.1 Stratospheric aerosol injection (SAI)	41
2.2.2 Marine cloud brightening (MCB) / marine sky brightening (MSB)	44
2.2.3 Desert reflectivity modification	46
2.2.4 Vegetation reflectivity modification	47
2.2.5 Cirrus cloud thinning	48
2.2.6 Results from idealised modelling studies	49
2.2.7 General effectiveness and constraints of modifying the planetary albedo	55
2.2.8 Carbon cycle climate feedbacks between modifying the planetary albedo and removing greenhouse gases from the atmosphere	56

3	Emerging societal issues	58
3.1	Perception of potential effects of research and deployment	58
3.1.1	Moral Hazard	58
3.1.2	Environmental responsibility	60
3.1.3	Public awareness and perception	61
3.1.4	Participation and consultation: questions from example cases	63
3.2	Societal issues around potential deployment	70
3.2.1	Political dimensions of deployment	73
3.2.2	Economic analysis	74
3.2.2.1	Assessing costs and benefits	74
3.2.2.2	Socio-economic insights from climate engineering scenarios	76
3.2.3	Distribution of benefits and costs	77
3.2.4	Compensation	80
<hr/>		
4	International regulation and governance	82
4.1	Emerging elements of a potential climate engineering regime in the activities of international treaty bodies	83
4.1.1	UNFCCC – Climate engineering as a context-specific response to climate change?	84
4.1.2	LC/LP – Climate engineering as an activity or technical process?	86
4.1.3	CBD – Climate engineering judged in light of its effects on the environment?	88
4.1.4	Outlook: bringing together the regulatory approaches of context, activities and effects	89
4.2	The EU law perspective: considering a potential regulatory strategy for climate engineering including application of the approaches of context, activities and effects	90
4.2.1	EU Primary Law – An overarching context for climate engineering regulation and competences for its implementation within the EU	91
4.2.2	EU Secondary Law	92
4.2.3	Taking a regional perspective on climate engineering	93

5	Research options	94
5.1	Background	94
5.2	Arguments for and concerns with climate engineering research	96
5.2.1	Arguments in favour of climate engineering research	96
5.2.2	Concerns with climate engineering research	97
5.3	Knowledge gaps and key research questions	98
<hr/>		
6	Policy development for climate engineering	103
6.1	Policy context	103
6.2	General policy considerations for climate engineering	105
6.2.1	Urgency, sequencing and multiple uses of climate engineering research	105
6.2.1.1	Urgency and timeliness of climate engineering research	105
6.2.1.2	Sequencing: Advantages and disadvantages of a parallel research approach	107
6.2.1.3	Multiple uses of knowledge: Connection to other research	107
6.2.1.4	Outlook: a challenge and opportunity	108
6.2.2	Policy considerations in developing principles for climate engineering governance	108
6.2.3	Strategies based on principles	110
6.2.4	Policy considerations for international governance of climate engineering	112
6.2.4.1	The United Nations Framework Convention on Climate Change (UNFCCC)	113
6.2.4.2	The Convention on Biological Diversity (CBD)	113
6.2.4.3	The London Convention and Protocol (LC/LP)	113
6.2.4.4	Possible future development of the emerging regime complex on climate engineering	114
6.3	Technique-specific policy considerations	115
6.3.1	Policy development for BECCS	115
6.3.2	Policy development for OIF	118
6.3.3	Policy development for SAI	119
6.4	An EU perspective	122

7	Extended Summary	125
7.1	Introduction	125
7.2	Characteristics of techniques to remove greenhouse gases or to modify the planetary albedo	126
7.2.1	Greenhouse gas removal	126
7.2.2	Albedo modification and related techniques	128
7.3	Emerging societal issues	129
7.4	International regulation and governance	133
7.5	Research options	134
7.6	Policy development for climate engineering	135
7.6.1	Development of research policy	136
7.6.2	Development of international governance	136
7.6.3	Development of technique-specific policy	137
7.6.4	Potential development of climate engineering policy in the EU	138
<hr/>		
8	References	140

List of Figures

1.1	Observed global mean surface temperature anomalies from 1850 to 2012	17
1.2	Global surface–atmosphere solar and terrestrial radiation budget	19
2.1	Contributions of various technologies and changes in end-use to two mitigation scenarios, with a significant role for BECCS assumed in both scenarios	29
2.2	Air–sea CO ₂ flux and change in flux over time induced by ocean iron fertilisation in model simulations	35
2.3	Sizes of fossil carbon supply (reserves and resources) and potential carbon stores (in Gt CO ₂)	39
2.4	Surface shortwave radiative flux anomaly induced by a given annual rate of injection of stratospheric sulphate particles, for three different modelling studies	42
2.5	Depiction of cloud brightening by aerosol particle injection	45
2.6	Schematic of cirrus cloud thinning by seeding with ice nuclei, showing reduction in reflection of shortwave solar radiation and absorption of longwave terrestrial radiation	48
2.7	Idealised radiative forcing curves in each of the four original GeoMIP experiments (G1–G4)	51
2.8	Difference between the GeoMIP G1 simulation and the pre-industrial control simulation for surface air temperature and precipitation (mean of 12 GeoMIP models)	53
2.9	Multi-model ensemble simulations (GeoMIP G2) of the impact on temperature due to albedo modification by reduction of the solar constant	55
2.10	Enhanced carbon uptake due to a deployment of albedo modification (reducing global average temperatures from an RCP8.5 scenario down to the pre-industrial level)	57
3.1	Schematic overview of possible consequences of the deployment of SAI	71
3.2	Schematic overview of possible consequences of the deployment of BECCS	72
5.1	Main trends in scientific publications on climate engineering	95

List of Boxes

1.1	Definition of terms for responses to climate change	21
1.2	Detection and attribution of albedo modification consequences	24
2.1	Practical constraints surrounding SAI delivery mechanisms	43
2.2	The Geoengineering Model Intercomparison Project (GeoMIP)	50
2.3	SAI and vegetation productivity	54
3.1	What are public awareness, acceptance and engagement	61
3.2	LOHAFEX Iron Fertilisation Experiment	63
3.3	Bio-Energy with Carbon Capture and Storage in Greenville, Ohio	65
3.4	Bio-Energy with Carbon Capture and Storage in Decatur, Illinois	66
3.5	Stratospheric Particle Injection for Climate Engineering (SPICE)	67
3.6	Cost types	75
3.7	SAI as the 'lesser evil'?	78
3.8	Climate engineering deployment as a question of justice	79
4.1	Three regulatory approaches for climate engineering	82
4.2	CCS under the Clean Development Mechanism	85
6.1	Summary of arguments in support of or against field tests of albedo modification	107
6.2	Procedural norms	112

List of Acronyms

ADM	Archer Daniels Midland
AOGCM	Atmosphere–Ocean General Circulation Model
AR5	IPCC Fifth Assessment Report
ATP	The “Ability to Pay” Principle
BECCS	Bioenergy with Carbon Capture and Storage
BMBF	German Federal Ministry of Education and Research
BPP	The “Beneficiary Pays” Principle
CBD	United Nations Convention on Biological Diversity
CCAC	Climate and Clean Air Coalition
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CDM	Clean Development Mechanism
CFCs	Chlorofluorocarbons
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CMIP	Coupled Model Intercomparison Project
CO₂	Carbon Dioxide
COP	Conference of the Parties
DG	European Commission Directorate-General
DMS	Dimethylsulphide
ELD	European Union Environmental Liability Directive
ENGO	Environmental Non-Governmental Organisation
ENMOD	United Nations Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques
ENSO	El Niño Southern Oscillation
ESM	Earth System Model
ETS	European Union Emissions Trading System

EuTRACE	European Transdisciplinary Assessment of Climate Engineering
FP7	European Union Seventh Framework Research Programme
GHG	Greenhouse Gas
IAGP	Integrated Assessment of Geoengineering Proposals
IBDP	Illinois Basin-Decatur Project
ILUC	Indirect Land Use Change
IMO	International Maritime Organization
IMPLICC	Implications and Risks of Engineering Solar Radiation to Limit Climate Change
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
LC	London Convention
LP	London Protocol
MCB	Marine Cloud Brightening
MDG	United Nations Millennium Development Goals
MGSC	Midwest Geological Sequestration Consortium
MML	Mobilisation and Mutual Learning Action Plan
MSB	Marine Sky Brightening
NGO	Non-Governmental Organisation
NSEC	National Sequestration Education Center
NZEC	EU–China Near Zero Emissions Coal project
OFAF	Ocean Fertilisation Assessment Framework
OIF	Ocean Iron Fertilisation
PPP	The “Polluter Pays” Principle
RCC	Richland Community College
RCP	IPCC Representative Concentration Pathways
SAI	Stratospheric Aerosol Injection
SBSTA	Subsidiary Body for Scientific and Technological Advice
SDG	United Nations Sustainable Development Goals
SO₂	Sulphur Dioxide
SRMGI	Solar Radiation Management Governance Initiative
TEU	Treaty on European Union
TFEU	Treaty on the Functioning of the European Union
UNCCD	United Nations Convention to Combat Desertification
UNCLOS	United Nations Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
VCLT	Vienna Convention on the Law of Treaties

Preface

The project EuTRACE (European Transdisciplinary Assessment of Climate Engineering) was funded from June 2012 through September 2014 by the EU as a Coordination and Support Action (CSA) in the 7th Framework Programme (FP7). EuTRACE brought together a consortium of 14 partner institutions that worked together to compile this assessment report. Consortium members represented various disciplines with expertise on the topic of climate engineering. This assessment report is the main result of the project.

The EuTRACE assessment report is provided in three parts (all available via www.eutrace.org):

- *the full report*, which provides extensive details and references for any readers who are interested in an in-depth insight into the range of main issues associated with the topic of climate engineering;
- *an extended summary*, aimed at a broad range of readers, providing an overview of the main results of the report, but leaving out most details; the extended summary follows the overall structure of the assessment report but does not include literature references in order to enhance readability;
- *an executive summary*, aimed especially at policy makers and other readers interested in an overview of the main actionable results of the assessment.

Executive Summary of the EuTRACE Report

Background and General Considerations

There is a broad scientific consensus that humans are changing the composition of the atmosphere and that this, in turn, is modifying the climate and other global systems. The likely harmful impacts on societies and ecosystems, along with possibilities for mitigation and adaptation, have been documented in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC).

In this context, various researchers, policy makers, and other stakeholders have also begun to consider “climate engineering” (also known as “geoengineering” or “climate intervention”) as a further response to climate change. Most climate engineering techniques can be grouped into two broad categories:

- “greenhouse gas removal”: proposals for reducing the rate of global warming by removing large amounts of CO₂ or other greenhouse gases from the atmosphere and sequestering them over long periods;
- “albedo modification”: proposals for cooling the Earth’s surface by increasing the amount of solar radiation that is reflected back to space (“albedo” is the fraction of incoming light reflected away from a surface).

The EuTRACE assessment report provides an overview of a broad range of techniques that have been proposed for climate engineering. Research on climate engineering has thus far been limited, mostly based on climate models and small-scale field trials. To illustrate the range of complex environmental and

societal issues that climate engineering raises, the EuTRACE assessment focuses on three example techniques: bio-energy with carbon capture and storage (BECCS), ocean iron fertilisation (OIF), and stratospheric aerosol injection (SAI).

In general, it is not yet clear whether it would be possible to develop and scale up any proposed climate engineering technique to the extent that it could be implemented to significantly reduce climate change. Furthermore, it is unclear whether the costs and impacts on societies and the environment associated with individual techniques would be considered acceptable in exchange for a reduction of global warming and its impacts, and how such acceptability or unacceptability could be established democratically.

Against this background, a broad and robust understanding of the topic of climate engineering would be valuable, were national and international policies, regulation, and governance to be developed. This could be supported by coordinated, interdisciplinary research combined with stakeholder dialogue, taking into account a range of issues, including the potential opportunities, the scientific and technical challenges, and the societal context within which wide-ranging concerns are being raised in discussions about climate engineering.

Opportunities and Scientific and Technical Challenges

Greenhouse gas removal techniques could possibly be used someday to significantly reduce the amount of anthropogenic CO₂ and other greenhouse gases in the

atmosphere. This could present an important long-term opportunity to limit or partly reverse climate change, given that anthropogenic CO₂, once emitted, remains within the climate system for more than a hundred years on average. However, such techniques face numerous scientific and technical challenges, including:

- determining whether the techniques could be scaled up from current prototypes, and what the costs of this might be;
- determining the constraints imposed by various technique-dependent factors, such as available biomass;
- developing the very large-scale infrastructures and energy inputs, along with the accompanying financial and legal structures, that most of the proposed techniques would require; based on existing knowledge and experience, this could take many decades before it could have a significant impact on global CO₂ concentrations.

For albedo modification, initial model simulations have shown that several proposed techniques could potentially be used to cool the climate significantly and rapidly (within a year or less, and possibly at relatively low operational costs). This would be the only known method that could potentially be implemented to reduce the near-term impacts of unmitigated global warming. However, in addition to the societal concerns outlined in the next section, it is unclear whether any of the proposed albedo modification techniques would ever be technically feasible. There are numerous scientific and technical challenges that would first need to be addressed to determine this, including:

- very large and costly infrastructures that land-based techniques would require;
- delivery mechanisms for techniques based on injection of aerosol particles into the atmosphere, including delivery vessels (e.g., high-flying aircraft or tethered balloons) and associated nozzle technologies;
- a much deeper understanding of the underlying physical processes, such as the microphysics of parti-

cles and clouds, as well as how modification of these would affect the climate on a global and regional basis.

A further challenge that generally applies to both greenhouse gas removal and albedo modification is that their application could result in numerous technique-specific harmful impacts on ecosystems and the environment, many of which are presently uncertain or unknown.

Societal Context

The development and implementation of any of these proposed climate engineering techniques would occur within a complex societal context where numerous concerns arise, including:

- public awareness and perception;
- the “moral hazard” argument (the concern that research on climate engineering would discourage the overall efforts to reduce or avoid emissions of greenhouse gases);
- the sense of environmental responsibility in the Anthropocene;
- possible effects of various climate engineering techniques on human security, conflict risks, and societal stability;
- expected economic impacts;
- justice considerations, including the distribution of benefits and costs, procedural justice for democratic decision making, and compensation for harms imposed on some regions by measures that benefit others.

It can be expected that these concerns, as well as the scientific and technical challenges discussed above, would take considerable time to resolve, if this is at all possible. Thus, it appears imprudent to expect either greenhouse gas removal or albedo modification to play a significant role in climate policy developments in the next decade, or even within the next several decades, although it is possible that one or more of the climate engineering techniques that are currently being discussed will become an option for climate policy in the latter half of this century.

Development of Policies, Regulation, and Governance

Developing effective regulation and governance for the range of proposed climate engineering techniques would require researchers, policy makers, and other stakeholders to work together to address the uncertainties and risks involved. At present, no existing international treaty body is in a position to broadly regulate greenhouse gas removal, albedo modification, or climate engineering in its entirety. The development of such a dedicated, overarching treaty (or treaties) for this purpose would presently be a prohibitively large undertaking, if at all realisable.

Thus far, two treaty bodies, the London Convention/London Protocol (LC/LP) and the Convention on Biological Diversity (CBD), have taken up discussions and passed the first resolutions and decisions on climate engineering. Furthermore, it has often been suggested that the United Nations Framework Convention on Climate Change (UNFCCC) could contribute to regulating various individual techniques or aspects of climate engineering.

In light of this, one option that the EU could follow if it were to decide to try to promote a more coordinated approach to the regulation of climate engineering would be to bring together the LC/LP, CBD, and UNFCCC at the operational level. This could be done, for example, through parallel action, common assessment frameworks, and Memoranda of Understanding. A further option for EU member states (which are all parties to both the UNFCCC and the CBD) could be to pursue an agreement on a common position on various techniques or general aspects of climate engineering. In particular, such an agreement could be made consistent with the high degree of importance that EU primary law places on environmental protection.

For the more general development of climate engineering governance (in addition to formal regulation), the EuTRACE assessment highlights five overarching principles for guiding the academic research community and policy makers:

- minimisation of harm;
- the precautionary principle;
- the principle of transparency;
- the principle of international cooperation;
- research as a public good.

Based on these principles, the EuTRACE assessment proposes several strategies that could broadly be applied across all climate engineering approaches in support of developing effective governance:

- early public engagement, including targeted public communication platforms;
- independent assessment;
- operationalising transparency through adoption of research disclosure mechanisms;
- coordinating international legal efforts through activities like those discussed above, e.g., common assessment frameworks, as well as through development and joint adoption of a code of conduct for research;
- applying frameworks of responsible innovation and anticipatory governance to natural sciences and engineering research.

Should the EU decide to develop clear and explicit policies for research on climate engineering, or its potential future deployment, then a conscientious application of the principles and strategies discussed in the EuTRACE assessment may help ensure coherence and consistency with the basic principles upon which broader European research and environmental policy are built.

1. Introduction

There is a broad scientific consensus that humans are changing the composition of the atmosphere, and that this is leading to global climate change (IPCC, 2013a). The implications of climate change have been recognised internationally, reflected for example in the United Nations Framework Convention on Climate Change (UNFCCC). However, the national and international mitigation efforts encouraged by this recognition have not yet been sufficient to stop the global increase in greenhouse gas emissions (IPCC, 2013a, pp. 486). In light of this, numerous studies have been conducted and plans developed, from the local to the international level, for adapting to climate change, with the general recognition that while adaptation can reduce the vulnerability to some impacts, it can be difficult and often costly, and in some cases might not even be possible (Klein et al., 2014).

1.1 The context: climate change

The threats posed by global climate change are widely acknowledged and have recently been extensively described in the IPCC's Fifth Assessment Report (IPCC, 2013a), the key results of which are briefly summarised here. One of the most important global environmental changes caused by humans is the increase in the carbon dioxide (CO_2) content of the atmosphere from about 0.028% to about 0.04% over the last two centuries. This increase in CO_2 concentration has arisen mainly from the combustion of fossil fuels and is responsible for approximately half of the current anthropogenic global warming. The combined warming influence of other anthropogenic greenhouse gases, together with sunlight-absorbing soot particles, is of a similar magnitude to that of CO_2 (IPCC, 2013a). At the same time, other anthropogenic

aerosol particles containing sulphate and nitrate reflect sunlight, and also cause clouds to be more reflective, partially masking the warming trend. However, the strength of this aerosol effect on the climate is uncertain, shows significant regional variations, and does not simply reduce temperatures, but also affects other aspects of the climate such as precipitation patterns, so that it cannot merely be seen as cancelling out a fraction of the global warming. Taken together, these changes have resulted in a net increase in the average surface temperature of the Earth, as depicted in Figure 1.1. The IPCC indicates that the “best estimate of the human-induced contribution to warming is similar to the observed warming” (IPCC, 2013b, p. 15), which is about 0.8°C over the last two centuries, and that “it is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together” (IPCC, 2013b, p. 15).

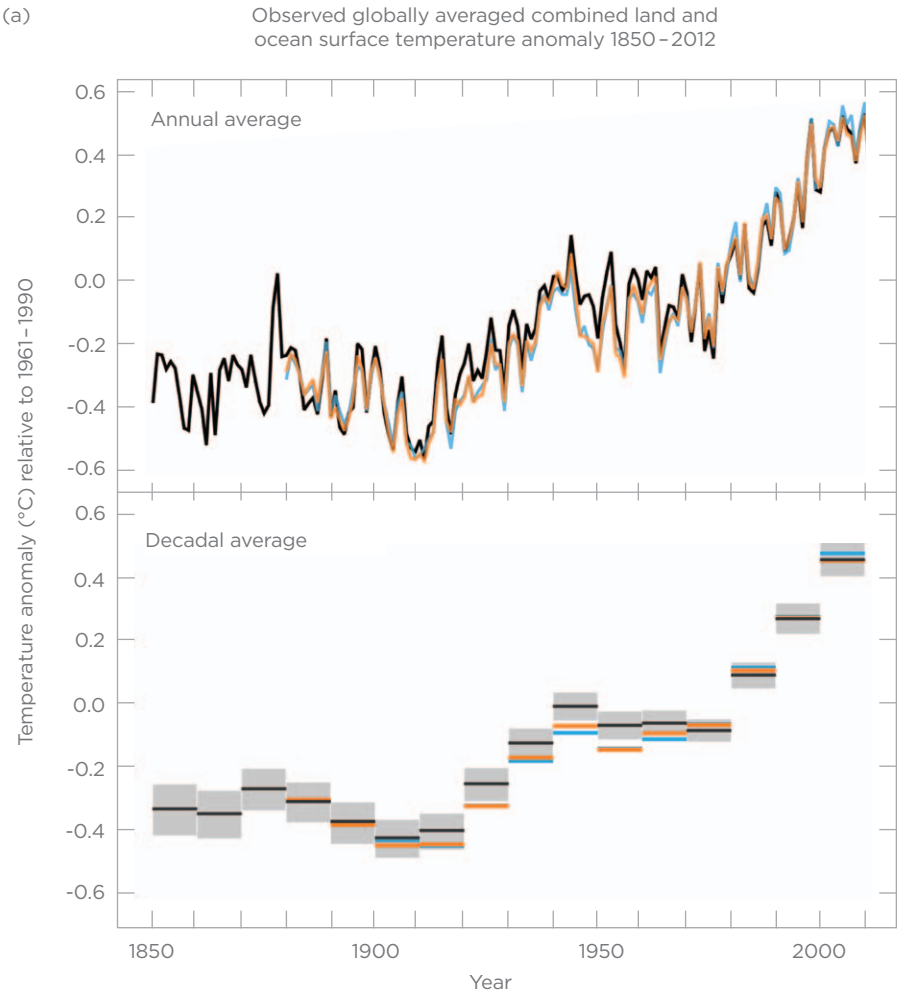


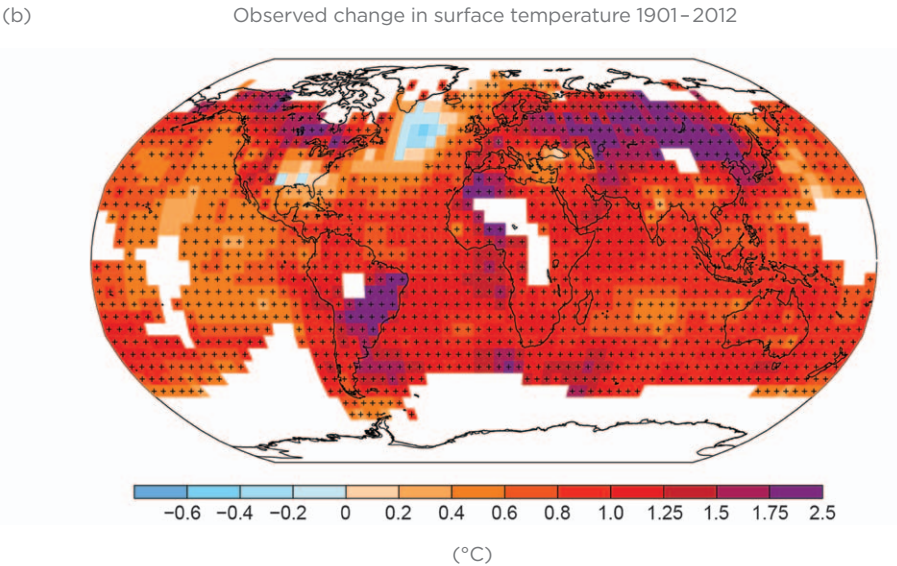
Figure 1.1:

(a) Observed global mean combined land and ocean surface temperature anomalies, from 1850 to 2012 from three data sets. Top panel: annual mean values; Bottom panel: decadal mean values including estimated uncertainty for one dataset (for both panels, the colours represent different datasets: black – HADCRUT4 (version 4.1.1.0); blue – NASA GISS; orange – NCDC MLOST (version 3.5.2); the shaded area in the bottom panel shows the uncertainty in the HADCRUT4 dataset). Anomalies are relative to the mean of the period 1961–1990.

(b) Map of observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset (orange line in panel a).

Source:

IPCC AR5 Working Group 1 Summary for Policymakers; see report for further details.



As part of the IPCC report, projections of the evolution of global mean temperatures for a range of future scenarios have been made using climate models. Compared to the contemporary climate (1986–2005 average), the projected warming for the end of the 21st century (2081–2100 average) ranges from 0.3 to 1.7°C under a scenario of stringent mitigation, and from 2.6 to 4.8°C under a fossil-fuel-intensive scenario (IPCC, 2013b). The large range of temperatures for each scenario is due to uncertainties in the magnitude of the climate feedbacks that both amplify and dampen the warming response, as well as to uncertainties in the treatment of many climate-relevant atmospheric processes, such as the formation of clouds and precipitation and how these are influenced by anthropogenic aerosol particles. Discussion of these scenarios often focuses on the change in the global mean temperature; however, within each scenario there are also considerable regional differences, with greater warming expected over land than over oceans, and the greatest warming occurring in the Arctic region (IPCC, 2013b).

The accumulation of CO₂ and other greenhouse gases in the atmosphere will have a profound effect on human societies and ecosystems, as will the broader changes in the climate and Earth system that will accompany the rise in global temperatures (IPCC, 2014c). Higher temperatures are likely to increase the frequency and intensity of heat waves (Meehl and Tebaldi, 2004), and lengthen the melting and growing seasons (Bitz et al., 2012; Tagesson et al., 2012) with far-reaching ecological consequences in cold regions (Post et al., 2009). The distribution of precipitation is expected to change, with dry regions frequently becoming drier and wet regions becoming wetter (Held and Soden, 2006), although uncertainties remain in both this and the differences between continental and marine responses. In general, the intensity of precipitation is expected to increase, with rain occurring in more intense downpours between longer periods of low precipitation (Liu et al., 2009), which could lead to more floods and more intense droughts (Held and Soden, 2006). Higher temperatures will also continue to cause rising sea levels as the warming ocean expands and glaciers and ice sheets melt (Schaeffer et al., 2012). Elevated CO₂ concentrations will also have a direct fertilising effect on vegetation, generally increasing net primary productivity (photo-

synthesis minus autotrophic respiration) and water-use efficiency (Franks et al., 2013). However, climate changes will also stress plants, potentially reducing net primary productivity in some regions (Lobell et al., 2011), with substantial consequences for terrestrial ecosystems and hydrology (Heyder et al., 2011). Rising CO₂ concentrations are also causing ocean acidification, affecting many marine organisms, particularly shell-forming organisms such as coral reefs and molluscs (Kroeker et al., 2010). These changes to the physical environment and the biosphere will affect human societies, for example through changes to natural hazards and effects on agricultural productivity and infrastructure (IPCC, 2014c).

1.2 Engineering the climate as a proposed response to climate change

Against this background, various researchers, policy makers, and other stakeholders have begun to consider responses to climate change via methods that cannot easily be subsumed under the categories of mitigation and adaptation. The first question that is often raised is: are there viable ways to remove large amounts of CO₂ and other greenhouse gases from the atmosphere? Many ideas have been proposed for this, which vary considerably in their approach, and include combining biomass use for energy generation with carbon capture and storage (Biomass Energy with Carbon Capture and Storage, BECCS), large-scale afforestation, and fertilising the oceans in order to induce growth of phytoplankton and thus increase the uptake of CO₂ from the atmosphere.

Going beyond ideas for removing greenhouse gases, the question has also been raised: are there also possibilities for directly cooling the Earth? Several ideas have been proposed that could potentially do so, most aiming to increase the planetary albedo, i.e., the amount of solar radiation that is reflected (mostly by clouds or at the Earth's surface) and therefore not absorbed by the Earth. Techniques have been proposed that would act at a range of altitudes, including whitening surfaces, making clouds brighter, injecting aerosol particles into the stratosphere, and placing mirrors in space. Another proposed technique would involve modifying cirrus clouds to increase the amount of terrestrial radiation leaving the Earth. In this report, all of these approaches are subsumed

under the term “albedo modification and related techniques”.

Taken together, ideas for greenhouse gas removal and for albedo modification are often referred to by the umbrella term, climate engineering. Both of these concepts would act on the global surface–atmosphere radiation budget, but in very distinct ways, as

depicted in Figure 1.2. Greenhouse gas removal would decrease the amount of outgoing radiation that is trapped by greenhouse gases in the atmosphere, thus decreasing the downward flux of infrared radiation at the Earth’s surface. Planetary albedo modification, on the other hand, would increase the Earth’s natural reflection of solar radiation at various possible altitudes, as noted above.

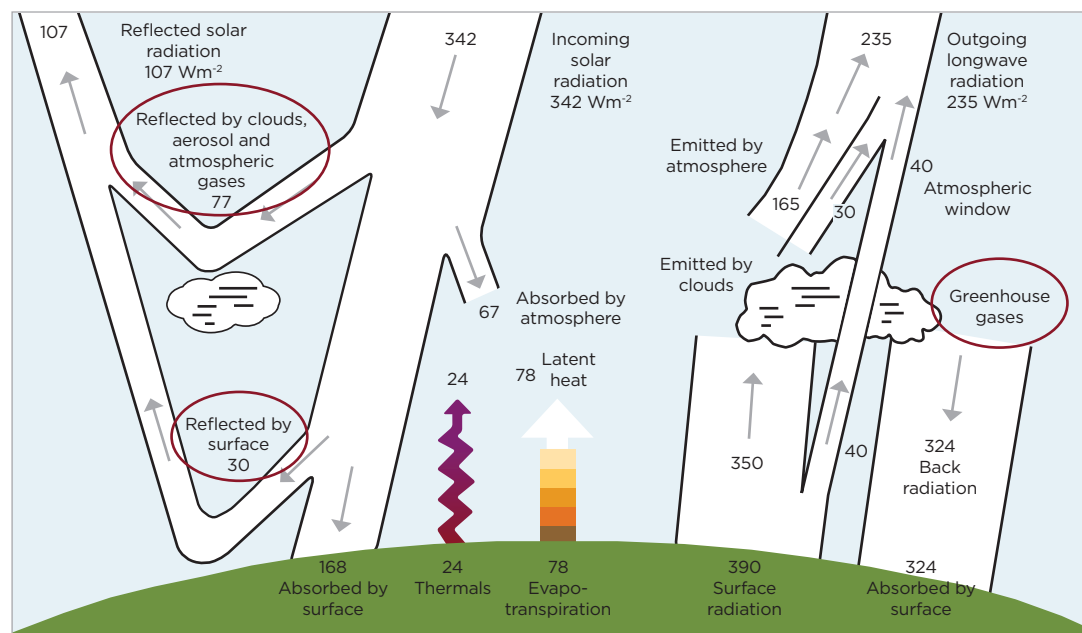


Figure 1.2:

Global surface–atmosphere solar and terrestrial radiation budget; solar radiation (largely visible) components are shown on the left, terrestrial radiation (largely infrared) components are on the right, and sensible and latent surface–atmosphere energy transfer are in the middle. Red-circled labels indicate the main foci of proposed climate engineering: removal of greenhouse gases, and increasing the planetary albedo, either at the surface, or via clouds or aerosol particles (space mirrors are not discussed in detail in this report and thus are not shown).

Source:

Adapted from Kiehl and Trenberth (1997).

Although this assessment focuses on the range of ideas being discussed under climate engineering, it is important to keep in mind that they are generally being considered within the broader context of mitigation and adaptation as the primary responses to climate change. Mitigation and adaptation are discussed extensively in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC).

Mitigation is defined by the IPCC as “technological change and substitution that reduce resource inputs and emissions per unit of output”, further specifying that “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, 2007a). This definition implies that methods aiming at reducing natural sources or enhancing natural sinks of CO₂ and other greenhouse gases can be considered to qualify as mitigation policies, and is consistent with the usage of this terminology by the UNFCCC. Therefore, techniques such as reforestation, afforestation, improved soil carbon sequestration, and enhanced weathering can, in principle, be classified as both mitigation and as climate engineering via greenhouse gas removal, depending on the definition of climate engineering that is being employed and, where appropriate, the scale of the intervention. Carbon capture and storage (CCS) usually refers to proposed mitigation technologies that would reduce CO₂ emissions directly at various sources, e.g., capturing CO₂ from flue gases of power plants, so is generally classified as mitigation (IPCC, 2005). However, in the sense that CCS would cause substantial modification of geological reservoirs if implemented at a scale that had a significant impact on the global atmospheric CO₂ burden, it is sometimes also classified as geoengineering (although usually not as climate engineering). CCS combined with bio-energy generation (BECCS) would remove CO₂ at the emission source, but can also be considered an enhancement of a natural sink (through vegetation). It accordingly sits at the boundary between mitigation and greenhouse gas removal. Removing CO₂ directly from the atmosphere is commonly referred to as “direct air capture” or “free air capture”, which is normally considered to be a type of climate engineering by greenhouse gas removal, distinct from mitigation efforts.

The fifth IPCC assessment report defines adaptation as the “process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects” (IPCC, 2014c). In its fourth assessment report, the IPCC (2007b) specified that “various types of adaptation exist”, and defined various axes such as “anticipatory and reactive”, “private and public”, and “autonomous and planned”. Key examples include raising and reinforcing dykes on rivers or coasts, and the substitution of plants sensitive to temperature shocks with more resilient species. Central to the concept of adaptation is the idea of reducing the vulnerability of natural and human systems to climate change through modification of these systems. Here, approaches such as whitening the facades and roofs of buildings are generally considered to be forms of adaption (to moderate the urban heat island effect), but if conducted on a sufficiently large scale they could also be classified as climate engineering by modifying the planetary albedo (Oleson et al., 2010; Akbari et al., 2009).

Whether an intervention into the Earth system qualifies as climate engineering is often considered to be a matter of intent and scale. Whilst some techniques can be considered either mitigation or climate engineering (or both), usually depending on their scale, it has been argued that the classification is not a purely technical matter; rather that the umbrella term climate engineering signifies that proposals for large-scale deliberate interventions into the Earth system deserve special scrutiny and attention (Jamieson, 2013). In this context, a general definition of climate engineering is proposed here, along with other terms used in this report, in Box 1.1. In the literature, the terms geoengineering and climate engineering are often used interchangeably with only subtle differences (as noted in the example above); the term climate engineering is adopted here, as it is more specific and the intent is more immediately apparent (Caldeira and Wood, 2008; Feichter and Leisner, 2009; GAO, 2011; Vaughan and Lenton, 2011; Rickels et al., 2011).



Definition of terms for responses to climate change

Box 1.1

EuTRACE term	Definition
Mitigation	Initiatives and measures to reduce or prevent anthropogenic emissions of climate-forcing agents into the atmosphere.
Adaptation	The process of adjustment to actual or expected climate; seeks to moderate or avoid harm or to exploit beneficial opportunities.
Climate Engineering (or Geoengineering)	A collective term for a wide range of proposed techniques that could potentially be used to deliberately counteract climate change by either directly modifying the climate itself or by making targeted changes to the composition of the atmosphere, without seeking to reduce anthropogenic emissions of greenhouse gases or other warming agents.
Greenhouse Gas Removal	Removal of atmospheric CO ₂ and other long-lived greenhouse gases.
Albedo Modification	Deliberate modification of incoming solar or outgoing terrestrial radiation on a regional to global scale.

The broad definition of climate engineering has been widely adopted and there is general agreement on many of the techniques that it should encompass. However, it is important to realise that the application of the blanket term can sometimes be misleading, and that there are limits to the applicability of general statements on climate engineering, since the effects, side effects, associated risks, ethical dimensions, and the economic, social, and political contexts differ greatly for each of the various climate engineering techniques (Heyward, 2013; Boucher et al., 2014). As a result, many arguments only apply to a sub-set of the techniques or to single techniques, and the research community faces the challenge of carefully differenti-

ating between the various climate engineering techniques and their implications in their analyses, as well as elucidating commonalities that justify the judicious use of the blanket term. The individual techniques are distinguished carefully in the report, and are generalised to either classes of climate engineering (i.e., greenhouse gas removal or albedo modification and related techniques) or to climate engineering as a whole only where appropriate. In some contexts the term climate engineering is applied, but only refers to one particular type or technique, in which case an appropriate modifier is applied (e.g., “climate engineering by greenhouse gas removal”, or “climate engineering by stratospheric aerosol injection”).

In order to help elucidate several of the physical and societal considerations associated with climate engineering more clearly and concretely, three selected techniques are discussed in greater detail. Two of these are techniques for greenhouse gas removal – bioenergy with carbon capture and storage (BECCS) and ocean iron fertilisation (OIF) – and the other is a technique for modifying the Earth’s albedo – stratospheric aerosol injection (SAI). These techniques were chosen for several reasons. They are among the most discussed techniques in the literature and in the broader socio-political context, including some of the most advanced governance discussions and – especially for OIF – the most advanced actual governance developments, as well as the most extensive field experimentation. They include one land-based, one ocean-based, and one atmosphere-based technique. They encompass techniques that could potentially be confined to small areas (BECCS), and thus are not always considered to be a climate engineering technique, and others that are transboundary in nature (OIF and SAI). They are currently at very different stages of research, as well as technological and governance development, and their presumed levels of effectiveness and potential risks also differ widely.

BECCS is a technique that fits the definitions given above for both mitigation and climate engineering. It was also included in the future climate change scenarios of the IPCC Fifth Assessment Report (Moss et al., 2008). Of particular importance, the only IPCC scenario with more than 50% probability of meeting the internationally agreed target of limiting mean global temperature rise to less than 2°C includes widespread use of BECCS in the second half of the 21st century.

OIF is a greenhouse gas removal technique that has received attention since natural variations in oceanic iron supply were first postulated to have played a role in glacial–interglacial changes in atmospheric CO₂ (Martin et al., 1990). More than a dozen field tests since the 1990s have consistently shown that, under specific circumstances, a small input of iron can have a large effect on iron-limited ocean ecosystems, producing large plankton blooms that might carry carbon to depth, although a large and long-term iron input would also perturb these ecosystems in ways that are difficult to foresee. Research over the past two dec-

ades has generally shown that OIF may have only a limited effect on atmospheric CO₂ concentrations (Boyd et al., 2007; Buesseler et al., 2008). However, OIF is still being considered and pursued by some as a possible means to remove excess CO₂ from the atmosphere, and is an interesting case study. This is especially relevant from the perspective of governance, since examination of past developments on OIF may yield insights into more general governance aspects of climate engineering (in both its main forms), since OIF has received the most regulatory attention, especially through the London Convention and London Protocol (LC/LP), as described in Section 4.1.2.

SAI is the albedo modification technique that is currently receiving the most attention. The goal of this technique is to create an effect roughly analogous to that of a large volcanic eruption, i.e., a cooling of the planet through the reflection of sunlight by aerosols in the stratosphere (Crutzen, 2006, Budyko, 1974), although with different timing and geographical distribution. If delivery and dispersal of particles were to prove technically feasible and politically implementable, SAI could induce a rapid cooling effect on the climate. It is thus often referred to as a “high-leverage” technique (Keith et al., 2010), which could have a large effect over a short period of time, potentially at a relatively low cost (Robock et al., 2010; McClellan et al., 2012). However, SAI and all other albedo modification techniques could not reverse the effects of elevated GHG concentrations, but would instead change the climate in ways that might reduce some climate impacts, not affect others, and potentially introduce new risks (Rasch et al., 2008; Robock et al., 2008; Tilmes et al., 2009).

1.3 Understanding climate engineering: the role of scenarios and numerical climate modelling

Our understanding of most of the physical effects of climate engineering primarily comes from theoretical and modelling studies. For most techniques, dedicated field tests have not been carried out. In addition, many details of the effects of full-scale deployment cannot be scaled up or anticipated from small-scale field tests. This section describes some of the modelling tools used to understand the potential effects of

greenhouse gas removal and albedo modification techniques on the Earth system.

Coupled Atmosphere–Ocean General Circulation Models (AOGCMs), often simply called “climate models”, have been the standard tool for studying climate variability and climate change since the 1990s. In the last decade, Earth System Models (ESMs) have also become common; these add the treatment of the carbon cycle and other large-scale processes to the AOGCMs. These global models are used to make projections of how the climate system will evolve in the coming century and beyond. The projections of these models are supported by a range of other modelling tools, from process models such as cloud-resolving models that help to improve the understanding of cloud feedbacks, to impact models such as crop models that evaluate the effects of climate change on crop yield. The communities working on modelling climate change are well developed and coordinated, and through projects such as the Coupled Model Inter-comparison Project (CMIP), where many AOGCMs are compared systematically, they work together to better understand the model projections and their uncertainties, forming the basis for the assessments that are carried out in the WG1 contributions to the IPCC reports.

The evaluation of the potential climate effects of greenhouse gas removal and albedo modification techniques is not as mature as the evaluation of anthropogenic climate change, but draws on the same tools and knowledge base. Greenhouse gas removal and albedo modification are fundamentally different in terms of their effects on the Earth system. Removing greenhouse gases from the atmosphere would reduce their concentration, or at least their rate of increase, indirectly reducing the amount of global warming, whereas modifying the planetary albedo would alter the climate directly. There has been little work on the detailed climate and Earth system consequences of greenhouse gas removal in general and only a few studies focused on specific techniques, e.g., afforestation (Ornstein et al., 2009; Swann et al., 2010). This is in part because the effects of greenhouse gas removal do not differ much from the effects of mitigation, as both approaches would alter the concentrations of greenhouse gases in the atmosphere. However, greenhouse gas removal enables scenarios

that include negative net global emissions of CO₂. This would allow concentrations of CO₂ to decline much faster than by means of natural processes. Some studies have investigated the climate consequences of such peak-and-decline scenarios (Boucher et al., 2012).

Since implementing an albedo modification technique would constitute a direct modification of the climate with the intention of reducing the impacts of climate change, evaluating of the consequences for the climate and the Earth system is critical to understanding the potential utility and risks. This understanding and the related decision-making process will eventually rely on effective detection and attribution of the impacts of any albedo modification technique, which presents challenges such as those discussed in Box 1.2. The observational component of detection and attribution will also depend on a complementary contribution from model analyses.

Thus far, most modelling studies have not yet focused on the specific issue of detection and attribution, but rather on the range of consequences of various albedo modification techniques for the climate and Earth system. These comprise both idealised model simulations that improve our understanding of the basic response to albedo modification (Lunt et al., 2008; Irvine et al., 2011; Kravitz et al., 2013a) as well as more realistic deployment scenarios to understand potential impacts in context. This can be achieved, for example, by using the scenarios employed in the IPCC assessments as a baseline and then applying albedo modification to achieve a specific temperature or radiative forcing target (Kravitz et al., 2011; Niemeier et al., 2013). The Geoengineering Model Intercomparison Project (GeoMIP) (Kravitz et al., 2013a; Kravitz et al., 2011), and prior to that the EU FP7 Project IMPLICC (Implications and Risks of Engineering Solar Radiation to Limit Climate Change (Schmidt et al., 2012b)), attempted to systematise this investigation, where a number of albedo modification experiments were conducted in the same way by many modelling groups in order to develop a better understanding of the projections and their uncertainties.

These modelling efforts have also been supported by detailed process studies investigating smaller-scale processes, for example with detailed cloud-resolving models and aerosol models (Cirisan et al., 2013;

Jenkins et al., 2013). The understanding of the potential climate consequences of SAI and a number of other albedo modification techniques is currently limited by various uncertainties, such as how the small-scale aerosol microphysical processes, upon which SAI depends, scale up to the global scale, especially since many global models involve relatively simplistic treatments of these processes. Additionally, to date, there has been no detailed and systematic evaluation of the range of impacts of various forms of albedo modification on other components of the Earth system besides climate. This makes the evaluation of these techniques incomplete, although there are a number of notable studies on the impacts of albedo modification on crop yields and sea level rise (Moore et al., 2010; Irvine et al., 2012; Pongratz et al., 2012). The results of these modelling efforts are assessed in Chapter 2.

The consequences of greenhouse gas removal and albedo modification techniques will depend on the manner and the context in which they might eventually be deployed. To determine possible evolution pathways of population, energy demand, and the other aspects of the social and economic spheres as they relate to climate, future scenarios are often used, such as the Representative Concentration Pathways (RCPs) used in the IPCC's Fifth Assessment Report (AR5) (Meinshausen et al., 2011; van Vuuren et al., 2011a). The RCP scenarios were developed via broad, interdisciplinary collaboration and represent coherent scenarios for policy and technology development, constrained by an understanding of available resources that outline possible futures. For the scenario with the lowest projected temperature increase by 2100, RCP2.6, large-scale afforestation and BECCS is assumed for the second half of the 21st century. These are a necessary part of the scenarios to achieve negative net global emissions of CO₂, making it possible to reduce the atmospheric concentration of CO₂ much more quickly than through natural processes.

Box 1.2

Detection and attribution of albedo modification consequences

One of the greatest challenges for climate science has been to robustly detect and attribute the consequences of human actions on the climate system (Barnett et al., 1999; Stone et al., 2009; Bindoff et al., 2013). The role of anthropogenic influences on the observed changes in surface air temperature at the global and continental scales can now be clearly attributed (Bindoff et al., 2013). However, explicitly detecting and then attributing changes at smaller spatial scales and for other climate variables has proven challenging, due to uncertainties in climate models as well as uncertainties in the magnitude of anthropogenic influences (e.g., emissions of various greenhouse gases and aerosol particles), and most importantly due to the large internal variability of the climate system (Stott et al., 2010; Bindoff et al., 2013).

These same difficulties would be faced when attempting to detect and attribute the consequences of an albedo modification intervention. This means that it could take years or even decades to detect and attribute the effect of albedo modification on global mean temperatures, and longer still for changes at smaller spatial scales and for more variable climate parameters such as precipitation patterns and extreme weather events (MacMynowski et al., 2011; Bindoff et al., 2013). The difficulty of attribution poses many challenges for governance, especially in the context of compensation and liability (Svoboda and Irvine, 2014).

1.4 Historical context and overview of this report

This report presents the results of EuTRACE (the European Transdisciplinary Assessment of Climate Engineering), a project funded by the European Union's 7th Framework Programme, assessing from a European perspective the current state of knowledge about the techniques subsumed under the umbrella term climate engineering. It brings together scientists from 14 partner institutions across Europe, with expertise in disciplines ranging from Earth sciences to economics, political science, law, and philosophy.

This assessment follows several other assessments, starting with the 2009 assessment report by the Royal Society (Shepherd et al., 2009). While some of the techniques presently being discussed have received some limited attention over several decades, the current wave of interest was sparked by a few developments, including a series of open ocean experiments to examine the potential of ocean iron fertilisation for reducing atmospheric CO₂, along with the 2006 publication of a special section of the journal *Climatic Change*, in which Nobel laureate Paul Crutzen contributed the lead essay (Crutzen, 2006). In the essay, Crutzen asked whether introducing reflective particles into the stratosphere to cool the planet could contribute to resolving the policy dilemma that states face when reducing certain types of pollution, especially sulphate aerosol particles, which mask warming.

While the ocean iron fertilisation experiments and the essays in *Climatic Change* clearly focused on particular techniques, the discussion quickly broadened to cover other possible means to achieve “deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change” (Shepherd et al., 2009).

This assessment report moves the discussion forward in several respects. For one, in a field with such a rapidly-evolving literature base and global discussions, regular assessments are important for tying in the different strands of literature and debate, and providing accessible compilations of the state of the art. A number of recent activities have moved the field forward, including progress in the Geoengineering Model Intercomparison Project (GeoMIP), building

partly on the EU FP7 project IMPLICC; the advances made by the LC/LP in the regulation of marine climate engineering activities; planning of the first field campaigns for atmospheric albedo modification techniques; publication of the IPCC's Fifth Assessment Report; and a host of workshops, mostly in Europe and North America, but also a few in other parts of the world, e.g., those organised by the Solar Radiation Management Governance Initiative (SRMGI). Through the large and interdisciplinary composition of the EuTRACE project consortium, this report is able to capture a broad range of perspectives across disciplines and reflect on the field's development through all of them. The report is also the first to reflect on the field from a particularly European perspective, especially in its analysis of existing governance and possible policy options. Based on a strong focus on ethical considerations, the report analyses research needs and policy options at an important point in the development of individual climate engineering techniques and their governance.

Within this broader context, the EuTRACE assessment is intended to provide valuable support to the European Commission and the broader policy and research community in the assessment of climate engineering, including the development of governance for research and the potential deployment of various techniques. This first chapter of the assessment report has provided an overview of climate engineering, particularly placing it in the context of climate change. Chapter 2 describes the individual techniques that have been proposed for greenhouse gas removal and albedo modification. The state of scientific understanding and technology development is outlined, including a brief discussion of what is known about the potential operational costs of individual techniques, with consideration of the uncertainties around all of these factors.

Beyond the challenges of understanding and controlling the impacts on the Earth system, the different techniques present great challenges in the social, ethical, legal, and political domains. Chapter 3 considers several of these issues that have informed this debate, such as: the possible influence of climate engineering techniques on mitigation and adaptation efforts; how these techniques are perceived by the public; their conflict potential, economic aspects, distributional

effects, and compensation issues; as well as implications for governance. Chapter 4 then considers the current regulatory and governance landscape with a particular focus on EU law, while taking into account and discussing the wider developments at the international level. Chapter 5 outlines major knowledge gaps and provides options for future research, as a guide for how the European Commission might approach funding decisions for future research on climate engineering. Finally, Chapter 6 illustrates how policy options can be developed and justified, based on the principles that underlie EU law in its application to climate engineering (as identified in Chapter 4), the extensive basic knowledge of the science and technologies that are fundamental to the various climate engineering approaches (as described in Chapter 2), and the multiple concerns that climate engineering raises (as discussed in Chapter 3). Conscientious application of such an approach, based on the principles embodied in existing legal and regulatory structures, the scientific state of the art, and the concerns raised in connection with climate engineering, may help lead to the development of European policies, on research and the potential future implementation of climate engineering techniques, that are coherent and consistent with the basic principles upon which broader European research and environmental policy are built.

2. Characteristics of techniques to remove greenhouse gases or to modify planetary albedo

This chapter provides an overview of the currently most discussed options to remove CO₂ from the atmosphere or to increase the planetary albedo to reflect more sunlight back into space. The chapter assesses the technical feasibility, potential environmental consequences, current knowledge of the operational costs, and the various uncertainties associated with the main proposals for greenhouse gas removal (Section 2.2) and albedo modification (Section 2.3). With regard to costs, it is worth noting that only the operational costs (installation and maintenance) will be discussed here; this is only one of three basic types of costs, along with price effects and social costs, which are discussed in more detail in Section 3.2.2.1. For each greenhouse gas removal and albedo modification technique discussed, the current state of knowledge of the effectiveness and impacts specific to that technique is summarised, while some impacts that are common to all of these techniques are discussed in sections 2.1.9 (for greenhouse gas removal) and 2.2.7 (for albedo modification).

2.1 Greenhouse gas removal

Proposed methods for the removal and long-term sequestration of CO₂ and other greenhouse gases from the atmosphere range from those with primarily domestic influence that have minor consequences outside a given domain (except for the small global reduction in the atmospheric greenhouse gas concen-

trations), to those with transboundary influences on the environment and on global economics, and thus on global societies.

In this section, the full range of techniques that are primarily being discussed for greenhouse gas removal are considered, both terrestrial and marine, as well as biotic and chemical. Among the primarily terrestrial biotic techniques are afforestation, BECCS, biochar, and additional biomass techniques; the main terrestrial chemical technique is direct air capture, while enhanced weathering is both terrestrial and marine; finally, two techniques are considered that would aim to increase the rate of carbon transfer to the deep ocean, with ocean fertilization involving the “biological pump”, and artificial upwelling involving the “physical pump”. The remaining chapters focus mainly on BECCS and OIF as two example techniques that have very different implications. In the case of BECCS, scale plays an important role. For example, small-scale application of BECCS utilising waste biomass that is obtained from the same national jurisdiction likely has few transboundary consequences, whereas larger-scale applications using biomass grown specifically for the purpose and purchased on the global market will have transboundary consequences for the global economy, even if the actual application remains domestically confined. In contrast, ocean fertilisation purposely modifies systems in the global commons, and thus qualifies as

transboundary regardless of the scale of application. Overall, the processes involved in many techniques are by nature transboundary, or become transboundary if they involve global markets, and it is very likely that all methods of greenhouse gas removal will have at least some transboundary impacts (beyond the climate and other impacts of reduced concentrations of greenhouse gases such as CO₂) if applied at a sufficiently large scale to have noticeable effects on global atmospheric greenhouse gas concentrations. For CO₂, this would require a removal rate comparable to that of current global emissions, which now exceeds 30 Gt CO₂/yr (IPCC, 2013a).

2.1.1 Afforestation

Description: Removing CO₂ by afforestation would enhance the terrestrial carbon sink by increasing forest cover and/or density in unforested or deforested areas.

Effectiveness: Estimates of both the annual and the overall carbon uptake potential of afforestation vary widely. An estimate based on the physical potential might consider regrowth of all deforested regions (around 660±290 Gt C) (IPCC, 2014c). However, such deployment is incompatible with current and projected land-use demand (Powell and Lenton, 2012), which reduces the estimates for global deployment of afforestation to around 1.5–3 Gt CO₂/yr (Shepherd et al., 2009) including a reduction in the rates of deforestation. Consideration of the “payback period” from any biomass or soil carbon loss during planting is also required (Jandl et al., 2007). Cost estimates in the literature vary widely as a consequence of differing and largely incomparable assessment criteria and methods. Afforestation is, technically, the simplest method of greenhouse gas removal to undertake, if carried out in regions with favourable conditions; however, the resulting carbon storage would be temporary, lasting only as long as the afforested regions are continually protected or managed, and would therefore be vulnerable to changes in the environment (e.g., fire, disease), climate (e.g., drought), and society (e.g., demands for wood or land). Afforestation potential is principally limited by the availability of land that is fertile, irrigated, and socially acceptable for afforestation.

Impacts: The impacts of afforestation include land-use

competition, environmental impacts (e.g., water consumption), possible ecosystem degradation where commercial forestry approaches are applied (e.g., non-native species, pest-control), societal impacts of landscape and usage change (e.g., access to fuel), and climatic impacts such as reduced albedo (depending on geographic location), which could even lead to a net warming despite the additional sequestering of CO₂, along with evaporative effects on the hydrological cycle including cloud formation (Bonan, 2008).

2.1.2 Biomass energy with carbon capture and storage (BECCS)

Description: BECCS is a proposed greenhouse gas removal technique that would combine carbon capture and storage (CCS) technology with biomass burning. The biomass, produced using energy from sunlight for photosynthesis, would draw its carbon source from CO₂ in the air. Any carbon that is then captured in the high-CO₂-concentration stream of the biomass burning exhaust gas, and subsequently sequestered, would thus effectively remove CO₂ from the atmosphere.

BECCS already figures prominently in the work on future emissions scenarios, as depicted in Figure 2.1. However, as can be seen in the figure, various scenarios currently differ substantially in their assumptions about the role of BECCs, which is in turn partly influenced by differing assumptions about the role of CCS combined with conventional technologies such as coal, oil, and natural gas burning.

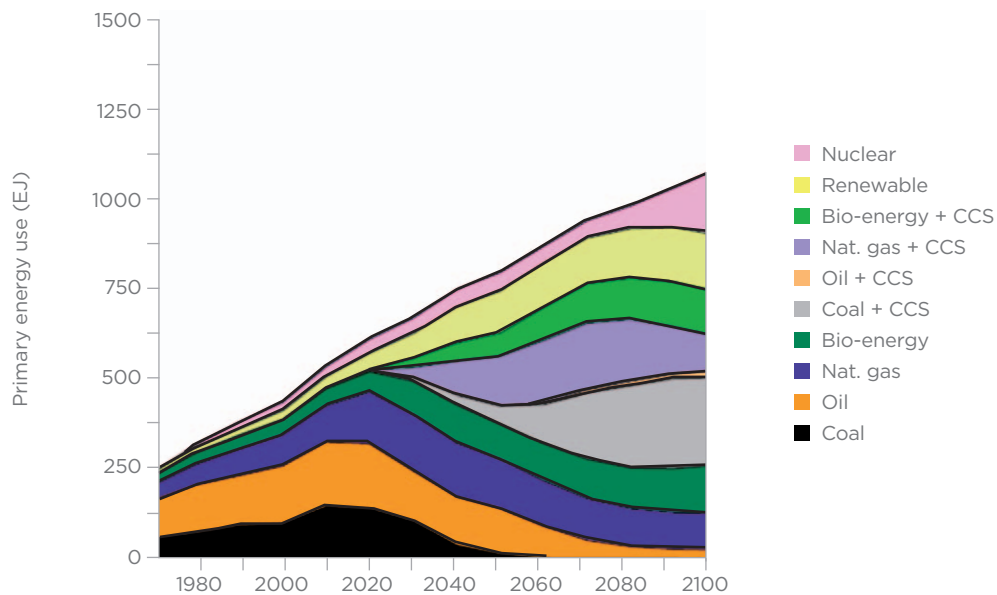


Figure 2.1:

Contributions of various technologies and changes in end-use to two mitigation scenarios. A significant role is assumed for BECCS in both scenarios (bright green in the top panel, turquoise in the bottom panel), especially in enabling net emissions to potentially go below zero in the second half of the century, but with notable differences in the relative role of BECCS in each scenario.

Top panel: for the RCP2.6 scenario from the IPCC Fifth Assessment Report.

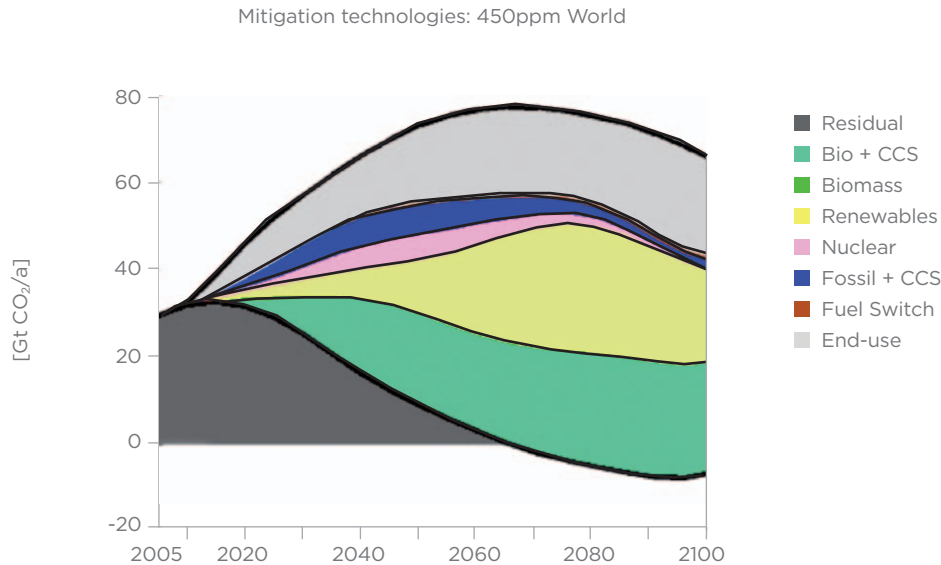
Source:

Van Vuuren et al. (2011b);

Bottom panel: from a scenario for limiting long-term global mean CO₂ mixing ratios to 450 ppm.

Source:

Luderer et al. (2012).



Nevertheless, despite these differences, many scenarios share the common feature of assuming some form of greenhouse gas removal. A study by Fuss et al. (2014) found that 87% (101 out of 116) of the scenarios that result in “...concentration levels of 430–480 ppm CO₂ equivalent (CO₂eq), consistent with limiting warming below 2°C, require global net negative emissions in the second half of this century, as do many scenarios (235 of 653) that reach between 480 and 720 ppm CO₂eq in 2100”. Accordingly, in these scenarios, limiting global mean warming to less than 2°C would generally require some form of what is currently thought of as climate engineering by greenhouse gas removal.

Within this context, as can be seen in Figure 2.1, considerable hopes are being placed in BECCS as a substantial component of many scenarios for keeping global mean warming below 2°C. However, there are also strong doubts about BECCS; for instance, Fuss et al. (2014) prominently conclude that “...its credibility as a climate change mitigation option is unproven and its widespread deployment in climate stabilization scenarios might become a dangerous distraction”. Thus, due to these contrasting perspectives and the prominence it already has in current scenarios of future emission pathways, BECCS warrants particular attention among the techniques being considered for climate engineering by greenhouse gas removal, and as noted in Section 1.2 it will be a particular focus of the following chapters. This section provides a basis for that later discussion by summarizing the basic current understanding of the potentials and limitations of BECCS.

In BECCS, the burning of biomass would be used either for electricity generation or in bio-ethanol production. Bio-ethanol production for transportation is well developed, with an annual global production of 85 billion litres (International Energy Agency, 2011). Bio-ethanol production by fermentation produces a relatively pure CO₂ waste stream that can be captured and compressed for geological storage. The first large-scale project combining bio-ethanol production with CCS is underway at the ADM Decatur ethanol plant in Illinois, USA (see Box 3.4). Electricity generation by co-firing a small proportion of biomass (typically around 3% of energy input) mixed into coal feedstock is widespread in large coal power plants where sup-

port incentives exist – biomass accounted for 1.5% of global electricity generation in power plants in 2010 (International Energy Agency, 2012). Biomass has a lower energy density than coal (30–80% less for wood pellets compared to steam coal) (International Energy Agency, 2012), although power plants using 100% biomass have been operated, such as RWE Tilbury (UK) (RWE, 2012). Appropriately processed bio-methane can be added to the natural gas pipeline network for co-firing in gas power plants (Weiland, 2010). CO₂ capture from biomass burning (including co-firing) can be adapted to existing CO₂ capture technologies but introduces additional considerations such as impurity variation and greater flue gas volume for post-combustion capture, managing tars released during gasification, and more variable combustion properties in oxyfiring (International Energy Agency GHG R&D Programme, 2009).

Effectiveness: Possible scales of deployment of both bio-ethanol and biomass power generation with CCS are limited by three main factors:

- biomass availability and the sustainability of intensive, large-scale agricultural practices;
- the amount of infrastructure available and/or that could be built for CCS (Luckow et al., 2010), along with the energy requirements for running the infrastructure; and
- long-term CO₂ storage availability, noting that geological storage of captured CO₂ offers possible CO₂ removal on an “effectively permanent” timescale.

The availability of biomass for BECCS (as well as for other biomass-based techniques) is subject to many technical, climatic, and societal factors. Estimates of sustainable biomass supply differ by orders of magnitude, resulting from differing assumptions around biomass types, bio-technology development, future climatic conditions and food demand, and the availability of land, water, and nutrients, future climatic conditions, and food demand (Bauen et al., 2009; Berndes et al., 2003; Dornburg et al., 2010). Higher estimates of potential removal of atmospheric CO₂ by terrestrial biomass-based techniques likely require conversion of agricultural land or carbon-rich ecosystems for biomass crops, and/or massive application of fertiliser.

In addition to considerations of the payback period and soil carbon availability, the purposeful increase in biomass for greenhouse gas removal will likely have both environmental (for example, ecosystem change) and climatic effects (due to changes in regional albedo and in the hydrological cycle), which may constrain deployment and limit the cooling effect on the climate. However, in the immediate future, the primary limitations on terrestrial biomass availability will likely result from dietary choices and the efficiency of food production (Powell and Lenton, 2012). Upper limit estimates of the potential of terrestrial biomass-based methods generally presume that all biomass that is potentially available for CO₂ removal will be used specifically for that purpose. Therefore, upper limit estimates of the amount of CO₂ that can be removed by methods that use biomass are not additive, although there is likely some potential for overlap, for example turning waste from biomass for biofuel production into biochar. The most feasible and effective method will likely vary according to regional considerations.

Regarding CCS infrastructure, CO₂ capture techniques are diverse (Fennell et al., 2014). Some techniques, such as amine solvent capture, have been understood well industrially since the 1920s, but require up to 25% of the energy output from a power plant. Such approaches can still achieve an overall carbon capture efficiency of 90–95%, including the CO₂ emitted from the additional fuel required to maintain the same total power output. Newer techniques, such as IGCC (integrated gasification combined cycle) have an energy penalty of only 1%, and are now starting to be built at commercial scale. Research techniques such as oxycombustion, chemical looping, and cryogenic cycles are under active development and hold the promise of capture penalties of only a few percent, along with possible improvements in the efficiency of CO₂ capture.

Issues around the long-term storage of CO₂ are discussed below, in Section 2.1.9.2.

Finally, cost estimates range widely due to differing methodologies, assumptions around the value of the product (electricity, transport fuel), and the potential for cost reduction via improved CO₂ capture technologies. CCS deployment presently lags considerably

behind that envisaged in CO₂ emission reduction strategies (Scott et al., 2013). Estimates vary widely for the deployment timescale of BECCS and the potential for greenhouse gas removal (2.5–10 Gt CO₂/yr), with higher values requiring considerable conversion of land to grow feedstock (McGlashan et al., 2012).

Impacts: The impacts include land-use and water supply competition, local environmental degradation associated with industrial agriculture and biofuel production facilities, and prolonged use of coal if the power plants are co-fired.

2.1.3 Biochar

Description: Greenhouse gas removal through biochar aims to increase the longevity of biomass carbon through conversion to a more stable form (char) combined with burial or ploughing into agricultural soils. Char is produced by medium-temperature pyrolysis (>350°C) or high-temperature gasification (~900°C) of biomass in a low-oxygen environment. There are many varieties of biomass feedstock (defined by the US Department of Energy as “any renewable, biological material that can be used directly as a fuel, or converted to another form of fuel or energy product”; see www.energy.gov). Biomass feedstocks range from pelleted or chipped wood to agricultural residues and wastes, producing char with differing char yields and stable carbon fractions. Flammable syngas and bio-oil are co-produced with the char and might in turn be used for input energy to the production process (Lenton and Vaughan, 2013).

Effectiveness: Under current conditions, the potential for sustainable removal of CO₂ by biochar is estimated at a maximum of 3.5 Gt CO₂/yr, equivalent to sequestration of up to 350 Gt CO₂ over a century (Woolf et al., 2010). Application to all agricultural and grassland areas gives a technical long-term global potential of storing 1500 Gt CO₂ (Lehmann et al., 2006). The greenhouse gas removal potential of biochar is influenced by many factors, including feedstock production, handling losses, energy input, char yield, labile carbon fraction, and mean residence time of carbon (Hammond et al., 2011). Under conservative estimates for biochar yield (25% dry feedstock mass) and stable carbon fraction (50% over 100 years), sequestration of 0.46 t CO₂ (or 0.17 t C) per tonne of dry feedstock is

attainable, with higher values possible using better-optimised feedstock. Additional CO₂ uptake may also occur from increased vegetation productivity—bio-char can increase soil retention of moisture and plant-available nitrogen. Quantification of enhanced productivity, char-type specific influences, and accounting remain uncertain but are an active area of research. Cost estimates in the literature are within the range \$30–100 per tonne of CO₂ (Shackley and Sohi, 2011; McGlashan et al., 2012). Biochar potential is primarily limited by feedstock availability and logistical constraints on application. With a carbon residence time of decades to centuries, maintenance (re-application) is required. Char prior to burial could also be appropriated for use as fuel.

Impacts: The impacts include land-use competition, possible health risks from associated dust production, and the potential to reduce albedo by up to 80% on application and 20–26% post-harvest (Genesio et al., 2011), reducing the climate change mitigation effect by 13–22% (Meyer et al., 2012).

2.1.4 Additional biomass-based processes: non-forest, burial, use in construction, and algal CO₂ capture

Description and effectiveness: While forests have the greatest above-ground carbon density, several other techniques have significant potential for using terrestrial biomass for greenhouse gas removal, including modified agricultural practices and peatland carbon sink enhancement (Worrall et al., 2010; Freeman et al., 2012). Introduction of organic material (crop wastes, compost, manure) to agricultural land is widely practiced and might be increased to enhance soil carbon, but would only achieve a limited uptake, not exceeding 2 Gt CO₂/yr and the residence time of the carbon would be short (years to decades). The natural formation of peatland is slow (vertical accumulation of approximately 1 mm/yr). This sink might be enhanced by burying timber biomass in anoxic wetlands, but such approaches are logistically complex and the plausible scale is unknown (Freeman et al., 2012). A related possibility, with similar lack of knowledge about the plausible scale, is waste biomass burial in the deep ocean (Strand and Benford, 2009). A further sink for terrestrial biomass involves widespread use in construction, with a carbon residence of

decades to centuries, including both structural use (timber) and for insulation (e.g., straw); this has the additional benefit of displacing some CO₂ emissions from cement production (Gustavsson et al., 2006). The potential overall contribution, limited primarily by demand, is likely to be small (<1 Gt CO₂/yr). Finally, CO₂ could be captured from concentrated flue streams and directly from free air by using algae in bioreactors, or using organic enzymes as catalysts; these are areas of active research, although the costs and potential for deployment are presently ill-defined (Bao and Trachtenberg, 2006; Rahaman et al., 2011; Savile and Lalonde, 2011; Pires et al., 2012).

Other impacts: As with other processes that employ biomass, the impacts include land-use, water supply competition, and potential ecosystem alteration.

2.1.5 Direct air capture

Description: Greenhouse gas removal by direct air capture is currently being investigated in the context of scrubbing CO₂ from the atmosphere for subsequent long-term storage. Techniques that use biomass were mentioned in the previous section; non-biomass techniques are considered here. Two basic concepts are regularly proposed (Goeppert et al., 2012; McGlashan et al., 2012): adsorption onto solids and absorption into high-alkalinity solutions. In all cases, the three main challenges are: 1) overcoming the high thermodynamic barrier resulting from the low (0.04%) concentration of CO₂ in air, with a theoretical minimum of 500 MJ per tonne CO₂ (Socolow et al., 2011), which would be equivalent to approximately 500 GW (i.e., 500 large power plants) of continuous power supply to compensate current global CO₂ emissions; 2) sustaining sufficient airflow through the system; and 3) supplying additional energy for the compression of CO₂ for storage. Different proposals include using amine-based resins that adsorb CO₂ when ambient air moves across them, followed by release of concentrated CO₂ by hydration in a vacuum (Lackner, 2009), or mechanically driving air across sodium hydroxide produced via calcination of limestone, and subsequently heating the solvent to release the absorbed CO₂ (<http://carbonengineering.com/>, last accessed on 28 May 2015).

Effectiveness: The potential deployment scale is unknown. Should direct air capture processes reliably and economically work at scale, extraction of a few Gt CO₂/yr would be possible. However, since the capture of CO₂ from higher-concentration sources will generally be cheaper (Brandani, 2012), it is possible that direct air-capture, even if it becomes technologically feasible, may remain a niche technology (Bala and Nag, 2012). Cost estimates are contested and range widely. Proponents suggest around \$200 per tonne CO₂ for initial facilities and that the subsequent costs will drop by an order of magnitude (Lackner, 2009; Lackner et al., 2012). Other estimates are much higher: \$600 or more per tonne CO₂ (Socolow et al., 2011), or possibly of the order of \$1000 per tonne CO₂ (House et al., 2011). Resource requirement is unknown, but includes land-area, energy input, and geological CO₂ storage capacity. Other approaches include accelerated thermal degradation of CO₂ through catalysis using, for example, nickel (Bhaduri and Siller, 2013), synthesised enzymes (Bao and Trachtenberg, 2006), or exothermic reaction with lithium nitride (Hu and Huo, 2011). All of these proposals are in the very earliest stages of research. While activity is focused on CO₂, air-capture concepts might also be applied to other greenhouse gases, especially methane (Boucher and Folberth, 2010).

Other impacts: The impacts are unknown but likely include land-use conflicts, water supply, industrial development, and societal acceptance of large-scale CO₂ storage.

2.1.6 Enhanced weathering and increased ocean alkalinity

Description: In the pre-industrial carbon cycle, natural CO₂ emissions from volcanic sources were removed from the atmosphere, primarily by CO₂ reacting with minerals in rocks, a process known as chemical weathering. Erosive processes eventually bury these weathering products or transport them via rivers to the oceans, sequestering the carbon for geological timescales. The natural rate of weathering is less than one hundredth of the current rate of anthropogenic CO₂ emissions. Chemical methods for increasing the uptake and storage of carbon are based on artificially accelerating these weathering processes. These methods include dispersing mined, crushed, and ground silicate rocks (e.g., olivine) on land, preferably in

warm, humid tropical areas (Hartmann et al., 2013), or onto the sea surface (Köhler et al., 2013). Alternatively, silicates could be used to neutralise hydrochloric acid produced from seawater, thereby enabling additional CO₂ uptake by the ocean (House et al., 2007). The use of limestone has also been suggested, either by dispersion into upwelling regions (Harvey, 2008), or by heating it to produce lime (calcination), which would then be dispersed in the ocean to increase ocean alkalinity and promote additional CO₂ uptake (Kheshti, 1995). Alternatively, silicate materials might be developed to make cements that absorb CO₂ during setting (Shao et al., 2006).

Effectiveness: Due to an abundance of raw material, the physical potential of enhanced weathering is high. However, as the chemical reaction that captures one tonne of CO₂ requires one tonne of olivine, the scale of operations required to remove a substantial fraction of annual emissions would be huge – comparable to existing mining and distribution industries. Estimates for the technical potential of CO₂ uptake by dispersal of silicates range widely, from the Mt CO₂/yr range (Hartmann and Kempe, 2008) to a few Gt CO₂/yr (Köhler et al., 2010). Costs are very uncertain, with only one study estimating \$25–50 per tonne CO₂ (Köhler et al., 2010), but the potential range of costs is likely much larger, given the present lack of infrastructure developments and the potential limitations at full-scale operation. In particular, production of hydrochloric acid on an industrial scale requires large amounts of electricity, and similarly, lime production requires a heat source, along with capture and storage of the CO₂ released during the calcination process. The logistical limitations, similar to those for silicates, suggest that an uptake of at best a few Gt CO₂/yr might be achievable with large-scale deployment.

Other impacts: All methods would have impacts associated with the major mining, processing, and distribution operations. Silicate dispersal on land might result in alkalisation of water resources. Methods that increase global ocean alkalinity would nominally work favourably to counteract ocean acidification but other effects that have not yet been investigated might also be expected, resulting from the optical, chemical, and potentially harmful characteristics associated with the quantities of material involved and the mineral impurities they contain.

2.1.7 Ocean fertilisation, including ocean iron fertilisation (OIF)

Description: While the oceans only contain a small portion of the global biomass (1–2%), marine phytoplankton in the surface layers are responsible for about half of the planet's net primary productivity, the biological conversion of CO₂ into organic carbon (Groombridge and Jenkins, 2002). A small fraction of this biomass sinks to great depths or to the bottom of the ocean before remineralisation processes break down the organic material into CO₂, nutrients, and other chemicals. This transport of biomass carbon from the surface to the deep ocean is known as the “biological carbon pump” (Volk and Hoffert, 1985). Photosynthesis can only occur when there are sufficient macro- and micro-nutrients and sunlight. The distribution of the nutrients in the surface ocean depends on input from rivers, the atmosphere, and deeper waters. There are large areas of the surface ocean where phytoplankton growth is limited by a lack of nutrients such as nitrate and iron. In these regions, biological processes could theoretically be enhanced to increase oceanic carbon storage in the deep ocean by fertilising the water to stimulate phytoplankton growth and intensify the biological carbon pump. The removal of CO₂ from the surface waters then increases the net uptake of CO₂ into the ocean from the atmosphere through air–sea gas exchanges.

Effectiveness: In determining the effectiveness of ocean fertilisation, it is important to distinguish between the use of macronutrients (e.g., nitrate, phosphate) and the use of micronutrients (e.g., iron). For macronutrients, the same order of magnitude of mass is needed as the amount of exported CO₂ (i.e., of the order of one tonne of macronutrient per tonne of carbon), while for micronutrients, many orders of magnitude less mass would be needed, making them generally more attractive in terms of logistical considerations. Fertilisation with macronutrients obtained on land would thus necessitate enormous logistical and energetic investments and would compete with agriculture for the necessary nutrient supply. Consequently, most proposals for ocean fertilisation have focused on micronutrients.

The main micronutrient that has been proposed for fertilisation is iron. Ocean iron fertilisation is one of the three exemplary techniques that are primarily discussed throughout the rest of the report. OIF has particularly been proposed for large regions of the North Pacific, the Equatorial Pacific, and the Southern Ocean, where macronutrients are sufficient and the growth of phytoplankton is mainly limited by a lack of soluble iron. Natural evidence for this limitation is seen when blooms form, coinciding with large deposition episodes of iron-rich desert dust or volcanic ash (Olgun et al., 2013), as well as in regions of the Southern Ocean where natural fertilisation by iron-containing rock that dissolves in the wake of islands also causes phytoplankton blooms (Blain et al., 2007; Pollard, 2009).

Thirteen scientific experiments have been carried out since the early 1990s in the open ocean, with widely varying results. The experiments have shown that it is possible to induce plankton blooms in all three of the target regions, but that the connection between additional blooms on a small-to-medium scale and actual increases in CO₂ uptake and drawdown is very uncertain (Boyd et al., 2007; Buesseler et al., 2008; Williamson et al., 2012). For instance, in the LOHAFEX experiment in the Southern Ocean, phytoplankton were quickly consumed by grazers, which was attributed to the low silicate levels of the fertilised waters, leading to the formation of mostly soft-shelled plankton that limited the export of the sequestered carbon to relatively shallow depths where storage times are believed to be short (Martin et al., 2013). Fertilised blooms can also be rapidly diluted or fragmented by oceanic mixing. Model simulations suggest that the best location to achieve a sustained drawdown of CO₂ by iron fertilisation is the Southern Ocean, since fertilisation elsewhere would frequently lead to the depletion of macronutrients, thereby limiting phytoplankton growth (Sarmiento et al., 2010). The only study to demonstrate a substantial increase of CO₂ uptake and export to the deep waters was EISENEX (Smetacek et al., 2012), in which fertilisation was carried out in a closed gyre that remained intact for a few weeks following initial fertilisation, giving time to observe the sedimentation of biomass through the ocean mixed layer. Model computations of large-scale iron fertilisation in the Southern Ocean indicate that the additional carbon export to the deep ocean could offset

CO₂ emissions of about 70 Gt(C) during a 100-year period of continuous fertilisation (Oschlies et al., 2010a). Total carbon uptake is strongly dependent on the duration of fertilization, as shown in Figure 2.2. Based on early indications of its potential effective-

ness, patents have been filed for various methods of iron fertilisation (Howard Jr. et al., 1999; Maruzama et al., 2000; Lee, 2008) and for a monitoring method (Suzuki, 2005).

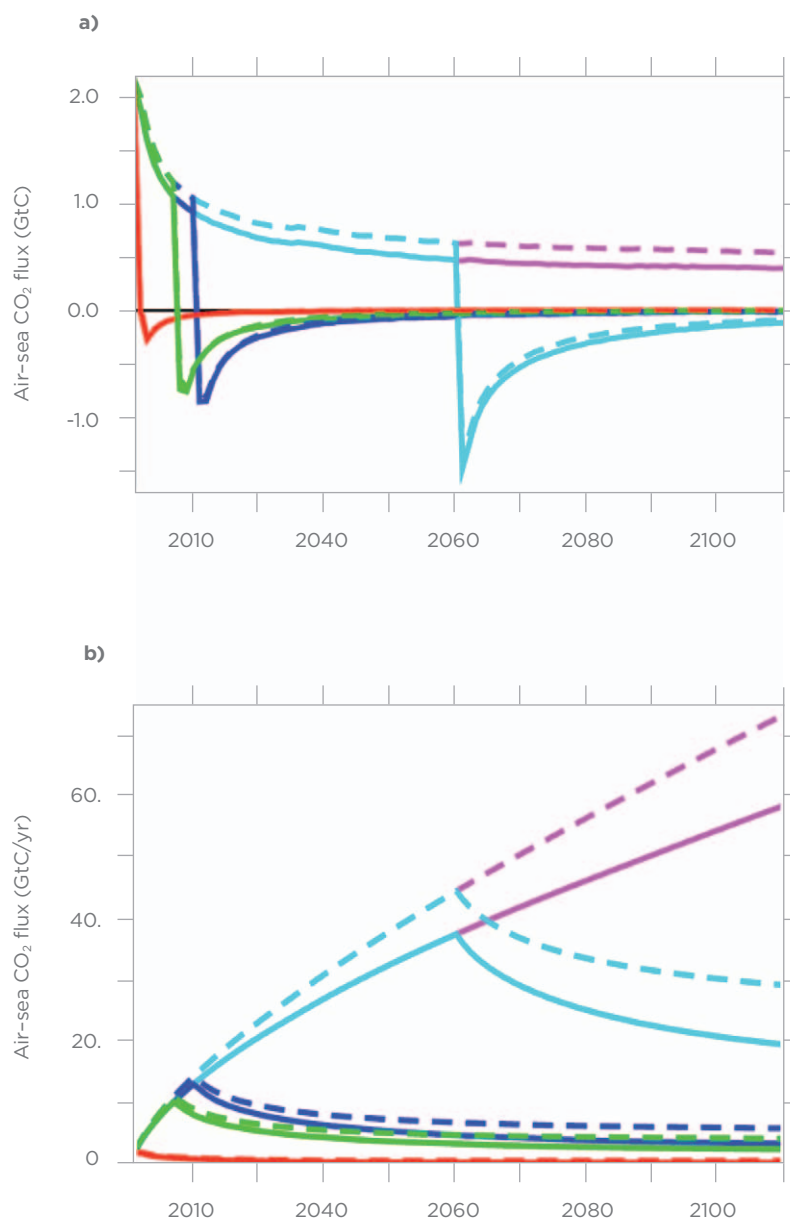


Figure 2.2:

(a) Simulated fertilisation-induced annual air-sea CO₂ flux south of 30°S (dashed lines) and integrated over the global ocean (solid lines). Units are Gt C/yr.

(b) Simulated cumulative temporal integral of the fertilisation-induced change in air-sea flux of CO₂ south of 30°S (dashed lines) and for the global ocean (solid lines); units are Gt C. Coloured lines refer to the different fertilisation experiments: stopping fertilisation after 1 year (red), 7 years (green), 10 years (blue), 50 years (cyan), and not at all within the first 100 years (magenta).

Source:

Oschlies et al. (2010a).

In addition to fertilisation by dissolution of micronutrients such as iron, it has also been proposed to use macronutrients that are already dissolved in the deep ocean, via enhancing the upwelling of nutrient-rich water from a depth of several hundred meters, employing methods such as wave-driven pump systems (Lovelock and Rapley, 2007). This is distinct in purpose from the artificial upwelling discussed in the next section, since the focus here is on enhancing nutrients for biological uptake, whereas in the next section the focus is on enhancing physical uptake of CO_2 . Model calculations show that pumping deep water upwards would be expected to result in phytoplankton blooms, thus leading to increased oceanic drawdown of CO_2 . However, even assuming an optimum distribution of perfectly functioning pump systems, the sequestration potential is low, estimated at about 0.5 Gt CO_2/yr (Yool et al., 2009). A complication arises because nutrient-rich deep water is generally also enriched in CO_2 compared to less nutrient-rich water, since both nutrients and CO_2 arise from the re-mineralisation of organic material. However, since the older, deeper waters have not been in recent contact with rapidly rising atmospheric CO_2 concentrations, they still may be undersaturated with respect to today's elevated atmospheric CO_2 levels, and thus take up some anthropogenic CO_2 in addition to the CO_2 sequestered via enhanced phytoplankton productivity (Oschlies et al., 2010b). The potential use of artificial upwelling to increase CO_2 uptake is discussed further in Section 2.1.8.

Other impacts: The effects of manipulating ocean ecosystems on large scales are not restricted to carbon export, and several side effects and difficulties of potential implementation have been pointed out (Chisholm et al., 2001; Lawrence, 2002; Strong et al., 2009b). Most significantly, ocean fertilisation would alter the productivity of large regions of the ocean (Gnanadesikan et al., 2003) and since plankton form the base of the marine food chain (Denman, 2008), significant side effects on marine ecosystems could be expected. In addition to the marine biological effects, ocean fertilisation would also be expected to lead to enhanced oxygen consumption at depth and to increases in marine emissions of various trace gases (Jin and Gruber, 2003; Lawrence, 2002). Most important among these is nitrous oxide (N_2O), which is formed as a by-product of increased remineralisation,

especially by bacteria in sub-surface waters that become depleted of oxygen due to the increased through-flux of biological material. N_2O has high global warming potential (GWP), approximately 300 on a 100-year time horizon, which could partly counteract the cooling from the removal of CO_2 , depending on the region, timing, and intensity of fertilisation (Jin and Gruber, 2003; Oschlies et al., 2010a). Further impacts include possible increases in toxic phytoplankton blooms (Trick et al., 2010). Given the current level of scientific understanding, it is not yet possible to confidently predict the long-term effects of large-scale ocean fertilisation (Wallace et al., 2010).

2.1.8 Enhancing physical oceanic carbon uptake through artificial upwelling

Description: Physical methods that could theoretically increase oceanic CO_2 uptake involve increasing the natural rate (due to ocean circulation) at which ocean water has contact with the atmosphere, either by increasing circulation or by directly transporting CO_2 into the deep sea. Any CO_2 introduced to deep waters will ultimately dissolve in the surrounding seawater, return to the surface with ocean circulation over longer timescales (centuries), and re-equilibrate with the atmosphere via air-sea gas exchange. Thus, these methods do not result in permanent CO_2 storage.

Effectiveness: Models suggest that for a CO_2 discharge depth of 3,000 m, slightly less than half of the CO_2 will return to the atmosphere within 500 years (Orr, 2004). Zhou and Flynn (2005) analysed the possibility of accelerating oceanic CO_2 uptake via intensifying downwelling ocean currents, brought about by cooling CO_2 -rich surface waters at high latitudes so that they sink and transport CO_2 ; this is, however, very likely to be energetically infeasible. Alternative methods are based on artificially forcing cold water from the deep ocean up to the surface, for example by using wave-driven pumps for which prototypes and concepts have been developed (Bailey and Bailey, 2008). Water brought to the surface by this method is typically colder and “older”, has greater CO_2 solubility due to the lower temperature, but was equilibrated to a lower historical atmospheric CO_2 level, so that when brought to the ocean surface layer it more effectively takes up CO_2 compared to contemporary surface

waters. Upwelling cold water also cools the atmosphere. This in turn results in changes in terrestrial ecosystems, especially reduced respiration in soils, and thereby increased uptake of CO₂ by the soils and vegetation. However, the potential for CO₂ removal via this mechanism is low, estimated at less than 1 Gt CO₂/year. Model simulations indicate that considerably less than half of this uptake would occur in the oceans, while most would occur in terrestrial ecosystems, although this is difficult to quantify (Oschlies et al., 2010b; Oschlies et al., 2010a; Keller et al., 2014).

Other impacts: Modelling suggests that the redistribution of warm and cold waters associated with enhanced upwelling from the deep ocean would lead to significant changes in the global ocean, atmosphere, and land energy balance, in turn modifying terrestrial ecosystem respiration, resulting in a small carbon uptake that is difficult to attribute. Turning off the pumping would lead to rapid warming, resulting in average global surface temperatures that would be even higher than they would have been if no upwelling had been applied (Oschlies et al., 2010b). There would also likely be unanticipated and unknown ecosystem impacts similar to those discussed in Section 2.2.1 for stratospheric aerosol injections.

2.1.9 Cross-cutting issues and uncertainties

There are several key cross-cutting issues and associated uncertainties that apply to a range of greenhouse gas removal techniques, which depend on the scale of application, and are associated with both domestic and transboundary impacts. One of the largest uncertainties concerns operational costs, both for installation and maintenance. In the previous sections, cost estimates were given where available in the literature. Due to the extensive uncertainties, these are not discussed in further detail here, although it is noted that this is one of the most important issues to resolve before serious consideration is given to scaled-up implementation of any of the greenhouse gas removal techniques. This section focuses on two further, important cross-cutting issues: the application of lifecycle assessments to the various techniques, and the overall limitations on CO₂ storage capacity.

2.1.9.1 Lifecycle assessment of greenhouse gas removal processes

Most techniques for removing greenhouse gases, if applied at scales sufficient to significantly impact the global atmospheric CO₂ burden, would involve sizeable industrial development with direct and indirect effects. Full life cycle assessments would be required to assess their potential, accounting for both the CO₂ lifecycle and other impacts on the climate and environment, for example, biogeochemical cycle changes, albedo, other greenhouse gas emissions or hydrological cycle changes, as well as changes in ecosystems. In addition to considering emissions from energy sources, a CO₂ lifecycle assessment would include several processes such as the supply chain, construction, direct and indirect land-use changes, fugitive emissions, transportation, by-product end use, and waste disposal (e.g., Davis et al., 2009; Weisser, 2007). For biomass-intensive techniques such as BECCS, a proper assessment of the effects on the carbon cycle would take into account the carbon costs of land conversion, planting, maintaining, harvesting, and processing of the biomass, and must account for the fact that woody vegetation takes many years to regrow. Whether, and how, the indirect land-use change associated with biomass cultivation should be included is currently being debated. It is possible that biomass overuse without equal rates of biomass regrowth — or with unintended impacts on land conversion to replace “lost” agricultural land — could ultimately increase the global atmospheric CO₂ burden.

There is little consensus on the system boundaries applied to lifecycle assessments of current climate change mitigation technologies, e.g., whether or not to include indirect land use change impacts due to bio-fuel crops, which are subject to order-of-magnitude uncertainty (Plevin et al., 2010; Mathews and Tan, 2009). Biomass-based or biomass-impacting greenhouse gas removal systems represent what might be the greatest complexity and uncertainty in lifecycle assessments of climate impacts, involving the possibility of positive local impacts such as enhanced growth, in combination with negative impacts such as soil carbon release (Anderson-Teixeira et al., 2009), as well as wider environmental, social, and climatic effects. Many of these impacts are temporal, involving a “pay-back period” to replace losses of CO₂. Generally,

lifecycle assessments need to consider that any application of a technique that removes CO₂ from the atmosphere may result in a “rebound effect”, in which the removed CO₂ is counterbalanced by reduced uptake of CO₂, or by the release of CO₂ from other components of the global carbon cycle (Ciais et al., 2014). Development of frameworks for lifecycle assessments of greenhouse gas removal methods focusing on the impacts on the climate and the broader environment should be considered, in order to develop an informed assessment of their applicability (building on, for example, Sathre et al., 2011).

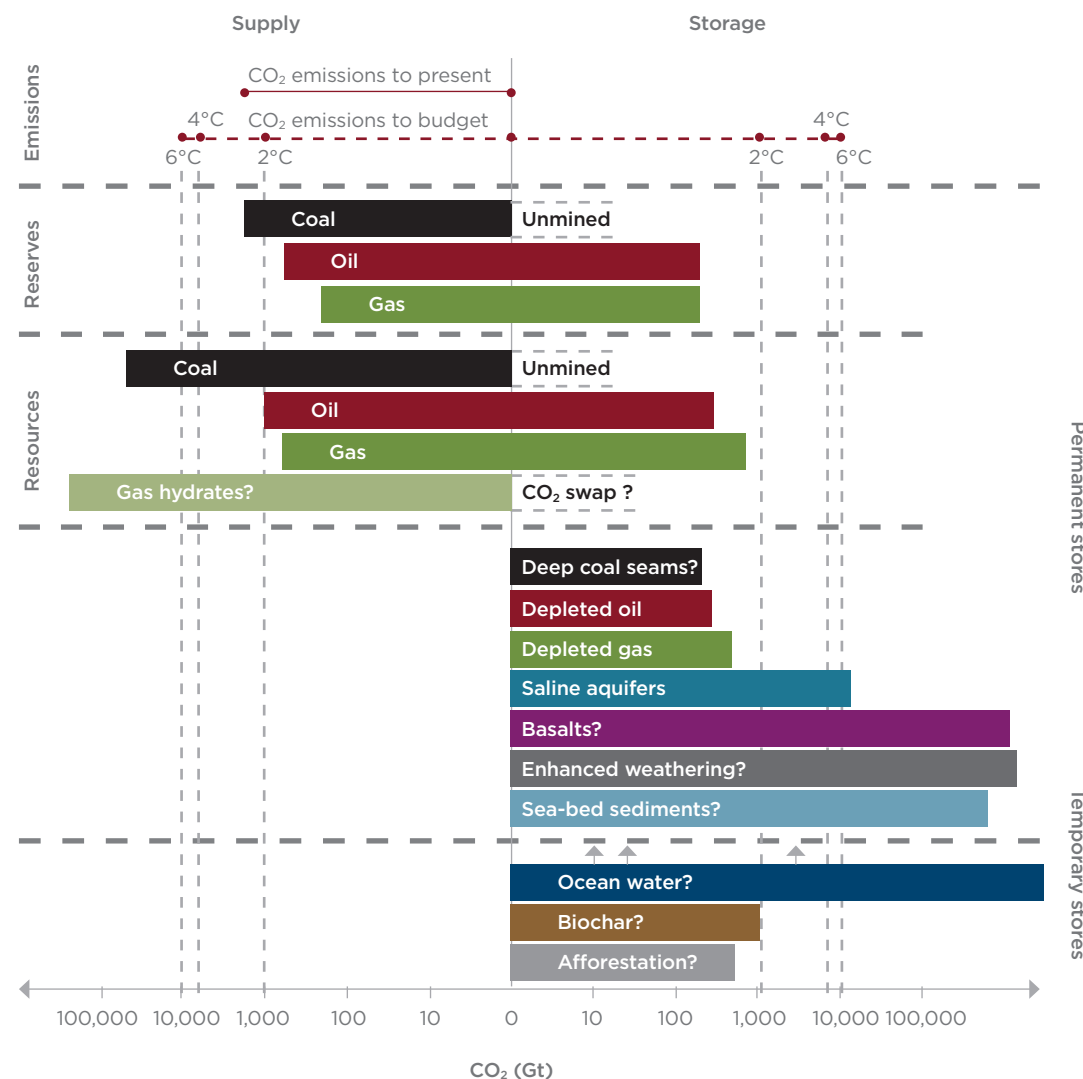
2.1.9.2 CO₂ storage availability and timescale

Options for long-term storage (>10,000 years) — primarily geological or geochemical storage — have the potential to mitigate climate change on a “permanent” basis (Scott et al., 2013). Shorter-term CO₂ removal or fixation options eventually release the stored carbon back into the atmosphere as CO₂, so that the removal process would need to be continually maintained in order to have the effect of long-term storage. Shorter-term storage is also potentially vulnerable to climatic and societal changes, e.g., subsequent clearance of afforested regions. As such, these shorter-term opportunities have been posed as “buying time” while longer-term alternatives are being developed (Dornburg and Marland, 2008). These considerations would apply similarly to the removal of other greenhouse gases.

Captured CO₂ can potentially be used as a feedstock for chemical manufacturing processes, e.g., liquid fuels, carbonate, methane, methanol, and formic acid. However, net CO₂ removal is not achieved if it is used to form a product that is subsequently combusted (e.g., liquid fuels) or subjected to reactions that pro-

duce CO₂, either in deliberate processing or in the natural environment. Demand for long-term, chemically stable CO₂-based products is very likely to remain extremely small compared to current anthropogenic emissions of CO₂ (Kember et al., 2011). Consequently, carbon capture and utilisation (CCU) projects may be important as a step towards developing closed-cycle perspectives in the private sector and general public, and towards adding value to some of the CO₂ that is captured by various processes, but are not likely to have a large impact on global atmospheric CO₂ concentrations. Using CO₂ to increase recovery from oil and gas reservoirs (enhanced oil recovery), which is sometimes considered as a form of CCU plus storage, does result in geological CO₂ storage but the full lifecycle of the process, particularly the net effect on the atmospheric carbon budget once the oil and gas are combusted, needs to be considered in more detail (Jaramillo et al., 2009).

The cumulative capacities of the various proposed CO₂ storage options are uncertain, with most estimates based on limited data and desk-based studies. Nonetheless, as discussed in Scott et al. (2015), useful insights can be gained by comparing these estimates with the estimated availability of fossil carbon *reserves* (very high confidence in quantity and extractability) and the much larger total available *resources* (identified, but without cost estimates for extraction). These are depicted, along with storage capacities, in Figure 2.3. The total storage capacity on the global land surface (in biomass and soils) is at least an order of magnitude smaller than available fossil carbon reserves. The ocean has much greater storage capacity, theoretically in excess of all known fossil carbon resources, but methods to access this storage and the timescales of such storage have not yet been established, and it is unclear if it will ever be possible to establish appropriate long-term storage methods for the oceans.



Among the possible storage reservoirs, depleted hydrocarbon fields and saline aquifers are the best understood, proven, and quantified, providing secure CO₂ storage on geological timescales (Scott et al., 2013; Sathaye et al., 2014). Estimates suggest that they have sufficient global capacity to contain the CO₂ resulting from the use of all current fossil carbon reserves, with plausible engineering interventions, such as pumping out formation waters to reduce pressures, being able to further increase individual reservoir capacities. At the continental scale, sedimentary basins with potential as geological CO₂ storage sites are relatively well distributed.

However, storage sites are not necessarily co-located with major emissions sites, so that CCS source–sink matching would require the development of significant CO₂ transportation infrastructures (Metz et al., 2005; Stewart et al., 2013), and factors such as social acceptability (see example cases in Section 3.1.4) can limit the practical availability of storage sites. Relocation of CO₂-emitting facilities or implementation of direct air capture might offer improved co-location to storage, but would require appropriate above-ground conditions (e.g., labour and markets for products, or suitable meteorological conditions for CO₂ air capture).

While secure storage capacity in geological reservoirs is estimated to be sufficient to match known fossil carbon reserves, it is not established whether it would be sufficient to accommodate all estimated fossil carbon resources (Scott et al., 2015). Very large theoretical storage CO₂ potentials have been identified in basalts (McGrail et al., 2006; Matter and Kelemen, 2009), seabed sediments (House et al., 2006; Levine et al., 2007), and through acceleration of mineral weathering (Hartmann et al., 2013), but their feasibility at scale is effectively unknown at the present time.

2.2 Albedo modification and related techniques

The Earth's climate depends upon the balance between absorbed solar radiation and emitted terrestrial radiation (see Figure 1.2 for reference). Albedo modification refers to deliberate, large-scale changes of the Earth's energy balance, with the aim of reducing global mean temperatures. The proposed methods are designed to increase the reflection of solar (short-wave) radiation from Earth. Suggestions for increasing the Earth's reflectivity include: enhancing the reflectivity of the Earth's surface; injecting particles into the atmosphere, either at high altitudes in the stratosphere to directly reflect sunlight or at low altitudes over the ocean to increase cloud reflectivity; and placing reflective mirrors in space.

Albedo modification techniques are distinct from mitigation and from most greenhouse gas removal techniques, in three key ways:

- their operational costs are potentially low;
- their effects are potentially rapid and large;
- their evaluation is better characterised as a risk-risk trade-off (Goes et al., 2011).

In light of this distinction, various potential roles for albedo modification have been proposed:

- employing albedo modification on a large scale with the goal of reducing climate risks as much as possible, potentially substituting for some degree of mitigation (Teller et al., 2003; Carlin, 2007; Bickel and Lane, 2009);

- employing albedo modification as a “stopgap” measure to allow time for reducing emissions (Wigley, 2006);

- reserving albedo modification for use in a potential “climate emergency”, such as the large-scale release of methane from permafrost and ocean deposits (Blackstock et al.; 2009, see also Box 3.7).

Of course, it is also possible that albedo modification techniques will have no role in future responses to climate change, if it is decided not to employ any of them at all, given that they do not address the fundamental cause of global warming, namely emissions, and thus the increasing atmospheric concentrations of greenhouse gases (Matthews and Turner, 2009). Discussions on the potential role of albedo modification frequently focus on three key drawbacks. Firstly, since albedo modification impacts the climate in a manner that is physically different from the impact of greenhouse gases, it would not be possible to simply reverse the effects of global warming. Thus, whilst albedo modification may reduce some risks associated with climate change, it may in turn increase others. The way in which an albedo modification technique is deployed would affect the distribution of benefits and harms (Irvine et al., 2010; Ricke et al., 2010a; Mac Martin et al., 2013). Secondly, albedo modification carries the risk of a “termination shock”: if it were deployed for some decades at large scale and thereafter terminated, there would be a rapid warming globally, back towards the temperatures that the Earth would have already reached in the absence of a deployment of albedo modification (Matthews and Caldeira, 2007; Irvine et al., 2012). Such an event would likely be particularly damaging, given that there are indications that the impact of climate change on human populations and ecosystems depends strongly on not only the amount but also especially on the rate of climate change (Goes et al., 2011). Thirdly, albedo modification does not address the direct effects of CO₂ on the environment, such as ocean acidification and impacts on terrestrial vegetation (Matthews and Caldeira, 2007).

Finally, beyond these physical risks, it is also important to note that the potential future role of albedo modification, if any, will also depend on how the initial scientific results are interpreted, framed, and com-

municated, as well as on how the socio-technical context, into which discussions of climate engineering are emerging, shapes these techniques and their usage. This is discussed further in Chapter 3.

The Sections below (2.2.1–2.2.5) assess several of the key methods that are currently being discussed, which mostly involve increasing the planetary albedo, either at the Earth's surface, or in the atmosphere via modifying low-level clouds or stratospheric aerosol particles. Using space mirrors for climate engineering is not discussed in detail, since the technological development, material and energetic requirements, and associated operational costs would at present be so prohibitive that this technique is not realistically being considered for implementation in the mid-term future, although it is used as a form of “thought experiment” for idealised climate model simulations, as discussed in Section 2.2.6. While the majority of studies have concentrated on albedo modification, a few other related techniques have been proposed that would alter the Earth's energy balance by increasing the amount of terrestrial radiation emitted from the planet (see Section 2.2.5). Numerous additional methods beyond those discussed below have also been proposed. An overarching description of the research findings on the responses of the climate to the various methods is presented at the end of this section.

2.2.1 Stratospheric aerosol injection (SAI)

Description: Stratospheric aerosol injection involves increasing the amount of aerosol particles in the lower stratosphere (at altitudes above about 20 km) as a means to increase the reflection of sunlight beyond what is reflected by the naturally-occurring stratospheric aerosol layer (Niemeier et al., 2011; Rasch et al., 2008). Particles could either be injected directly or formed via injection of precursor gases such as sulphur dioxide (SO_2), which are then converted into particles. SAI is currently the most discussed albedo modification technique. It was first proposed by Bud-yko (1974), but was not widely discussed until the idea was reiterated by Crutzen (2006); since then it has been heavily investigated, including numerous model-based studies and first proposals and plans for field experiments, as well as studies on societal aspects such as perception, ethical concerns, and governance.

Effectiveness: Analyses of the global temperature record subsequent to large volcanic eruptions that inject millions of tonnes of SO_2 into the stratosphere leave little doubt that the introduction of aerosols into the stratosphere cools the climate (Robock, 2000). It has been suggested that the technical feasibility, effectiveness, affordability, and timeliness of stratospheric climate engineering techniques could make them a possible option for counteracting global warming (Robock et al., 2009), but many concerns have also been raised, including geographically inhomogeneous climate effects and potential side effects (Robock, 2008).

Candidate gases for injection into the stratosphere include SO_2 or hydrogen sulphide (H_2S) (Robock et al., 2008; Shepherd et al., 2009; Rasch et al., 2008), which are oxidised to form small sulphuric acid aerosol particles (Robock et al., 2009). H_2S has a lower molecular mass and is around twice as effective as SO_2 in creating molecules of stratospheric sulphuric acid per kg of gas, but is highly toxic and thus may be problematic for transport to the stratosphere in large masses. Detailed aerosol microphysical modelling studies reveal a very complex picture of the interplay between injection rate, location, particle growth, and microphysical and optical properties; based on these, it appears likely that continuous injection of SO_2 or H_2S would lead to the formation of larger particles than observed subsequent to volcanic eruptions, if the total annual injection rates are comparable (Heckendorn et al., 2009; Timmreck et al., 2010; Niemeier et al., 2011). Direct injection of sulphuric acid, H_2SO_4 , has also been proposed as a way to potentially gain more control over aerosol size, but given the higher molecular mass, a greater weight of material would then need to be lifted to the stratosphere (English et al., 2012; Pierce et al., 2010). Larger particles are less effective at scattering sunlight back to space and have a shorter atmospheric residence time because they sediment more rapidly, which means that one would expect diminishing returns in terms of the cooling impact for increased rates of injection (Niemeier and Timmreck, 2015). Such diminishing returns are demonstrated in Figure 2.4, which also shows that there are large differences between models in terms of the estimated injection rate needed to achieve a certain amount of radiative forcing. Particles of various chemical compositions have been proposed, including titanium diox-

ide (Pope et al., 2012), soot (Kravitz et al., 2012), and limestone (Ferraro et al., 2011), and nanoparticles that would photophoretically levitate, i.e., would be self-lifting into the upper stratosphere (Keith, 2010). Customised particles could theoretically be designed to maximise the cooling impact while minimising side

effects, for example on stratospheric ozone. Soot would dramatically heat the stratosphere, and would also decrease ozone levels and thus increase the UV flux at the Earth's surface, and thus it has been suggested that it is not a suitable particle type or SAI (Kravitz et al., 2012).

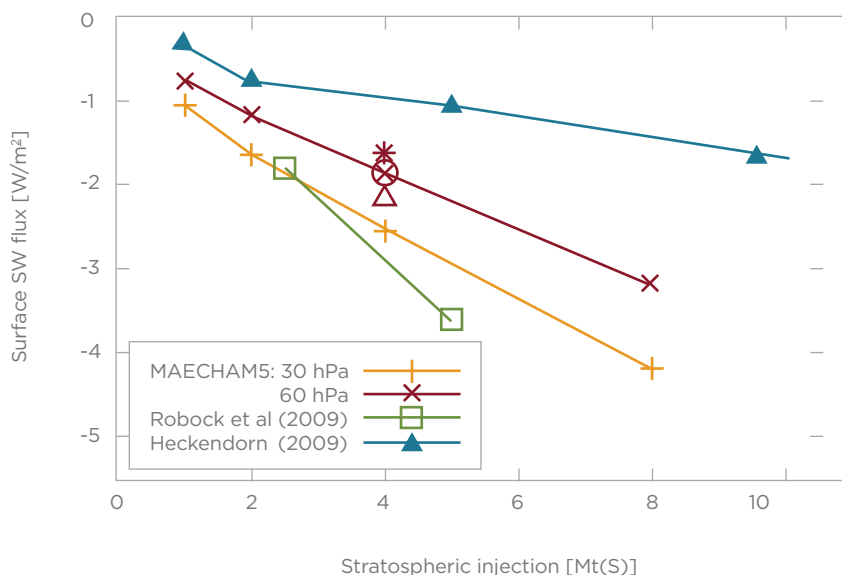


Figure 2.4:

Surface shortwave radiative flux anomaly induced by a given annual rate of injection of stratospheric sulphate particles, for three different studies; the concave upward shape of the curves indicates the diminishing returns that are simulated at higher injection rates.

Source:

(Niemeier et al., 2011).

Particles with a smaller radius and higher refractive index (for example titanium dioxide, TiO_2) could be around three times more effective than the same mass of sulphuric acid particles (Pope et al., 2012). However, coagulation of candidate solid particles in the stratosphere still needs to be comprehensively investigated. If the customised particles were to coagulate, particularly when mixed with the naturally occurring sulphate aerosol layer, then this would lead to much larger particles than those initially injected. This would in turn reduce their optical efficiency, increase absorption of terrestrial radiation, and increase their sedimentation rates. This may be of particular relevance should future large volcanic eruptions coat the candidate particles with a layer of sulphate.

Delivery mechanisms have received considerable attention. Estimates of the operational costs of various potential delivery mechanisms have been provided by Robock et al. (2009); Davidson et al. (2012);

and McClellan et al. (2012). Those studies considered injection via: aircraft payloads, artillery shells, rockets, stratospheric balloons, and other possibilities. The main conclusion was that the most economically feasible injection mechanisms are likely to be injection via high-flying (higher than 15 km) aircraft, or by tethered balloons in the tropics. For aircraft delivery, installation cost estimates range from about \$1–30 billion, plus annual maintenance costs in the range of \$0.2–20 billion, depending on the injection strategy. Artillery shells and missiles were estimated to have maintenance costs in the range of 10–100 times more than those associated with aircraft delivery. Estimates for stratospheric balloon delivery are comparable to aircraft injections, in the range of \$1–60 billion for installation costs with annual maintenance costs of \$1–10 billion. The results of the initial studies vary widely, with some having nearly opposing trends. For example, Davidson et al. (2012) indicate maintenance costs for aircraft injections that are ten times those of

balloon injections, whereas McClellan et al. (2012) suggest that balloon injections would instead be about ten times the maintenance costs of aircraft injections. These disparities are due to different underlying assumptions about the amount of material that is to be injected, with airplanes being more efficient at injecting smaller amounts and balloons becoming more cost-effective when larger amounts are injected (because they can continuously inject material, while airplanes can only inject a limited amount of material and would then have to pick up a new payload and refuel). There is, nevertheless, a broad consensus that dispersing megatons of particles into the stratosphere could be feasible and achievable at total operational cost that might be within the reach of individual nations, if the various practical constraints surrounding SAI delivery mechanisms were to be overcome (see Box 2.1).

The operational costs will depend on many factors, such as the altitude of deployment and the total amount of aerosol particle mass or precursor that is injected. The amount of sulphur that would need to be injected into the stratosphere to offset a warming corresponding to a doubling of atmospheric carbon concentration was estimated in Shepherd et al. (2009) to be between 1 and 5 Mt sulphur, while more recent estimates suggest that up to several tens of Mt could be required (Pierce et al., 2010; Niemeier et al., 2011). An important general consideration is that the forcing would not increase linearly with the injected mass, since greater injection rates will normally lead to larger particles that have shorter residence times and less favourable radiative properties, thus giving diminishing returns. As shown by Niemeier and Timmreck (2015), there may be an upper limit of the order of 10–15 W/m² for the cooling that can be achieved by stratospheric aerosol particle injection.

Box 2.1

Practical constraints surrounding SAI delivery mechanisms

Tethered balloons are subject to constraints on the intrinsic mechanical properties of tethers, as well as to meteorological phenomena such as horizontal and vertical wind shear, clear air turbulence, cumulus convection, icing, and lightning, which would influence the possible locations of year-round operating bases (Davidson et al., 2012). Delivery from aircraft by increasing the sulphur content in aviation fuel and using the current distribution of civil aircraft flight paths would be ineffective, since the injection altitude is too low and most of the injection would be too far north to result in significant global cooling (Anton et al., 2012). Furthermore, under this scenario, stratospheric aerosol particles would be confined to the Northern Hemisphere, with impacts on the patterns of tropical rainfall (Haywood et al., 2013). Thus, if aircraft were used to deploy stratospheric aerosols, a new fleet of high-flying aircraft dedicated to the task would likely be the preferable option (McClellan et al., 2012).

Other impacts: Stratospheric ozone is affected by stratospheric aerosols. The eruption of Mount Pinatubo reduced the total global amount of stratospheric ozone by approximately 2% (Harris, 1997), since stratospheric particles offer heterogeneous surfaces for chemical reactions that deplete stratospheric ozone (Tilmes et al., 2008). However, this effect is small relative to the existing ozone reduction caused by chlorofluorocarbons (CFCs), and will also decrease pro-

portionally as the amount of available chlorine decreases (as CFC concentrations decrease in the future). Candidate particles could theoretically be chemically engineered (Pope et al., 2012) by coating them to have less impact on stratospheric ozone than sulphuric acid particles. Scattering by the injected particles would serve to reduce the amounts of harmful UV radiation reaching the surface of the Earth, but this would only partially compensate the increases in

UV radiation resulting from ozone loss (Tilmes et al., 2012). Reductions in ozone and the absorption of terrestrial radiation by the stratospheric aerosols could change the heating rates in the stratosphere, with consequent impacts on the dynamics of the stratosphere (Ferraro et al., 2014). Post-Pinatubo modelling shows that the absorption of terrestrial radiation by sulphate aerosols altered the stratospheric dynamics so that the aerosol was transported more strongly into the Southern Hemisphere rather than remaining primarily isolated in the Northern Hemisphere (Young et al., 1994).

In addition to stratospheric ozone, tropospheric cirrus clouds may also be impacted by stratospheric aerosols injections when the particles sediment from the stratosphere into the troposphere. Global GCM simulations (Kuebbeler et al., 2012) suggest that stratospheric aerosol injections would reduce ice crystal number concentrations in cirrus clouds by between 5 and 50%, which would lead to enhanced global cooling, highlighting a potentially important feedback mechanism. However, this effect is highly uncertain and not supported by observations, which have shown abnormally high ice crystal number concentrations in cirrus clouds due to aerosol particles that originated from the Mt. Pinatubo eruption sedimenting from the stratosphere into the upper troposphere (Sassen et al., 1995).

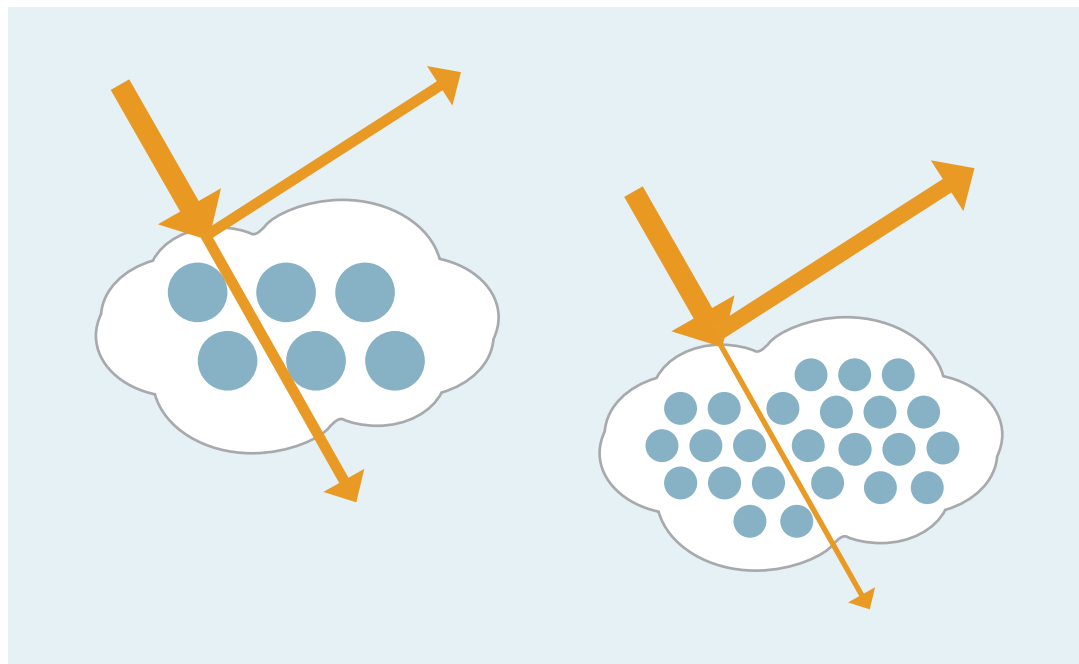
SAI may also influence vegetation growth by reducing solar radiation at the surface, which will reduce photosynthesis. This might be partly counteracted by the increased fraction of diffuse- to direct-radiation (Vaughan and Lenton, 2011) which would result in higher photosynthesis rates (Mercado et al., 2009; Gu et al., 2002). The aforementioned ozone depletion might harm plants by letting more harmful UV radiation reach them, rather than being absorbed at high altitudes (Stapleton, 1992), although the aerosol itself will reduce levels of harmful UV radiation. Temperature changes on the regional scale will also influence vegetation, which also depends on how SAI is implemented: warming in polar regions might lead to enhanced vegetation growth, whereas in other regions it might have a different effect. Due to its effects on the global atmospheric circulation, SAI will change water availability. This may be especially important in water-limited regions, potentially increasing water

availability and hence vegetation growth despite a globally weaker hydrological cycle. However, model simulations suggest that, due to elevated atmospheric CO₂ concentrations, vegetation growth would increase significantly and that SAI would not change this by much (Bala et al., 2002; Naik et al., 2003; Jones et al., 2011).

Taken together, the various feedback mechanisms mentioned here make it challenging to anticipate the distribution of stratospheric aerosols, their impacts on other components of the climate and Earth system (such as ozone and cirrus clouds), and hence the overall resultant environmental consequences of an injection of stratospheric aerosol particles or their precursors.

2.2.2 Marine cloud brightening (MCB)/marine sky brightening (MSB)

Description: First proposed by Latham (1990), this method involves using water-soluble particles to seed low-level warm clouds over the oceans. These clouds tend to have a net cooling effect on the climate because of their strong reflection of solar radiation. The aim of this technique would be to increase their albedo, as well as to possibly also increase their lifetimes. This could be achieved by injecting suitable particles into the cloud updrafts, whereupon the particles act as cloud condensation nuclei, around which water vapour can condense. Increasing the number of cloud condensation nuclei increases the number of droplets in the clouds, meaning that the available water forms into more and smaller droplets than in non-seeded clouds. Since the ratio of surface area to volume increases for smaller droplets, the smaller droplets have a greater surface area and thus reflect more sunlight than fewer, larger droplets, as depicted in Figure 2.5. In addition to this impact on reflection by cloud droplets, the increased concentration of aerosol particles also directly causes an increase in the reflection of sunlight; however, the indirect effect via cloud droplets is usually larger than the direct effect via the much smaller aerosol particles themselves.

**Figure 2.5:**

Depiction of cloud brightening by aerosol particle injection. On the left is an unperturbed cloud in which the available liquid water is spread over fewer, larger droplets; on the right is a cloud in which cloud condensation nuclei particles have been injected, creating more particles over which the available liquid water is spread. The particles in the perturbed cloud have a larger total surface area and thus let less sunlight through the cloud than in the unperturbed case.

For seeding clouds, the type of aerosol particle most commonly suggested is naturally occurring sea salt. Since aerosol particle residence times are much shorter (days) in the lower troposphere near the Earth's surface than in the stratosphere (order of 1–2 years), the particles would need to be continuously replenished and large masses would need to be injected in order to be effective. Recent model studies have shown that injection of sea salt could also be effective over cloud-free, low-latitude oceans, since the sea salt particles themselves also reflect solar radiation. The relative effectiveness of marine cloud brightening and this “clear-sky sea-salt effect” is currently not well known, but they appear to be of the same order of magnitude (Partanen et al., 2012; Jones and Haywood, 2012; Alterskjær et al., 2013). Throughout the report, the combined method is referred to as “marine sky brightening (MSB)”.

Effectiveness: Published estimates indicate that marine cloud brightening could potentially exert a radiative forcing of -1.7 to -5.1 Wm⁻² (Jones et al., 2011; Partanen et al., 2012; Alterskjær et al., 2012; Latham et al. 2008; Lenton and Vaughan, 2009; Rasch et al., 2009; Alterskjær and Kristjánsson, 2013). This high potential effectiveness is due to the extensive regions over

which the technique could be applied: about 17.5% ($89.3 \times 10^6 \text{ km}^2$) of the Earth's surface area is covered by marine stratiform clouds (Latham et al., 2008) and cloud-free areas over the subtropical oceans represent another 5–10% of the Earth's surface area. The method would be most effective when there are no or few higher-level clouds overlying the targeted low clouds and the air is unpolluted (Alterskjær et al., 2012; Bower et al., 2006). The effectiveness would be dependent on meteorological conditions such as horizontal and vertical wind speeds, as well as the formation of precipitation (Wang et al., 2011). The meteorological conditions could also influence the efficiency of the spraying process (Jenkins et al., 2013). The resulting size of the sea salt aerosol particles is crucial. For particles that are too large, cloud seeding might even lead to a reduction in cloud droplet number concentration, opposing the desired effect (Alterskjær and Kristjánsson, 2013; Pringle et al., 2012). Clouds are among the most complex and least understood components of the climate system, and there are large uncertainties associated with aerosol–cloud interactions (Korhonen et al., 2010; Stevens and Boucher, 2012) and aerosol–radiation interactions (Partanen et al., 2012).

The most commonly discussed delivery strategy involves wind-driven vessels that would pump sea spray into the overlying air, whereupon evaporation would form sea salt aerosols that would then be transported up to the base of overlying low-level clouds by below-cloud updrafts and turbulent motion in the marine boundary layer (Salter et al., 2008). Challenges associated with this method include coagulation of the injected sea salt particles into fewer and larger particles (that sediment more quickly), and reduced updraft speeds or formation of downdrafts due to cooling by the sea spray as it evaporates. One study showed that the former effect can reduce the cloud droplet number concentration by 46% over emission regions, thereby reducing the effectiveness of the technique by almost a factor of 2 (Stuart et al., 2013), while the latter effect appears to be less significant (Jenkins and Forster, 2013). Despite these limitations, other delivery methods, for example using aircraft, are likely infeasible given the very large mass of cloud seeding particles required. The costs of research and development for unmanned floating vessels are estimated at about \$100 million, whilst each ship is estimated to cost \$1.5–3 million (Salter et al., 2008). Estimates of the number of vessels needed to achieve a 3.7 Wm^{-2} radiative cooling (equivalent to the forcing from a doubling of pre-industrial CO_2) vary from ~1500 (Salter et al., 2008) to ~25000 (Alterskjær et al., 2013). The method is deemed to have a low technical feasibility, largely because of the difficulty of developing a reliable spray-generation technology that could efficiently produce particles of an appropriate size in sufficiently large quantities. More fundamentally, the level of understanding of the effects of such aerosol spraying is currently very low, as there are only a few numerical experiments available, of which the results are quantitatively quite divergent, for example due to differences in the treatment of sub-cloud updrafts (Jenkins et al., 2013).

Other Impacts: As for other forms of albedo modification, changes in the hydrological cycle are expected for MSB (Robock et al., 2009; Jones et al., 2011; Rasch et al., 2009; Rasch, 2010; Jones et al., 2009; Baughman et al., 2012; Bala et al., 2010; Bala and Nag, 2011; Alterskjær et al., 2013). Particularly for implementations in the Pacific Ocean, there is the potential for changes in the El Niño Southern Oscillation (ENSO) due to the strong localised cooling that would need to be

induced in one of the key target regions, off the coast of Peru (Baughman et al., 2012). MSB is expected to enhance precipitation over low-latitude land regions; this may enhance agricultural productivity in some regions but could also lead to increased flood risk (Bala and Nag, 2011; Alterskjær et al., 2013). The emitted sea salt could cause corrosive destruction of infrastructure and have detrimental effects on plants if local deposition rates were sufficiently high (Paludan-Müller et al., 2002; Muri et al., 2015).

2.2.3 Desert reflectivity modification

Description: Deserts are considered one of the most optimal areas for land-based reflectivity modification, due to low population density, a relatively stable surface, sparse vegetation, a large surface area ($11.6 \times 10^6 \text{ km}^2$, 2.3% of the Earth's surface area, not including aeolian deserts), limited cloud cover, and low-latitude locations. A reflective material could be placed on desert surfaces, e.g., aluminium coated with polyethylene (plastic) (Gaskill, 2004), with the intention of increasing the albedo from the present value of 0.2–0.5 to about 0.8 (Tsvetsinskaya et al., 2002).

Effectiveness: Covering all deserts (i.e., 2.3% of the Earth's surface) with material that would increase its albedo from 0.36 to 0.8 would give a maximum globally averaged radiative forcing of -1.9 to -2.1 Wm^{-2} , assuming permanently clear skies in the desert regions (Lenton and Vaughan, 2009). The effectiveness of the method is likely to be reduced with time, as sand and debris are windblown onto the sheets, reducing their reflectivity, thus adding maintenance costs; for near-complete coverage, the logistics of access to the surfaces for such maintenance would present an additional challenge (although near-complete coverage would limit the amount of sand debris that might be mobilised by winds to coat the material). Installation costs have been estimated at ca. \$0.3 per m^2 of surface area (Shepherd et al., 2009), based on the simple assumption that costs would be comparable to painting human structures, with possibly comparable maintenance costs if the surfaces needed to be renewed or recovered on a regular basis. Under this assumption, the total cost for achieving -2 Wm^{-2} of forcing would thus be several trillion dollars, which is likely to be prohibitively costly for full-scale deployment. The technology to produce the plastic sheets

already exists, but nevertheless the feasibility is low, due to the high installation costs and the challenging maintenance issues. Reversal of deployment would in principle be straightforward, since the sheets would be readily removable, although plastic waste would likely be a major issue, as polyethylene is not readily biodegradable.

Other Impacts: The most significant impact expected from this technique would be a substantial perturbation of desert ecosystems, due to the physical coverage by the sheets and the reduced energetic input due to the increased albedo. No studies of these implications are known. Furthermore, the increased desert reflectivity is expected to lead to considerable regional climatic changes. Irvine et al. (2011) found large reductions in regional precipitation adjacent to deserts and a severe reduction in monsoon intensity due to increasing albedo in desert regions. Another potential impact is a substantial reduction in the nutrient supply to the Amazon, for which the Sahara is an important source (Koren et al., 2006; Swap et al., 1992). There has been very little research on this topic, and thus the present level of understanding is very low.

2.2.4 Vegetation reflectivity modification

Description: Another proposal for increasing Earth's surface albedo involves growing or producing varieties of plants with a higher albedo than current varieties, for example in crops, grasslands, or pasture grasses. The impacts are expected to be mainly local or regional with likely minimal impact on the global commons and with minimal transboundary effects, except the large-scale climate cooling effects resulting from the albedo modification. The permanence of the effect will depend on the lifetime and the planting rotation cycles of the crops. To have a global impact, the modified crops would need to be planted over very large regions (see the estimations of necessary surface area in Section 2.2.3), particularly since the potential increase in albedo by modifying crops will generally be less than what could be achieved by covering deserts with reflective foil. The natural variability of albedo within one crop variety is typically within the range 0.02–0.08 (Ridgwell et al., 2009), but for some crops, e.g., wheat, it can be as much as 0.16 (Uddin and Marshall, 1988). The albedo depends

on plant morphology, leaf spectral properties, and canopy structure (Doughty et al., 2010). Genetic modification and selective breeding of crops could be used to “design” plants with certain traits. This way, or by simply choosing naturally brighter varieties, a different variety of the same type of crop could continue to be grown. The consequences for food production and processing would thus be minimised or avoided.

Effectiveness: The impacts of modified plant albedo would be mainly regional and seasonal (summer) (Irvine et al., 2011; Ridgwell et al., 2009; Doughty et al., 2010; Singarayer et al., 2009). Grassland and crop albedo modifications are estimated to have a radiative forcing potential of -0.6 and -0.3 Wm⁻² respectively, or -0.9 Wm⁻² in combination (Lenton and Vaughan, 2009; Ridgwell et al., 2009; Hamwey, 2007). Approximately 2.7% of the Earth's surface is covered by crops, whilst around 7.5% is covered by grassland. No new infrastructure or technology would be needed, making the technical feasibility of this method high.

Other Impacts: As for other techniques that remove greenhouse gases through modifying vegetation, such changes in land use may conflict with other goals of land use management such as biodiversity preservation and carbon sequestration. Changing crop types on a large scale could affect market prices, biodiversity, and local ecosystems. The background climate state is important for determining the impacts of increasing vegetation albedo. During post-harvest periods and regrowth, the albedo would vary, resulting in a seasonal variation of the additional radiative forcing effect (Zhang et al., 2012). The effects on soil moisture are uncertain, and changing crops could lead to changes in moisture advection and cloud cover, which could in turn either counteract or enhance the albedo cooling (Irvine et al., 2011; Ridgwell et al., 2009; Doughty et al., 2010). Net primary productivity and crop yields could be influenced by changes in photosynthesis as a result of the higher albedo (Shepherd et al., 2009), and reduced leaf-heating due to increased plant albedo could also result in a reduction of water demand, again likely influencing net primary productivity (Singarayer et al., 2009; Moreshet et al., 1979). There is presently limited understanding of such techniques, as few studies are available.

2.2.5 Cirrus cloud thinning

Description: In addition to the various schemes discussed above for increasing the planetary albedo, other related ideas for directly cooling the Earth's surface have been proposed. Most discussed among these is the idea of cirrus cloud thinning. Cirrus clouds, like all other clouds, both reflect sunlight and absorb terrestrial radiation. However, cirrus clouds differ from other types of clouds in that, on average, absorption outweighs reflection, with the result that cirrus clouds have a net warming effect on the climate (Lee et al., 2009). It has been suggested that seeding the cirrus-forming regions in the upper troposphere with relatively few, highly effective ice nuclei could induce a fraction of the haze droplets in cirrus clouds to freeze by interacting with the ice nuclei, forming fewer and larger ice crystals (Mitchell and Finnegan, 2009). These ice crystals would quickly grow large, at the expense of smaller, supercooled water droplets, thus more rapidly sedimenting out of the clouds and thereby reducing the optical thickness and lifetime of

the seeded cirrus clouds (see Figure 2.6). Seeding material would need to be added regularly, because it too would fall out together with the large ice crystals. Reducing the optical thickness and lifetime of cirrus clouds would increase outgoing terrestrial radiation, causing a cooling effect. Bismuth tri-iodide, BiI_3 , has been suggested as a seeding material, as it is relatively cheap and non-toxic (Mitchell and Finnegan, 2009). Sea salt has also been suggested as another potential seeding candidate (Wise et al., 2012). The seeding aerosols can have an atmospheric residence time of up to 1–2 weeks, depending on their size and thus their sedimentation velocities. Commercial airliners and unmanned drone aircraft have been suggested as potential delivery mechanisms (Mitchell et al., 2011). The seeding substances could be dissolved into the jet fuel, or a flammable solution could be injected into the jet engine exhaust. Given that global cirrus cloud coverage is 25–33% (Wylie et al., 2005) ($128\text{--}168 \times 10^6 \text{ km}^2$), large areas of the Earth would, in principle, be susceptible to modification.

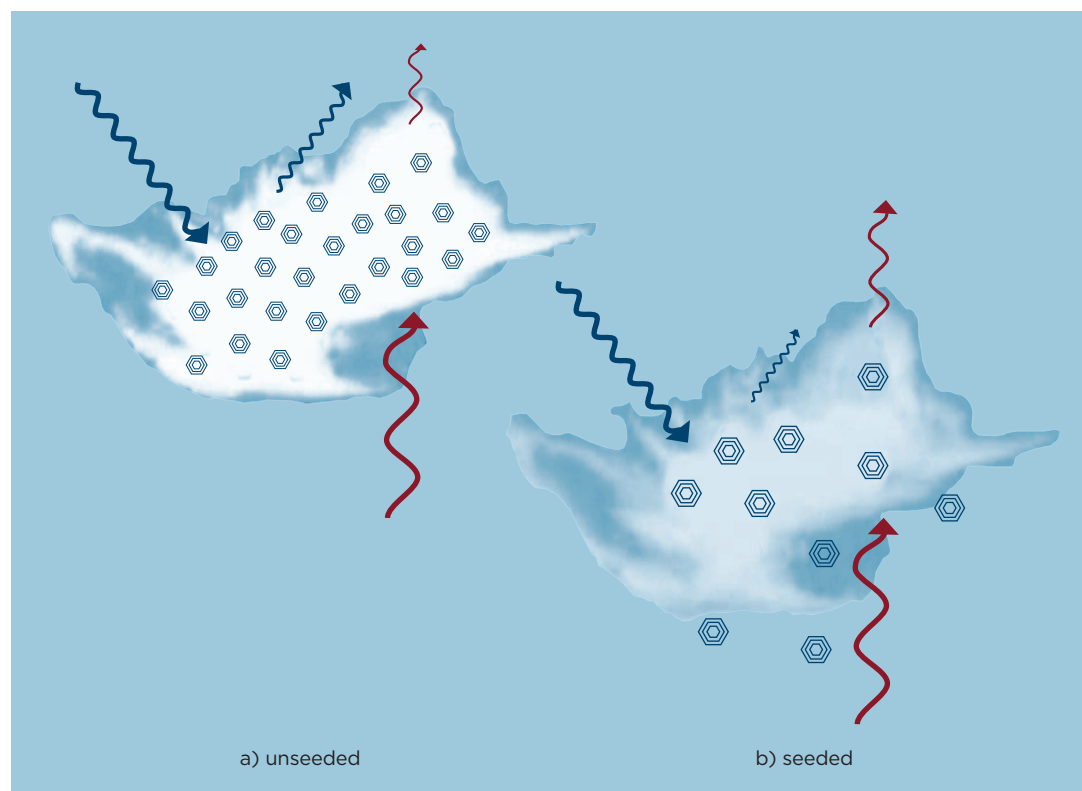


Figure 2.6:

Schematic of cirrus cloud thinning by seeding with ice nuclei, reducing reflection of shortwave solar radiation (blue arrows) and absorption of longwave terrestrial radiation (red arrows). The seeded cirrus clouds on average reflect slightly less shortwave radiation back to space, but also allow more longwave radiation to escape to space, with the latter effect dominating.

Source:

Storelvmo et al. (2013).

Effectiveness: A net cloud forcing of up to -2.7 Wm^{-2} has been found in model studies (Storelvmo et al., 2013; Muri et al., 2014). The method would be most effective at high altitudes ($\sim 10 \text{ km}$), in air with low background aerosol particle concentrations, and at night-time. The method would also be most effective outside of the tropics, since ice crystals in tropical cirrus clouds (typically anvil clouds) are predominantly formed in strong updrafts in convective clouds, making seeding a challenge. Combined with recent findings of heterogeneous nucleation in tropical anvil cirrus (Cziczo et al., 2013), this effectively rules out tropical cirrus for seeding (Storelvmo and Herger, 2014). Very little is currently known about the feasibility or operational costs of this approach; there are very few theoretical studies, and to the extent of our knowledge, no experimental field studies or implementations have been attempted to date. The maintenance cost of procuring the seeding material, BiI_3 , is likely negligible given the relatively small mass required (140 tonnes, Marshall, 2013), although there are other, likely more expensive, components of the total operational costs, for example aircraft deployment in susceptible regions, for which no estimates are yet available.

Other Impacts: In the context of cirrus cloud thinning, the cloud–aerosol–climate interactions are not well understood. Factors that control the heterogeneous freezing process are uncertain, as ice growth kinetics are not well documented. “Over-seeding” might lead to warming, as opposed to the desired cooling (Storelvmo et al., 2013). Vertical velocities are important for activation of ice nuclei, but current estimates are uncertain due to lack of observations. Heterogeneous freezing may already be common in cirrus (Cziczo et al., 2013), which would render the method less effective than expected. There could be a number of climatological side effects. However, as cirrus cloud-thinning targets terrestrial radiation — effectively directly countering the greenhouse effect by reducing the amount of terrestrial radiation that is re-radiated from the atmosphere towards the surface, albeit not with the same geographical distribution of radiative forcing by greenhouse gases — it may nevertheless reduce the degree of atmospheric circulation changes and regional changes to the hydrological cycle that would be expected with most of the albedo modification schemes (Muri et al., 2014). With few numerical experiments available, the current level of understanding is very low.

2.2.6 Results from idealised modelling studies

Prior to potential future field tests or implementation, an initial understanding of the climate response to modifying the planetary albedo can be gained from both highly idealised studies and more realistic scenarios of deployment. Idealised studies have proven very useful as they allow individual aspects of the response to be clearly identified. However, these idealised experiments are inevitably oversimplifications and omit many of the subtleties that would be involved in the deployment of an albedo modification scheme. Realistic scenarios of deployment, in contrast, are important for discussions with stakeholders about the topic; however, since many factors generally influence the climate simultaneously in such simulations, it can be difficult to isolate the causes of various responses.

In many idealised numerical model studies to date, a reduction in the incoming solar radiation (solar irradiance) has been used as a simple proxy for the various forms of albedo modification. While it might be possible to achieve such a uniform reduction by placing an array of mirrors in space, this technology is not considered a realistic option in the foreseeable future. However, since such simulations involving a uniform reduction in incoming solar radiation are straightforward to set up and compare with each other, this approach has been favoured to enable many climate modelling centres to conduct the same simulations, providing more confidence in the results. This has been done under the auspices of GeoMIP (see Box 2.2), providing a valuable background knowledge base for future, more realistic and more complicated experiments that are being initiated in the next phase of GeoMIP.

The Geoengineering Model Intercomparison Project (GeoMIP)

Since the first assessment of climate engineering by the UK Royal Society (Shepherd et al., 2009), considerable further modelling work has analysed the climatic effects of albedo modification techniques. Following the protocol of the Coupled Model Intercomparison Project (CMIP5), which has been extensively utilised by the IPCC (IPCC, 2013a), the Geoengineering Model Intercomparison Project (GeoMIP) project (Kravitz et al., 2011) provides the most comprehensive multi-model assessment to date of the impact of albedo modification on climate. The GeoMIP setup is designed to enable nominally identical simulations to be carried out by the full range of coupled atmosphere–ocean models. GeoMIP originally included four experiments, each of which built on standard CMIP5 experiments, and added an additional forcing to simulate the implementation of various techniques for modifying the planetary albedo (see Figure 2.7). Experiment G1 builds on the CMIP5 experiment of an instantaneous quadrupling of the atmospheric CO₂ concentration, and employs a global reduction in the total solar irradiance to compensate for the radiative forcing due to the increased CO₂ concentration, resulting in a net zero global radiative forcing. G2 follows the same principle, but builds on the CMIP5 experiment of a 1% annual CO₂ increase since pre-industrial times. The approach of reducing total solar irradiance (e.g., Bala and Caldeira, 2000) was favoured for these first experiments because its simplicity allowed the participation by many models (for example, Kravitz et al., 2013a; Schmidt et al., 2012a). G1 and G2 may be thought of either as representing an implementation of space mirrors or as a useful but imperfect analogue of stratospheric aerosol injection (Niemeier et al., 2013; Ferraro et al., 2014; Kalidindi et al., 2014). Nevertheless, it is important to keep in mind that the simple GeoMIP G1 and G2 experiments fail to account for side effects that are germane to stratospheric sulphur injections, such as stratospheric ozone depletion (Tilmes et al., 2008), effects on cirrus clouds (Kuebbeler et al., 2012), or changes in tropical convection (Ferraro et al., 2014). Therefore, GeoMIP experiments G3 and G4 use the injection of sulphur dioxide into the stratosphere to compensate for a specified fraction of the radiative forcing after the year 2020 in the CMIP5 future scenario RCP4.5: G3 keeps the total net radiative forcing (GHG warming minus SAI cooling) constant at 2020 levels, while G4 has a constant SAI forcing while the GHG forcing continues to increase based on the RCP4.5 scenario (see Figure 2.7). An overview of the GeoMIP project and of recently published results is given by (Kravitz et al., 2013c). GeoMIP is continuing and has defined a new set of modelling experiments, including a new focus on the cloud brightening approach (Kravitz et al., 2013b).

2. Characteristics of techniques to remove greenhouse gases or to modify planetary albedo

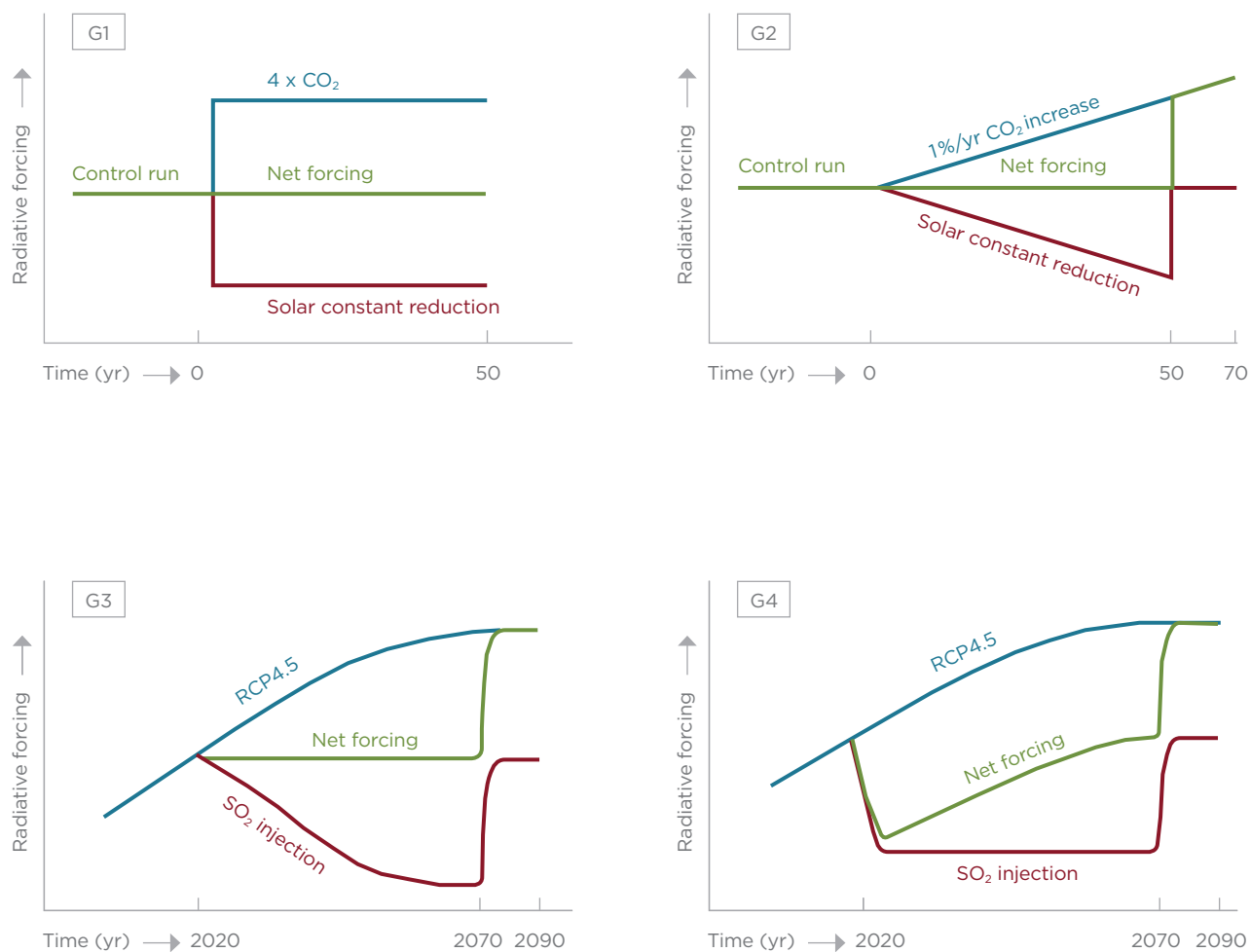


Figure 2.7:

Idealised radiative forcing curves in each of the four original GeoMIP experiments (G1-G4), along with the radiative forcing for the pre-industrial control simulation and the standard CMIP5 simulation

Source:

Kravitz et al., 2011

Numerous studies show that albedo modification cannot reverse all aspects of greenhouse gas-driven climate change, and that a large-scale implementation of SAI sufficient to offset a significant fraction of current or future global warming would still result in a significantly altered climate compared to the present-day climate. One fundamental difference between the response of climate to greenhouse gas forcing and the forcing from albedo modification is their effect on global precipitation, so that either global mean temperature or global mean precipitation could be returned to earlier conditions, but not both at the same time (Kravitz et al., 2013a; Irvine et al., 2010; Ricke et al., 2010b; Jones et al., 2010; Robock et al., 2008; Bala et al., 2010; Bala et al., 2008). Furthermore, the cooling effect of SAI, or any form of albedo modification, would have a different spatio-temporal pattern from the warming effect of greenhouse gases. Accordingly, even if global mean temperatures are returned to some earlier condition, there will be some warmer and some cooler regions (Kravitz et al., 2013a). The multi-model ensembles of the GeoMIP project (simulation G1, Kravitz et al., 2011, see Box 2.2) indicate that if the sunlight reaching the top of the atmosphere is reduced enough to completely offset the global mean warming due to a large increase in greenhouse gases, then the Equator would end up becoming cooler than under the pre-industrial climate, whereas the poles would be warmer (Schmidt et al., 2012a; Kravitz et al., 2013a). Albedo modification would also alter the regional distribution of precipitation and evaporation with consequences for regional hydrology (Tilmes et al., 2013). Figure 2.8 illustrates the temperature and precipitation differences between a pre-industrial simulation and the GeoMIP G1 simulation (see Box 2.2) with elevated CO₂ concentrations compensated by a reduction in solar irradiance (Schmidt et al., 2012a). Whilst albedo modification could not reverse all the effects of greenhouse gas-driven climate change and would accordingly result in an altered climate, studies suggest that in most regions, the changes in climate would nevertheless be of a smaller magnitude than under scenarios that consider only the effects of greenhouse gases (Ricke et al., 2010b; Moreno-Cruz et al., 2011).

SAI differs from idealised solar irradiance reduction (for example, by space mirrors) in a number of ways that need to be considered in evaluating its potential climate response. Firstly, sulphate aerosols absorb terrestrial radiation, leading to heating within the stratospheric aerosol layer, thereby reducing the top-of-atmosphere net forcing. This will have impacts on the atmospheric circulation and hydrological cycle (Jones et al., 2010; Ferraro et al., 2014). Secondly, the spatial distribution of aerosols will not be homogeneous and thus will not produce as homogeneous a cooling effect as in the simple solar reduction experiments (Jones et al., 2010; Robock et al., 2008; Niemeier et al., 2011). Thirdly, the distribution of the stratospheric aerosol layer could be deliberately unbalanced, for example by restricting most of the aerosol layer to one hemisphere or only to one pole. Model simulations indicate that SAI solely in the Northern or Southern Hemisphere stratosphere would lead to shifts in the position of the inter-tropical convergence zone (ITCZ), with particularly significant implications for the Sahel region, while injecting into both hemispheres would not shift the location of the ITCZ significantly (Haywood et al., 2013). The impact of injection at different latitudes and altitudes has been more generally assessed by Volodin et al. (2011), showing that injecting at extreme northern latitudes is less effective than equatorial injection in terms of producing a long-lived stratospheric aerosol layer, and thus in cooling the planet. Volodin et al. (2011) also emphasised that, to be effective, delivery needs to be within the stratosphere, noting that the altitude at which the stratosphere starts ranges from around 8 km at the poles to around 20 km at the Equator. Schallock (2015) conducted a similar study, although varying a larger range of parameters, and similarly found that the most effective region for injection is around the Equator. Schallock (2015) also determined that the simulated mass retention in the stratosphere is nearly twice as large for injections at 25 km compared to injections at 20 km (and that this ratio is nearly the same for simulated particles of 100, 200, and 400 nm). Particle injection at tropical latitudes would pose a substantial technical challenge for many proposed delivery methods, given these indications of very high altitudes being required for SAI to be highly effective. Much remains to be understood, as current climate model simulations do not capture the full spatial patterns of response to stratospheric aerosol forcing, particularly the ob-

G1 - piControl, precipitation (mm/day)

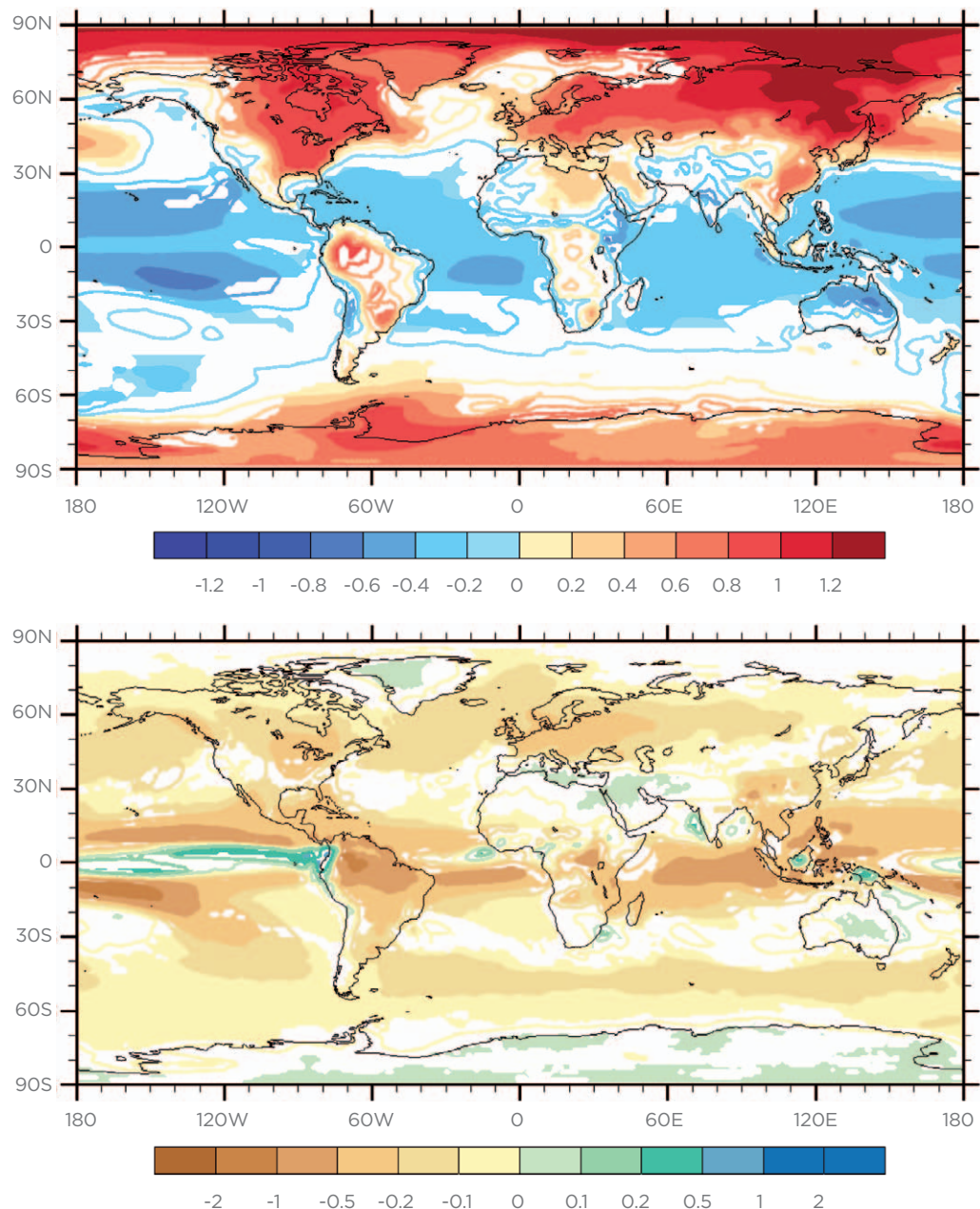


Figure 2.8:

Difference between the GeoMIP G1 simulation and the pre-industrial control simulation for surface air temperature (top panel) and precipitation (bottom panel), computed as the mean of the GeoMIP ensemble of 12 models. Areas where at least nine models show a response with the same sign are colour-shaded.

Source:

Figure updated from Schmidt et al. (2012a), using data from Kravitz et al. (2013a).

served warmer and wetter European winters that have historically occurred after large volcanic eruptions (Stenchikov et al., 2006; Driscoll et al., 2012).

Some albedo modification techniques or combinations of techniques could potentially offer considerable control over the distribution of the induced radiative forcing. In theory, this could allow optimisation

of the forcing, although no albedo modification deployment could reverse all the climatic effects of greenhouse-gas-induced warming. Simulations using an idealised latitudinal distribution of aerosols to minimise regional temperature and precipitation changes (Ban-Weiss and Caldeira, 2010; MacMartin et al., 2013) or to minimise loss of Arctic and Antarctic sea ice (Caldeira and Wood, 2008; MacCracken et al.,

2012) show potential in addressing these specific concerns but do not address how these latitudinal distributions of aerosols can be achieved in practice. Thus, while it is clear that albedo modification could effectively reduce global mean temperature, offering some degree of control over the amount and distribution of the reduction, it is unclear whether a sophisticated optimisation of albedo modification forcing is achievable.

Albedo modification, combined with various greenhouse gas scenarios, would have numerous other impacts on the climate system beyond changes in precipitation and temperature. The response of the overall hydrological cycle to albedo modification is an area of active research. Whilst albedo modification would reduce precipitation, it would also reduce evaporative demand, and the water-use efficiency of plants is expected to increase under elevated CO₂ concentra-

tions (Franks et al., 2013); Box 2.3 describes some of the broader vegetation results of albedo modification studies. A study by Pongratz et al. (2012) indicates that albedo modification would increase crop yield relative to a scenario with rising greenhouse gases, as the heat stress on plants would be reduced (see also Xia et al., 2014). Sea level rise would also be reduced under scenarios of albedo modification, reducing the thermal expansion of the oceans and likely reducing the melting of ice sheets and glaciers, although these changes would mostly take effect over longer (multi-decadal) timescales (Irvine et al., 2009; Moore et al., 2010; Irvine et al., 2012). Evaluation of these various climate impacts predicted for various albedo modification scenarios is at a very early stage, and it is not yet possible to predict with confidence the extent to which different regions would benefit from or be harmed by the deployment of a given albedo modification scheme.

Box 2.3

SAI and vegetation productivity

Plants are sensitive to temperature, light conditions, and water availability. All these parameters will be influenced by albedo modification through the induced cooling, changes in rainfall patterns, evaporation, and through impacts on available photosynthetically active radiation. Vegetation productivity is frequently characterised by the vegetative net primary productivity (gross primary productivity minus autotrophic respiration). Simulations suggest that under business-as-usual scenarios, as well as in a hypothetical future world in which global temperatures are held at present-day values via SAI, net primary productivity would increase due to CO₂ fertilisation (Jones et al., 2013; Glienke et al., 2015). GeoMIP simulations show that models with an interactive nitrogen cycle (Thornton et al., 2009) predict a far smaller CO₂ fertilisation effect than without the nitrogen cycle, owing to carbon-nitrogen cycle interactions (Jones et al., 2013; Glienke et al., 2015). Considerable uncertainties remain in parameterisations of the CO₂ fertilisation effect and in projected vegetation productivity changes. There is only limited observational evidence of these relationships; for instance, the rates of atmospheric CO₂ increase slowed after the eruption of Pinatubo (Gu et al., 2003), which has been suggested to be due to increased photosynthesis under the more diffuse radiation conditions (Roderick et al., 2001) or a decrease in microbial respiration associated with the global cooling (Jones et al., 2003). Stratospheric climate engineering may further increase net primary productivity by increasing the diffuse component of solar radiation (Mercado et al., 2009), although this would depend strongly on latitude and other factors; this might also result in further effects on the hydrological cycle via evapotranspiration (Oliveira et al., 2011).

2.2.7 General effectiveness and constraints of modifying the planetary albedo

The effectiveness of albedo modification in preventing temperature rise is reliant on its continued operation. Accordingly, if greenhouse gas emissions continue, and it were desired to keep global mean temperatures below some threshold (e.g., the 2°C limit frequently discussed by policy makers), then the scale of deployment would need to be increased to counteract the increase in greenhouse gas concentrations. If albedo modification were then abruptly terminated, global mean temperatures would quickly return to approximately the same temperatures as would have been expected had albedo modification never been implemented (Jones et al., 2013; Alterskjær et al., 2013; Irvine et al., 2012). As can be seen in Figure 2.9, this

rapid warming following the abrupt termination of intervention is a robust response that is seen in all models of the GeoMIP multi-model ensemble. A similarly rapid response is found for precipitation and sea ice (Jones et al., 2013). These rapid rates of change would be expected to have significant impacts on ecosystems, which might have even greater difficulty adapting than under a business-as-usual or modest mitigation scenarios with slower rates of temperature increase. Thus, if albedo modification ever were to be deployed at a scale that exerted a significant cooling effect, and were to then be terminated for some reason, then the resulting rate of temperature increase (and associated impacts on ecosystems) could be made less severe by phasing out the implementation over the course of many years or decades, rather than abruptly (Irvine et al., 2012).

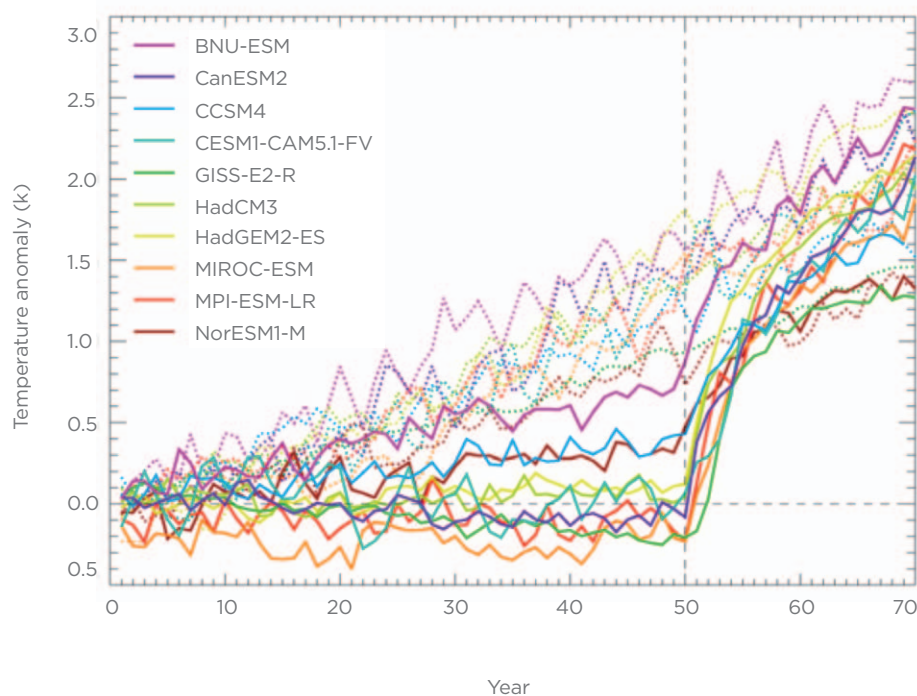


Figure 2.9:

Multi-model ensemble simulations (GeoMIP G2) of the impact on temperature due to albedo modification by reduction of the solar constant. The global mean temperature change compared to the pre-industrial control simulation is shown for each of the models, with the dotted lines representing simulations with no albedo modification and solid lines representing simulations with albedo modification up to year 50, after which the albedo modification is terminated.

Source:

Jones et al. (2013).

2.2.8 Carbon cycle climate feedbacks between modifying the planetary albedo and removing greenhouse gases from the atmosphere

Feedbacks between the climate and the carbon cycle mean that intervention in one will influence the other. On the one hand, reducing global surface temperatures via albedo modification would impact carbon cycle fluxes both by altering terrestrial and marine biological productivity and changing the solubility of CO₂ in the ocean surface (due to temperature changes). On the other hand, greenhouse gas removal methods that modify the land or ocean surface will alter the radiation balance of the Earth–atmosphere system.

The influence of albedo modification on the carbon cycle has been explored in a limited number of modelling studies (Jones et al., 2013; Matthews and Caldeira, 2007; Eliseev, 2012; Muri et al., 2015; Bala et al., 2002; Kalidindi et al., 2014; Jones and Haywood, 2012; Fyfe et al., 2013; Irvine et al., 2014a). Biological productivity is frequently characterised by the vegetative net primary productivity. As discussed in Box 2.3, under both business-as-usual scenarios and in a future climate-engineered world where global temperatures are held at present-day values, net primary productivity is projected to increase due to CO₂ fertilisation (Jones et al., 2013; Glienke et al., 2015; see also Box 2.2). Changes to the climate would also affect other aspects

of the carbon cycle. For example, the respiration rate of soil bacteria in a cooler climate is expected to be lower, resulting in more carbon being stored in soils. The response of the terrestrial residence time of carbon is uncertain under albedo modification. Furthermore, a cooler ocean can absorb more CO₂. In one study, applying albedo modification to return global mean surface temperatures of a business-as-usual CO₂ emission scenario (RCP8.5) back to pre-industrial values was projected to draw down about 920 Gt CO₂ from the atmosphere by the year 2100 (Keller et al., 2014), with the resulting decrease in the mean CO₂ mixing ratio shown in Figure 2.10. This predicted “unintended” drawdown of CO₂ is actually larger than the maximum drawdown that can be expected from some greenhouse gas removal techniques.

In turn, greenhouse gas removal methods can modify the surface solar radiation balance via changes in surface albedo. This is a largely unexplored topic, although initial indications are that the effects would likely not have a significant impact on the global climate system (Keller et al., 2014).

Overall, at present, there are very large uncertainties about the feedbacks in both directions, and considerable further work would be needed in order to develop a more robust understanding of the connections between greenhouse gas removal and albedo changes.

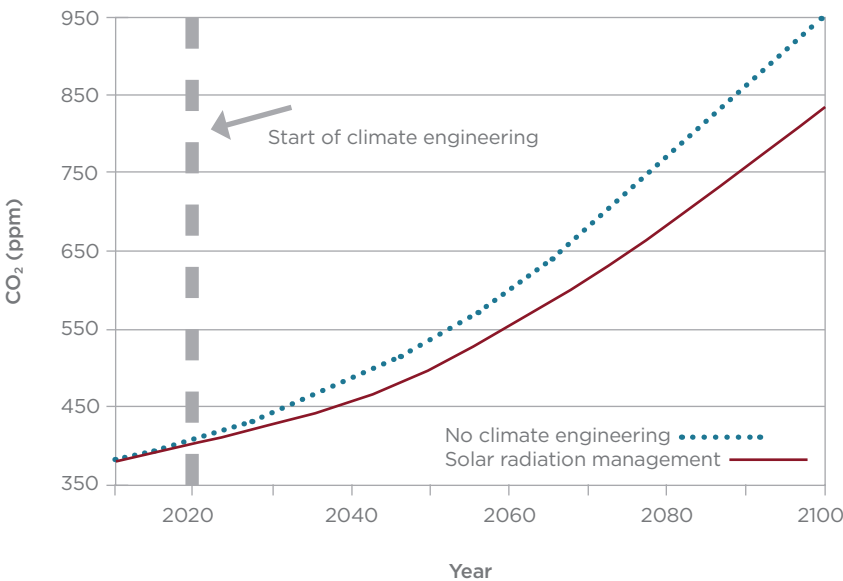
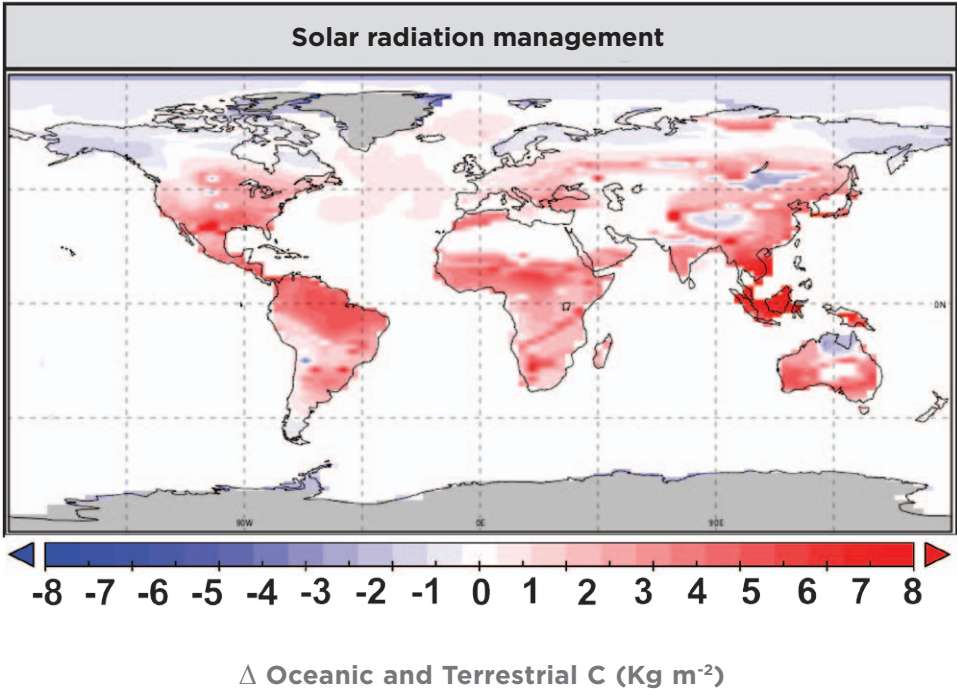


Figure 2.10: Enhanced carbon uptake from a deployment of albedo modification that brings global average temperatures back to the pre-industrial level in an RCP8.5 scenario. Top panel: Simulated changes in globally averaged annual atmospheric CO₂ mixing ratio for the control and albedo modification simulation; bottom panel: Simulated year 2100 mean annual differences in the terrestrial and oceanic carbon inventories for the albedo modification simulation minus the control simulation.

Source: Keller et al. (2014), adopted from original figures.



3. Emerging societal issues

Beyond the technical challenges of understanding and possibly exerting some degree of control over the impacts of climate engineering on the Earth system as described in the previous chapter, techniques that have been proposed for removing greenhouse gases or for modifying the planetary albedo or cirrus clouds all raise complex questions in the social, ethical, legal, and political domains (Shepherd et al., 2009). This chapter assesses several of these societal issues, which to a considerable degree shape the debate around different climate engineering techniques. Even the mere ideas of greenhouse gas removal or albedo modification raise important questions, for example about the possible influence that considering such techniques may have on efforts toward mitigation and adaptation (3.1.1), or about the responsibility that humans have toward the environment (3.1.2). This chapter also considers public awareness of the different techniques, and how this has developed in recent years (3.1.3), drawing on a preliminary analysis of four field experiments or trials to assess potential avenues for future research and attention. A second part of the chapter assesses aspects of potential climate engineering deployment, such as political conflicts that may ensue (3.2.1), along with economic considerations (3.2.2). As will be shown, this also raises normative questions of fairness and justice, based on the distribution of benefits and costs (3.2.3) and of compensation for harm (3.2.4). The different issues discussed in the first two parts make decisions on interventions in the climate system, as well as about research on such interventions, extremely challenging. Building on this, the assessment presented in Chapter 6 addresses some of the difficulties for decision making and draws on various principles to examine the possible directions that such decisions may take. Within the different subsec-

tions of the chapter, the issues are presented first in a general way and are then applied to the three techniques detailed in the previous chapters (BECCS, OIF, and SAI).

3.1 Perception of potential effects of research and deployment

There are several issues related to the manner in which the discourse around climate engineering is perceived by policy makers and the broader public, including possible responses to the perception — justified or not — of a near-future “solution” to climate change. This section focuses particularly on the responses to research on climate engineering and on various aspects of carrying out the discourse, e.g., participation and consultation.

3.1.1 Moral Hazard

A prominent concern around climate engineering has been the fear that discussing, researching, and developing climate engineering techniques may have negative effects on efforts to reduce emissions. In general, such concerns have been summarised under the term “moral hazard” (Keith, 2000), which originated in insurance theory (Arrow, 1963). These concerns prevented many researchers from engaging with the topic until an editorial by Paul Crutzen in the journal *Climatic Change* (Crutzen, 2006) served to break the “taboo” (Lawrence, 2006) perceived by many in the atmospheric research community. It has been suggested that the moral hazard effect may occur via several mechanisms, which may also interact. These include: increasing risk-prone behaviour; diverting attention, efforts, and incentives from the challenge of

decreasing greenhouse gas emissions; encouraging political stagnation; supporting a cost/benefit-based delay of emission reductions; and worsening existing coordination problems in climate policy (see, for example, Hale, 2012, Lin, 2013, Preston, 2013).

Three background assumptions are often associated with the moral hazard argument. First among these is the danger that climate engineering techniques could be misused to protect the vested interests of involved actors. In particular, this involves the possibility that developing and applying climate engineering techniques could be used to strengthen the position of those who oppose emission reductions, especially by those that profit from fossil-fuel-intensive production processes and fossil fuel extraction (Jamieson, 1996, Virgoe, 2009: 105, Ott, 2012). Secondly, many have associated the array of possible responses to climate change with hopes for more fundamental changes to the current systems of production and consumption. Proposals for climate engineering, however, generally focus on modifying the physical environmental aspects of global warming rather than on the underlying societal causes. This would potentially decouple other societal issues such as consumerist lifestyles, mass agricultural practices, unsustainable processes of energy and consumer goods production, tropical deforestation, and population trends from the debate on global warming (Corner and Pidgeon, 2010; Schäfer et al., 2014). Finally, such concerns about maintaining the status quo can be linked to an underlying concern about the use of technological fixes, which are seen as being based on a deep-rooted habit of solving problems with technology by changing the external circumstances (for example, applying more technology) rather than by changing behavioural patterns (Borgmann, 2012). Even though such fixes are used in many areas, their moral status is generally considered ambiguous and the techno-fix framing is often used negatively, to connote an inadequate and morally problematic solution to an underlying problem (Preston, 2013).

Views sceptical of the moral hazard argument have also been set forth. Firstly, the ethical implications of the suggested relationship between mitigation and climate engineering techniques are unclear. As Preston (2013) points out, warnings of a moral hazard are ambiguous and cannot provide clear guidance

because it is unclear what action should follow from such warnings. Secondly, behavioural change due to reductions in the risks one faces can be seen as a rational response to the emergence of a new situation. Often, the negative evaluation of such a behavioural change is linked to the specific characteristics of the behaviour for which insurance is sought, rather than the measure taken to reduce the risk (Hale, 2009). Thus, safety technologies that create or could create an increase in risk-prone behaviour are not always abandoned, at least not as long as the benefits are believed to outweigh the possible costs (Bunzl, 2009). What seems to make individual climate engineering techniques problematic is the assumption that they will contribute to an underestimation or intentional downplaying of the risks and uncertainties associated with emitting greenhouse gases, and thus to the transfer of those risks to others, especially future generations. Thirdly, very little empirical evidence is currently available in this area, and claims about a moral hazard may only be testable, if at all, if the situation ever actually develops in a substantial and observable form (Lin, 2012, Preston, 2013). Fourthly, it is unclear whether mitigation efforts would be more successful in the absence of discussions on climate engineering, as many different factors contribute to the political inertia against reducing emissions (Davies, 2011). Finally, some argue that the prospect of specific climate engineering techniques (especially SAI) could have the reverse effect, as the mere thought that they might be deployed might be perceived by some as being so threatening that they strengthen the support for mitigation (Davies, 2010, Davies, 2011, Moreno-Cruz and Smulders, 2010). Millard-Ball (2012) argues that it may be rational for other countries to respond to such a threat by reducing emissions to the level where a country that is threatening to deploy a technique such as SAI no longer perceives a necessity to do so.

The moral hazard arguments have been applied especially to SAI, which has been referred to as a fast and cheap “technological fix” (Corner and Pidgeon, 2010, ETC Group, 2010). Due to incomplete knowledge about potential side effects, high risks, and pervasive uncertainties, there is very little support in the literature for SAI as a replacement or substitute for mitigation (Rickels et al., 201; Shepherd, 2009).

Greenhouse gas removal techniques such as OIF and BECCS might also create a moral hazard, which would have both similarities and differences to the moral hazard potentially created by SAI. Here the focus is not on the possibility of rapidly counteracting specific effects of climate change, but rather on the potential for developing techniques, or for creating the perception that it will be possible at some point to develop such techniques, that might help address the physical causes of global warming at a later point in time. Given the prominent role that greenhouse gas removal techniques are given in the mitigation pathways underlying RCP 2.6 (and to some extent RCP 4.5), this concern seems particularly noteworthy (see Section 2.1.2). Even though the effectiveness of many techniques that aim to remove greenhouse gases from the atmosphere seems questionable in light of the scale of current emissions and the concentrations of atmospheric greenhouse gases that might occur in the future, the mere perception that greenhouse gases might be removed from the atmosphere at a large scale may still lead to reduced efforts towards mitigation. Techniques for removing greenhouse gases may therefore also exacerbate carbon-based path dependency in the near term (Unruh and Carrillo-Hermosilla, 2006).

3.1.2 Environmental responsibility

The potential use of different climate engineering techniques that have large-scale influences on the climate system has been ascribed various negative character traits, including hubris, arrogance, and recklessness (Kiehl, 2006, Hamilton, 2013). Some of these arguments are concerned with the potential negative influence of specific climate engineering techniques

on humanity's relationship to nature (Ralston, 2009). From this perspective, such techniques may not only have adverse effects on the environment, but could also exacerbate a perceived lack of environmental responsibility (Buck, 2012). In this sense, the intentional manipulation of the climate has been described as a further instance of humans' unwillingness to "live with nature" (Jamieson, 1996) and the "crossing of a new threshold on the spectrum of environmental recklessness" (Gardiner, 2011). This also hints at the potential hubris toward human capabilities in which domination or control over natural processes is sought (Ralston, 2009; Joronen et al., 2011). Concerns have been raised (Matthews and Turner, 2009) that, due to the potential for human error and unintended consequences of such interventions, the claim of controllability created by overconfidence and "appraiser's optimism" may turn out to be an illusion (Amelung and Funke, 2013). Nevertheless, the use of terms such as hubris may be misleading. Individual climate engineering techniques differ greatly with regard to their novelty, scalability, and expected environmental impacts (Preston, 2013, Heyward, 2013), so at a minimum an explicit differentiation between individual techniques is necessary. It is also debatable whether direct interventions in the climate system need to be understood as transcending a threshold in our relationship to the Earth (Ridgwell et al., 2012). Some argue that humanity is already engaged in a large-scale experiment with the climate through the use of fossil fuels (Davies, 2011). Here, the key point concerns an ethical distinction between intentional and unintentional interventions in natural systems and processes, and what this means for our responsibility. This is a discussion that has just started to emerge (Jamieson, 1996, Tuana, 2013).

3.1.3 Public awareness and perception

Box 3.1

What are public awareness, acceptance, and engagement?

- **Public awareness** refers to what people think they know about climate engineering, whether correct or not, and can therefore consist both of factual information and beliefs about the topic.
- **Public acceptance** refers to a widely shared belief held by politicians, industry, and citizens that a given activity or the application of a particular technology is beneficial for society. It should be distinguished from community acceptance (Wüstenhagen et al., 2007), which refers to whether a specific group of citizens are prepared to accept the siting of a given technology near to where they live.
- **Public engagement** is an umbrella term used to describe any activity that engages in a public dialogue. These can have different levels of depth (Rowe and Frewer, 2005), from communicating information (one-way) to participation/deliberation (two-way dialogue involving listening, reflection, and interaction).

The literature on public awareness and public acceptance of climate engineering techniques is recent and diverse. Since awareness is typically assumed to be a precondition for the formation of beliefs and attitudes toward a novel technology, social science research has investigated both public awareness and acceptance of different climate engineering techniques and proposals. Empirical studies have used a variety of methods, including questionnaires and focus groups, with research designs including correlational analyses of surveys (e.g., Bellamy and Hulme, 2011), a quasi-experimental study (Kahan et al., 2012), and deliberative focus groups (e.g., Macnaghten and Szerszynski, 2013). Given that awareness of climate engineering is particularly low (results of a UK-based study (Pidgeon et al., 2012) show that 75% of the respondents in the national sample had either “not heard of” the term climate engineering or knew “almost nothing about it”), some research has employed methods of public dialogue as a means to both raise awareness and to solicit attitudes from participants (Bellamy et al., 2013; Macnaghten and Szerszynski, 2013).

The literature has had varied foci, ranging from climate engineering in general to specific techniques or groups of techniques, particularly planetary albedo

modification (e.g., Mercer et al., 2011). Typically, techniques for greenhouse gas removal are not discussed in isolation, but within the context of contributions on climate engineering in general and as part of the literature on CCS, including BECCS. Additionally, some studies have primarily focused on perceptions of climate change, within which climate engineering has been incorporated as one element (e.g., Bostrom et al., 2012); or on the perceptions of possible responses to climate change — one being climate engineering (Poumadère et al., 2011).

Studies of public awareness suggest that wording is important. The use of the term “climate engineering” was associated with higher levels of public awareness than use of the term “geoengineering” (Mercer et al., 2011). In this context, it is counterproductive to think of individuals as being similar to “empty vessels” that need to be filled with scientific/factual information about climate engineering. The findings of qualitative and deliberative research (e.g., Pidgeon et al., 2012) indicate that members of the public associate climate engineering with diverse, complex ideas, including “messing with nature”, science-fiction, “Star Wars” and environmental dystopia.

Two studies that applied deliberative methods suggest a position of “qualified” or conditional acceptance, in which support for research into climate engineering may not correlate with support for actual deployment (Parkhill and Pidgeon, 2011; Macnaghten and Szerszynski, 2013; Pidgeon et al., 2013). Mercer et al. (2011) found some acceptance of research on albedo modification techniques in a web-based survey in the UK, US, and Canada. Support was found to decrease when respondents were asked about using such techniques immediately, or to stop a climate emergency, while respondents disagreed when asked whether such interventions should ever be undertaken. Pidgeon et al. (2012) found greater support in the UK for techniques to remove greenhouse gases than for albedo modification, which they suggest may be linked to concerns about “interference with nature” (see Section 3.1.2), as well as issues of reversibility and control.

A study by Macnaghten and Szerszynski (2013) found public concern regarding the potential for international conflict following unilateral actions by nation-states, together with scepticism concerning the ability of national governments and international institutions to effectively govern techniques such as SAI in light of the slow progress on coordinated climate change mitigation.

Public uncertainty regarding the value of field trials is a consistent finding, revealing doubts about avoiding unintended consequences to weather systems, as well as concerns about being fully able to predict the impacts of large-scale deployment following a relatively small-scale field trial (Parkhill and Pidgeon, 2011). Research on small-scale field trials suggest similarities with previous research on the “NIMBY” (Not In My Back Yard) concern of local communities, including issues of local governance regarding site selection and public consultation (Parkhill and Pidgeon, 2011; Pidgeon et al., 2013). Informing public audiences about past geopolitical attempts to shape weather and climate, and allowing deliberative discussions of the implications of this, appears to have the potential to lead to a hardening of participants’ attitudes towards consenting to any research on albedo modification (Macnaghten and Szerszynski, 2013). This demonstrates the significance of “framing effects”: public acceptance of climate engineering will

be influenced by how it is presented and by the issues or technologies with which it is associated.

Although these studies begin to indicate the complex array of worldviews, values and beliefs that are likely to influence public perception of climate engineering, conclusions based on their findings are necessarily tentative. Previous studies employed differing methodologies and independent variables; consequently, replication is required to corroborate their findings and to determine the dependence on regional and cultural contexts. Low levels of public awareness would suggest that attitudes may not yet have formed for many people and even if they have, those opinions are likely to be weak and unstable. For this reason, some have suggested that the use of qualitative research and deliberative methods of public engagement may be the more suitable methodological approaches to adopt (Corner et al., 2012).

By comparison, a more substantive literature exists on public acceptance of CCS, including several studies focusing on the case of BECCS (see section 3.1.4). Some of these studies have compared attitudes to CCS with those surrounding renewable energy (Oltra et al., 2010; Upham and Roberts, 2011a; Scheffran and Cannaday, 2013), indicating that public acceptance of the latter is higher than for the former. They also illustrate doubts about whether CCS could contribute to solving the climate change problem. Palmgren et al. (2004) report mixed results on attitudes to CCS, correlating with views on anthropogenic climate change. Providing more information resulted in stronger opposition to CCS, especially against storage in the ocean. They conclude that public acceptance of CCS would require prior acceptance of the climate change problem. Huijts et al. (2007) find a slightly positive attitude toward carbon storage in general, whereas Oltra et al. (2010) find that the dominant public view of CCS is sceptical due to perceived risks. Terwel and Daamen (2012) point out that NIMBY effects do not necessarily dominate initial reactions to CCS. Several contributions on CCS emphasise the importance of trust in government and in the actors involved (Upham and Roberts, 2011b; Itaoka et al., 2012; Terwel and Daamen, 2012).

The effect of information upon public acceptance is uncertain (Fischel et al., 2009; Itaoka et al., 2012). Huijts et al. (2007) find that information is not always asked for and does not necessarily increase acceptance — people that strongly object to technologies are often highly informed about them. As mentioned above, Palmgren et al. (2004) found that information provision increased resistance to CCS. Beyond the quantity of information provided, research suggests the importance of information qualities. When attitudes are weak or unstable, framing effects can play a significant role in shaping attitudes subsequently elicited. This poses a challenge for deliberative public engagement, since the a priori choices made by the research team regarding what information to provide to participants about climate engineering are likely to have a strong effect upon the results. Given this, increased use of experimental designs in future studies would be useful to test the impacts on public acceptance of providing specific forms of knowledge on climate engineering.

3.1.4 Participation and consultation: questions from example cases

This section examines four example cases (Box 3.2-3.5) that were selected because of their potential relevance to questions that arise in the context of discussions of the three main techniques examined in this assessment:

- one field experiment examining OIF;
- two projects aimed at developing prototype implementations of BECCS;
- one project that included a planned field test of a delivery technology for albedo modification by SAI.

The exploratory assessment of these example cases brings to the fore questions about the role of risk assessment, the impact of private sector involvement on public perception, and the role of trust and public participation, as well as governance in climate engineering field experimentation.

Box 3.2

LOHAFEX Iron-Fertilisation Experiment

Goal: The LOHAFEX project was designed to perform in-situ iron-fertilisation with ten tonnes of iron sulphate applied over 300 km² to improve scientific understanding of the relationship between plankton ecology and the carbon cycle and the role that this may have in both historical and future climatic changes (AWI, 2009).

Description: LOHAFEX has to be considered against the background of several previous experiments (Strong et al., 2009b), in response to which environmental non-government organisations (ENGOS) and the Conference of the Parties (COP) to the London Convention (LC) raised concern about violation of international laws on marine dumping (see Section 4.1.2). In May 2009, the UN Convention on Biological Diversity (CBD) passed a Decision that included a section on OIF (Convention on Biological Diversity, 2009), requesting all member states to ensure that OIF activities do not take place, with the exception of small-scale scientific studies in coastal waters, until there is more scientific evidence to justify such activities.

Prior to the CBD Decision, the LOHAFEX project started in 2005 as a collaboration between the Alfred Wegener Institute for Polar and Marine Research, in Germany, and the National Institute of Oceanography, in India, funded by the German Federal Ministry of Education and Research (BMBF) and the Government of India. The field experiment was to be carried out in the Southwest Atlantic in early 2009. It received publicity after the ship had left harbour, when a protest was initiated by three ENGOs (the ETC Group, followed by Greenpeace and WWF). The protests questioned the legality of the experiment and lack of independent monitoring. The BMBF postponed the project start for two weeks and organised independent assessments by experts, evaluating the scientific value of the experiment and whether the recent CBD Decision was to be considered binding. The three separate legal opinions that were solicited were in agreement that the experiment was legal, as the CBD decisions are legally non-binding; and that iron fertilisation experiments do not constitute 'dumping' if the goal is to undertake scientific research (Proelss, 2009).

The BMBF permitted continuation of the experiment, although calls for greater clarity and for a clear distinction between experiments and commercial projects followed (Strong et al., 2009b). The LOHAFEX results uncovered unforeseen difficulties in the applicability of iron fertilisation as a technique to remove atmospheric CO₂: iron addition stimulated phytoplankton production for a short time, but due to low silicic acid concentrations in the fertilised waters, there was only limited formation of diatoms, a type of phytoplankton with a glassy (silica) shell that provides protection against grazing, and which were primarily formed in previous fertilisation experiments. The softer phytoplankton that were formed were quickly consumed by a surge of zooplankton (copepods), and no significant increase in CO₂ drawdown was observed (Martin et al., 2013).

Bio-Energy with Carbon Capture and Storage in Greenville, Ohio

Goal: The Greenville, Ohio project described in this second example case aimed to demonstrate the feasibility of integrating bioenergy generation from corn ethanol with carbon capture and storage (CCS), with two main specific objectives: 1) to capture one million tons of CO₂ over four years from a corn ethanol plant and store it in a saline aquifer at 1,000 metres depth, and 2) to demonstrate the technical and commercial potential of large-scale BECCS.

Description: The project was led by Battelle Andersons Marathon ethanol plant and two local governments (Darke County and Greenville). It started in early 2007 with preliminary briefings between the companies and local government officials, and was publicly announced in May 2007 (Hammond and Shackley, 2010).

The first public meeting was organised by the companies in August 2008. In March 2009, a public movement called Citizens Against CO₂ Sequestration raised questions concerning: i) the possible risks, hazards and liabilities (e.g., groundwater contamination, use of explosives, increased risk of earthquakes, road closures, and decrease in property values); ii) a feeling of being experimented upon by the industry and government; and iii) a distrust of the companies involved and the science underpinning the technology, as well as scepticism concerning anthropogenic climate change. The group expressed their concerns about a perceived lack of transparency and consultation with the local community on the part of the developer, and was critical that plans did not include sufficient local development opportunities (Hammond and Shackley, 2010). Despite this opposition, the Ohio Environmental Protection Agency approved the project in June 2009, with a drilling test to be carried out in July 2009. Over the next three months, the opposition intensified, including a protest march and several protest meetings (attracting hundreds of people). Opposition to the project was also influenced by the circumstance that the company was new to the region and its motives for supporting a BECCS project were not fully trusted (with some residents believing that the motivation was to more broadly influence future planning permission processes).

In August 2009, the County Commissioners formally requested that the project be terminated, by which point it seemed that local and state political support had waned. The project was ultimately cancelled by the developers that same month. Since then, there have been no further attempts to develop BECCS or CCS technologies in this region, and Citizens against CO₂ Sequestration continues to support protests against CCS activities in other regions.

Bio-Energy with Carbon Capture and Storage in Decatur, Illinois

Goal: The BECCS activities in Decatur, Illinois have the same overall aim as was proposed for the Greenville, Ohio project: to demonstrate the feasibility of integrating bioenergy generation (corn ethanol) with CCS. The goal of the first project carried out in Decatur, of capturing and sequestering one million tonnes of CO₂, was achieved in January 2015 (<http://www.energy.gov>, last accessed 03 June 2015). In 2009, a second project was granted funding to build on and expand the first project. Its goal is to expand the first project to commercial-scale CO₂ storage capacity by integrating the original facilities with newly constructed facilities, and to sequester and store approximately one million tonnes of CO₂ per year (Gollakota and McDonald, 2014).

Description: The first project to be conducted in Decatur, the Illinois Basin-Decatur Project (IBDP), was carried out by the Midwest Geological Sequestration Consortium (MGSC, led by the Illinois State Geological Survey, ISGS), in partnership with Schlumberger Carbon Services and Archer Daniels Midland (ADM), a global food-processing and commodities trading company that operates a corn ethanol fermentation facility adjacent to the storage site. Injection is taking place on ADM's property, with ADM holding the permit for injection and providing the CO₂ (Streibel et al., 2014). The project is largely funded by the U.S. Department of Energy (Finley et al., 2013). Drilling of several wells started in 2009, and CO₂ injection began in November 2011 (Finley, 2014). The second Decatur project, the Illinois Industrial CCS Project, is a follow-on project to the IBDP. It received approval for DOE funding in 2009, and includes a partnership with Richland Community College (RCC).

RCC has provided a platform for community engagement (consultation, training, education, and open forums since 2010, with typically 100 or so people attending), but has also arranged presentations and question-and-answer sessions between the local community, technical experts (e.g., ISGS), and the companies involved (ADM and Schlumberger). RCC has devised a number of specialised degree options on CCS in the last few years. Additionally, a National Sequestration Education Center (NSEC) was formed as part of the Illinois Industrial CCS Project's implementation. With various classrooms and laboratory facilities, it is intended to provide community and regional outreach through an interactive visitor-centre. The centre also aims to position BECCS within the wider context of sustainable energy options, including wind turbines, solar power, and geothermal energy. The centre is located at the injection point for the CO₂ storage site, the long-term aim being that visitors can observe the injection process and witness how the project evolves.

To date, there has been no organised opposition to the Decatur BECCS project.

Stratospheric Particle Injection for Climate Engineering (SPICE)

Goal: The SPICE project was designed to investigate, via computer modelling, whether the intentional injection of large quantities of particles into the stratosphere could mimic the cooling effects of volcanic eruptions. In addition to computer modelling, SPICE set out to investigate a possible delivery mechanism: a tethered balloon with an attached hose and pump device. The team proposed constructing a 1-km-long prototype of the 20-km hose and associated balloon and pump equipment as a first step toward evaluating the feasibility of such a system for possible future use in SAI deployment.

Description: Although the “test bed” would not be a test of the physical impacts of a climate engineering technique (the trial was designed to spray only a small volume of water, testing the delivery device but not the climatic or atmospheric response to climate engineering suggestions), SPICE was due to undertake the UK’s first field trial related to implementation aspects of an albedo modification technique (Fischelick et al., 2009; Macnaghten and Owen, 2011). It was funded by three UK research councils (the Engineering and Physical Sciences Research Council, the Natural Environmental Research Council, and the Science and Technology Facilities Council), and was one of two projects on climate engineering, along with the Integrated Assessment of Geoengineering Proposals (IAGP) project, to emerge from a so-called “sandpit event”. Sensitivities over the potential “slippery slope” effect that such an experiment might produce, particularly given that the proposed test bed would move beyond laboratory tests, led to the establishment of a “stage-gate” approach to implement principles of “responsible innovation”. This was overseen by an expert panel (including scientists and a representative from an environmental NGO) that would advise on whether the experiment should go ahead based on the fulfilment of certain criteria: i) risks to be identified, managed, and deemed acceptable; ii) deployment to be compliant with relevant regulations; iii) clear communication of the nature and purpose of the project; iv) applications and impacts described and mechanisms put in place to review these; v) mechanisms identified to understand public and stakeholder views (Stilgoe et al., 2013).

In September 2011, following the advice of the stage-gate panel, the test bed was postponed to allow the team behind it to undertake additional work to fulfil criteria iii-v. At the same time, a vocal debate was taking place in the media, and a petition organised by ETC Group and signed by 50 NGOs was sent to the UK Government demanding that the project be cancelled. In May 2012, the project team cancelled the experimental part of SPICE, although the rest of the project (lab- and desk-based) continued. Several factors converged to result in the decision for cancellation: i) the lack of a clear regulatory framework by which to govern climate engineering field research (Stilgoe et al., 2013); ii) a potential conflict of interest around a patent application related to the tethered balloon delivery mechanism, submitted by one of the mentors at the “sandpit” and including one of the SPICE project investigators as an inventor, which was not apparent during the sandpit event (Stilgoe et al., 2013); and iii) the diminishing usefulness of the experiment as the project continued (see also the personal statement by the project’s principal investigator, Matthew Watson, on www.thereluctantgeoengineer.blogspot.de/; post from 16 May 2012).

The potential conflict of interest caused considerable consternation amongst the SPICE project partners, stage-gate panel members and within the broader research community (Stilgoe et al., 2013).

The opposition of ENGOS, and a subsequent public outcry have been cited as additional reasons for the cancellation (Cressey, 2012), although these claims were vigorously rebutted in the media by the SPICE project’s principle investigator (Watson, 2013).

The following sections distil questions that arise from these exploratory assessments of the example cases. While the exploratory assessments described above do not allow for making generalisable claims, their value lies in pointing to areas that deserve further attention and inquiry. For all areas described below, further research would be necessary to better understand the social dynamics involved.

What is the role of risk assessment in designing climate engineering field experiments?

Clearly distinguishing between what counts as experiment, test bed, demonstration, research, development, and deployment proves difficult. The experiences of this issue in the example cases indicate that openness and transparency about the intent behind an experiment, its scale, and possible routes to scaling up experiments to the level of demonstration or implementation play important roles in shaping public perception of various types of studies. Given the technical uncertainties and complexities in the example cases, and the breadth of stakeholder standpoints and motives, it is unlikely that all stakeholders involved would ever be fully satisfied with any particular risk assessment. This suggests it might be useful to develop principles for guiding decisions on whether or not to take forward a climate engineering experiment. Although different methodologies were used to frame, assess, and mitigate potential risks and impacts across the example cases (risk impact assessment and legal analysis in LOHAFEX; Underground Injection Control permit application for Decatur project, Illinois; use of the responsible innovation framework in SPICE), in all cases, novel assessment frameworks or modifications of existing frameworks were deemed necessary by those responsible for the projects.

What is the role of private sector interests in shaping public perceptions of climate engineering field experiments?

Personal and private-sector interests in a project, and how such interests are portrayed and perceived, may influence whether and to what extent a particular project can be realised. The existence of private sector or personal interests, whether as intellectual property rights on the part of individuals or the commercial interests of private companies, can become a source of conflict in the context of growing ethical and political debates around the commercialisation of and motivations for climate engineering research and technology development. The example cases suggest that, in order to prevent or resolve such conflicts, transparency and openness on intellectual property, and commercial or other vested interests may be beneficial. Entrenched views and scepticism concerning the will of private sector actors to work for the collective good may undermine consensus-building. Based on the example cases described here, it appears that building trust in project developers, project managers, and mediating institutions can prove fundamental to the acceptance of climate engineering research projects.

What is the role of trust and public participation in shaping public perceptions of climate engineering field experiments?

Public participation and engagement can be crucial to a project's success. Local communities intensively opposed one of the field tests described above (Greenville) and were supportive in two other cases (Decatur and SPICE), whereas LOHAFEX was more remote from local communities. In the LOHAFEX and SPICE cases, it was predominantly international environmental NGOs and the media that played a pivotal role by drawing public attention to the activity, and in the case of LOHAFEX also questioning its legality. The example cases seem to suggest that early and ongoing public participation and engagement is an important consideration for experiments in this sensitive area of research, but at the same time does not

guarantee acceptance. Effective public participation and engagement requires relationships of trust between the different actors and stakeholders involved, which in turn often requires a history of institutions working together effectively.

What is the role of governance for climate engineering field experiments?

The application of some form of governance did not guarantee the success of the projects (two of the four example projects were not completed). Lack of clarity regarding the applicability of an international resolution (the UN CBD) led to controversy and to the adoption of new assessment procedures by the relevant scientific and research funding communities. Further detailed consideration of such regulatory aspects is provided in Chapter 4.

3.2 Societal issues around potential deployment

While the preceding section has focused largely on climate engineering research, this section will consider issues surrounding the potential deployment of climate engineering techniques. Figures 3.1 and 3.2 illustrate that the deployment of climate engineering techniques such as SAI and BECCS may result in various potential impacts (black arrows) on physical, ecological, and social systems, possibly involving complex feedback processes (red arrows).

Figure 3.1 shows primary and secondary effects of climate engineering through SAI. According to model computations, SAI is capable of reducing the global mean temperature, but would also reduce the global intensity of the hydrological cycle and change regional weather patterns (Kravitz et al., 2013a; Tilmes et al., 2013). Although this could potentially reduce overall climate risk at a global scale, it would change the distribution of regional and local risks. Beyond the intended effects on climate, SAI would also change stratospheric temperature and chemistry, for instance influencing the ozone layer (Heckendorn et al., 2009; Tilmes et al., 2009), and would also affect the occurrence of acid rain, although it is unclear whether this impact would be significant in comparison to that attributed to surface-level pollution sources (Kravitz et al., 2009). In addition to side effects on natural systems, SAI has potential public health impacts, for example by decreasing the thickness of the ozone layer, in turn increasing UV radiation at the Earth's surface. It has also been suggested that the potential for conflict and social inequality could increase, for example through reductions in agricultural productivity and forestry or through dual-use problems that might arise from potential military applications, aggression and power plays associated with SAI techniques (Bodansky, 1996, Robock, 2008).

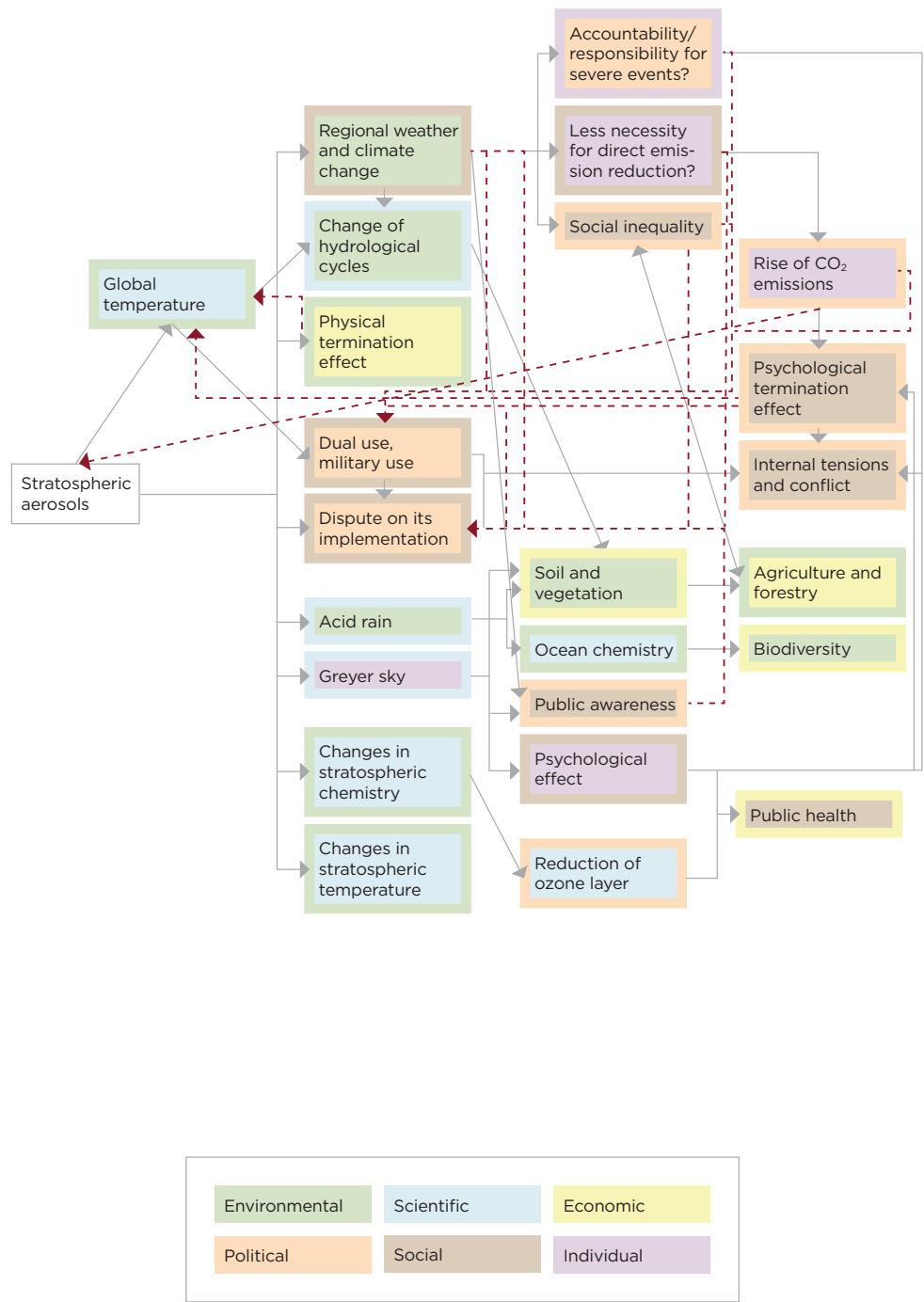
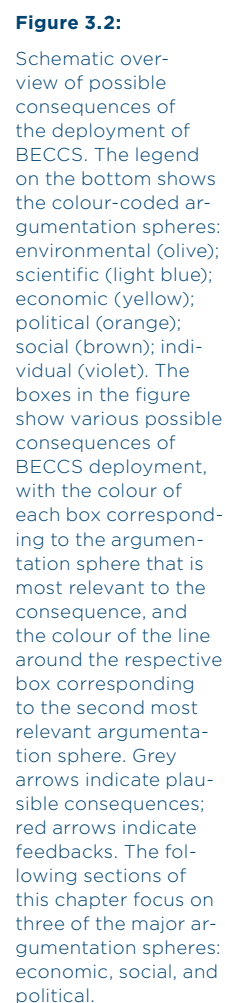


Figure 3.1: Schematic overview of possible consequences of the deployment of SAI. The legend on the bottom shows the colour-coded argumentation spheres: environmental (olive); scientific (light blue); economic (yellow); political (orange); social (brown); individual (violet). The boxes in the figure show various possible consequences of SAI deployment, with the colour of each box corresponding to the argumentation sphere that is most relevant to the consequence, and the colour of the line around the respective box corresponding to the second most relevant argumentation sphere. Grey arrows indicate plausible consequences; red arrows indicate feedbacks. The following sections of this chapter focus on three of the major argumentation spheres: economic, social, and political.

Source: Jasmin S. A. Link and Jürgen Scheffran, University of Hamburg.

scale, for instance if deliberate deforestation were to increase the albedo (Bonan, 2008; Peng et al., 2014). Deforestation can also lead to local increases in particulate matter, with implications for human health (Beckett et al., 1998), as well as for regional clouds and climate. Another effect might be accumulated health risks or even sudden deaths, if there were ever to be a substantial CO₂ leakage from underground storage sites (Solomon et al., 2007, *off.*).



Source:
Jasmin S. A. Link
and Jürgen Schef-
fran, University of
Hamburg.

Finally, the deployment of BECCS can also trigger local and national responses, for example due to the NIMBY effect (see Section 3.1.3), but also due to land use conflicts, increased food prices, or demands for subsidies for crop production.

3.2.1 Political dimensions of deployment

Since each technique is situated in a specific socio-political context, it is important to reflect on how this context might change through the emergence of that technique. Different political consequences would emerge along the lifecycles (concept development, research, deployment, and various possible side effects) of the various proposed techniques, if they were to be pursued. Critical issues include the use of resources during the deployment process, the direct impacts upon the environments in which the techniques might be implemented, as well as unexpected consequences of the techniques on nature and society (e.g., Caldeira, 2012; Honegger et al., 2012; Klepper, 2012; Lin, 2012; McLaren, 2012; NOAA, 2012; Mooney et al., 2012; Bellamy et al., 2012).

To date, there has been no integrated analysis of the linkages between climate change, the different climate engineering techniques, and their combined effects on human security, conflict risks, and societal stability.

Nonetheless, it has been argued that various conflict types may emerge throughout the lifecycle of climate engineering activities (Maas and Scheffran, 2012; Scheffran and Cannaday, 2013; Brzoska et al., 2012; Link et al., 2013). The following discussion distinguishes between five conflict types:

- competition over scarce resources;
- resistance against impacts and risks;
- conflicts over distribution of benefits, cost and risks;
- complex multi-level security dilemmas and conflict constellations;
- power games over climate control.

1) Competition over scarce resources: While many albedo modification techniques could likely be implemented with comparatively limited resources, most greenhouse gas removal techniques, such as BECCS or enhanced weathering, demand massive resource inputs to have a globally meaningful impact (see Section 2.1). Large-scale deployment of most techniques for the removal of greenhouse gases would need extensive infrastructures, thereby requiring the extraction and conversion of major resources (energy, raw materials, water, and land) that have an impact on natural and social systems in the affected regions. Thus, competition over physical resources; financial resources like investments; and immaterial resources such as human, social, and political capital could increase, affecting the availability of resources for mitigation and adaptation.

2) Resistance against impacts and risks: Anticipation of foreseeable or suspected impacts; detrimental side effects; and externalities such as pollution, modified rainfall patterns from SAI, or changes in ecosystems, vegetation, and crop yields; as well as principled opposition, might provoke resistance on local, national, and international scales. Furthermore, different techniques for the removal of greenhouse gases have specific local impacts (for example on water, biodiversity, forests, agriculture, or cities) that might encounter resistance from those who are affected and have inadequate coping mechanisms. Moreover, since technical, economic, and political limitations mean that some techniques are feasible only in certain regions, there may be particularly enhanced pressure on the resources and communities in these specific regions. This poses challenges for public acceptance and local coping mechanisms comparable to those associated with other forms of environmental modification, such as large-scale forest clearance for agricultural use, damming rivers, and the creation of artificial lakes (Conca, 2010; Balint, 2011).

3) Conflicts over distribution of benefits, costs, and risks: With its high leverage potential for short-term effects on the global climate system, as well as potentially unpredictable variations in regional impacts that might be adverse to local interests, SAI could provide ground for various conflicts. Given that, as discussed in Sections 2.2.1 and 2.2.6, temperatures would be decreased by different overall amounts depending on the amount of material that is injected,

and that the effects of this would differ regionally, there may be international disagreement over what form and scale of SAI deployment (if any) might be considered desirable, as well as over real or perceived injustices in the distribution of impacts from potential deployment. Distributional conflicts may also arise for greenhouse gas removal techniques, especially concerning cost-sharing as well as the distribution of risks of environmental degradation and detrimental impacts on human health or ecosystems.

4) Complex multi-level security dilemmas and conflict constellations: In the absence of international cooperation and broad consensus on high-leverage albedo modification techniques, individual attempts to regulate global mean temperatures could provoke countermeasures by states and the resistance of citizens, leading to potential security dilemmas ranging from local to global levels. In a hypothetical future world in which albedo modification techniques are utilised, it is conceivable that those deploying such techniques might be blamed for weather-related disasters and damage elsewhere, whether justified or not.

5) Power games over climate control: Some have argued that countries may use high-leverage techniques such as SAI as an instrument for power projection and hostile use (Dröge, 2012, Maas and Scheffran, 2012). During the Cold War, the superpowers supported a small amount of research on weather control for offensive and defensive purposes (Fleming, 2010). However, direct military applications of SAI or most other albedo modification techniques appear unlikely for the time being, due to the difficulty of accurately controlling the effects (and even detecting and attributing them). Should it become technologically feasible for countries to attempt to “optimise” their own climate, transboundary effects might trigger diplomatic crises and international disputes that hinder international cooperation.

3.2.2 Economic analysis

Economic analysis of climate engineering is in its infancy and has to be considered in the broader context of climate economics. Most of the focus in climate economics has been on how to control greenhouse gas emissions efficiently, and to explain under what circumstances the costs and benefits of emission control will support “early action” on mitigation.

The attention paid by economists to proposals for planetary albedo modification can be traced to a provocative article by Thomas Schelling (Schelling, 1996), who pointed out the difficulties in dealing with “something global, intentional, and unnatural” that at the same time has the potential to immensely simplify negotiations over how to address climate change. Schelling argued that albedo modification had the potential to reform climate policy, from an exceedingly complex regulatory regime into a problem of international cost-sharing — a problem with which the world is familiar. Barrett (2008a) subsequently argued that the economics of albedo modification through SAI are “incredible”, representing an opportunity to offset the warming effect of rising greenhouse gas concentrations at a very low cost. However, Barrett (2008a) also highlighted the challenges of governance and regulation (see also Chapter 4). These points of departure may explain why the economic literature on climate engineering has focused mainly on modifying the albedo, especially through SAI, rather than on removing greenhouse gases, which is instead generally discussed within the context of the economics of mitigation. To date, however, economic analyses of albedo modification have been primarily concerned with the possibility of cooling the planet at very low operational cost, often neglecting other costs that this would entail, such as price effects and social costs (see Box 3.6).

The economic literature on climate engineering can be divided into two branches that are further discussed in the subsections below:

- assessing costs and benefits;
- socio-economic insights from climate engineering scenarios.

3.2.2.1 Assessing costs and benefits

Different cost types need to be taken into account when considering the deployment of the various techniques (see Box 3.6 for definitions).

Cost types

1. **Operational costs:** cost of installing and maintaining a particular technique at current prices for capital goods and material inputs;
2. **Price effects:** the effect on prices due to increased demand for certain materials and goods by large-scale implementation of a technique;
3. **Social costs:** the overall economic cost of deploying a specific technique (i.e., operational costs plus external costs, accounting for price effects).

1) Operational costs

The broad range of estimates for the operational costs of several climate engineering techniques were previously discussed in Chapter 2 and will not be discussed further here.

2) Price effects

Large-scale deployment of greenhouse removal techniques and most proposed albedo modification techniques would generally require large investments, complicated infrastructures, and major material inputs to be effective (Klepper and Rickels, 2012). This may have a strong impact on those markets that provide the sources of such goods and materials. Existing cost studies usually neglect these effects. For example, measures such as spreading lime or iron in the ocean would require a large number of ships, which in turn would lead to a substantial demand shift in the global shipbuilding market (Klepper and Rickels, 2012). Similar effects, although smaller in scale, could be expected for the global airplane market if measures such as SAI were realised on a large scale using aircraft for the injection procedure. Price effects could also occur on the supply side if any techniques were deployed at very large scales: afforestation may increase the supply of wood once the trees mature, and CCS or BECCS may lead to the creation of additional CO₂ certificates, affecting the market price of carbon. These various effects would influence relative prices across the entire economy and should therefore be considered when assessing large-scale deployment of individual techniques.

3) Social costs

Despite the uncertainties concerning operational costs and the role of price effects, the greatest uncertainty about the costs of climate engineering, and in particular albedo modification through SAI, arises from its social costs, since present knowledge of such issues is basically non-existent (Klepper and Rickels, 2012). Scientific studies of the various techniques have shown that their use may have unintentional side effects, which can take the form of external costs or external benefits (where “external” in this context implies that a third party not involved in the market transaction has to bear costs or receives benefits). These costs and benefits could be related to the material in use, or to the deployment mechanism. They could also materialise as costs associated with impacts on specific ecosystems or with overall changes in the climate system. For a comprehensive analysis, potential side effects also need to be taken into account and incorporated in the social costs associated with each technique.

For BECCS, external costs are thought to be mainly related to competition for land use and water supply. External costs for OIF would predominantly involve impacts on marine ecosystems. Due to the dynamics of the ocean system, such effects could be distributed widely. Were SAI to successfully reduce global mean temperature, it would change the climate and climate impacts, for example impacting agricultural productivity and the occurrence of extreme weather events. There is limited research on the effect of SAI on various climate impacts, and there is uncertainty over the

regional climate response to SAI, which would in turn shape those climate impacts (Robock et al., 2008; Jones et al., 2009; Rasch et al., 2009; Ricke et al., 2010b; Berdahl et al., 2014). However, not all climate impacts are necessarily negative (Klepper and Rickels, 2014). For example, plant water stress is more strongly influenced by the number of extreme hot days than by variations in precipitation (Lobell et al., 2013). For example, high atmospheric CO₂ concentration is associated with greater water-use efficiency in some plant species (Keenan et al., 2013); in such a scenario, a reduction in extremely hot days via the deployment of SAI might provide agricultural benefits despite an overall reduction in precipitation, at least compared to an unmitigated climate change scenario (Pongratz et al., 2012). Furthermore, an increase in diffuse irradiation would be expected as a consequence of SAI implementation, which might further promote plant growth (Mercado et al., 2009). However, these considerations of the economic impacts of albedo modification techniques remain very preliminary, since the various interactions and feedbacks are not yet well understood (Klepper and Rickels, 2014) and potential gains in crop yields might only be observed for certain crops in certain regions (Xia et al., 2014).

3.2.2.2 Socio-economic insights from climate engineering scenarios

If one acknowledges the future technological potential for efficient abatement technologies and the slow transformation of industrial structures, then alternative approaches such as BECCS for removing greenhouse gases might “buy time” for such abatement technologies and transformations to develop (e.g. Kriegler et al., 2013). Nevertheless, it should be borne in mind that the atmosphere is only one reservoir of the global carbon cycle budget. Greenhouse gas removal will cause changes in natural carbon fluxes between the carbon reservoirs, which may significantly impact the effectiveness of the measures, either negatively or positively (e.g. Mueller et al., 200; Vichi et al., 2013; Klepper and Rickels, 2014). Accordingly, in order to properly conduct economic assessments of techniques for greenhouse gas removal and to appropriately model deployment scenarios, studies need to consider various carbon costs, which reflect the social costs that arise from scarcity of storage sites or from the changed ambient carbon fluxes between the

atmosphere and other carbon reservoirs (Lafforgue et al., 2008; Rickels and Lontzek, 2012).

Initial findings from modelling exercises and scenario analyses do not yet allow for an overall and comprehensive economic evaluation of SAI deployment or for identifying its potential role in a future portfolio of responses to climate change; however, they do provide a starting point for assessment and important guidance for further research. To date, several studies have already mapped the economic potentials of albedo modification techniques as a policy option, especially SAI (Nordhaus and Boyer, 2000; Bickel and Lane, 2009; Gramstad and Tjøtta, 2010; Goes et al., 2011; Moreno-Cruz and Keith, 2013; Aaheim et al., 2015 forthcoming; Bickel, 2013; Bickel and Agrawal, 2013; Emmerling and Tavoni, 2013). With the exception of Emmerling and Tavoni (2013) and Aaheim et al. (2015 forthcoming), these numerical evaluations employed various versions of William Nordhaus’ Dynamic Integrated Climate-Economy model (DICE; see Nordhaus, 2008). DICE is an integrated assessment model for assessing the costs and benefits of various climate policies. Climate is integrated into the model by linking emissions, via concentrations, to temperature and from there to an aggregated damage function. Climate policies are evaluated by assessing their implementation costs over a given period (usually hundreds of years), compared with the benefits associated with the avoided impacts of climate change. Future costs and benefits are discounted by a chosen rate, which is intended to reflect the return on alternative opportunities for investing the money spent on mitigation. The outcome is critically dependent on assumptions made about the discount rate, which is discussed in further detail in the next section.

The earliest studies aimed to assess the potential of albedo modification by assigning a value for future damages that would be avoided, assuming that the techniques could be implemented at negligible operational costs. Later studies put more emphasis on the influence of side effects (for example, Gramstad and Tjøtta, 2010) and in particular on uncertainties associated with implementations of SAI (Goes et al., 2011; Moreno-Cruz and Keith, 2013; Emmerling and Tavoni, 2013).

Aaheim et al. (2015 forthcoming) extended these earlier studies by incorporating precipitation changes in assessing the side effects of albedo modification. They employed the GRACE (Global Responses to Anthropogenic Changes in the Environment) model to compare the impacts of cloud whitening and sulphur injection to stabilise global mean temperature over the period 2020–2070 in the RCP4.5 pathway scenario. In Aaheim et al. (2015 forthcoming), SAI results in an economic loss globally. This is explained partly by a drier climate, which is expected to result from a combination of SAI with increasing greenhouse gases (see Section 2.2.6), and partly because the SAI simulation misses out on economic benefits that otherwise would have resulted from a moderate increase in temperature in the climate change scenarios without SAI implementation. Nevertheless, the model shows regional variations, with some regions benefiting from the simulated sulphur injection. On the other hand, the results suggested that marine sky brightening would provide an economic benefit in all regions (between 0.1 and 0.8 per cent of GDP). Overall, these studies predict small economic impacts of albedo modification on GDP, but demonstrate that the predicted outcomes are not necessarily beneficial even when the models neglect the operational costs associated with the proposed techniques. However, the model relies on a very simple description of the damages associated with the changes in temperature and precipitation. As discussed in Section 2.2.6, the regional distribution of precipitation changes is not yet well understood, precluding reliable assessment of their economic consequences. Nevertheless, despite these uncertainties, some have argued that the possibility to exert a quick influence on the climate through changes in the albedo allows for greater flexibility in dealing with the uncertainties associated with climate change. Consequently, Moreno-Cruz and Keith (2013) argue that SAI could be a valuable tool to manage risks even if it is relatively ineffective at compensating for CO₂-driven climate change, or if its costs are large compared to traditional abatement strategies. Based on this line of argument, they suggest that in any comprehensive risk management approach to climate change, emission reductions and the application of albedo modification techniques should be considered as complementary rather than as substitutes for each other.

3.2.3 Distribution of benefits and costs

The distribution of benefits and costs is not only an economic issue but also raises important normative questions (Burns, 2011). The distributional effects of benefits, burdens, and risks vary considerably between different climate engineering techniques, and therefore need to be discussed individually.

Several authors have argued that SAI would create so-called winners and losers (Caldeira, 2009; Scott, 2012; Barrett et al., 2014), while others have questioned the degree to which SAI would produce inequalities (Moreno-Cruz et al., 2012; Kravitz et al., 2014a). Whether the deployment of SAI would increase the existing inequalities and historical injustice of climate change is an open question. The distribution of benefits and costs would depend not only on existing and uncertain future climate conditions, but also on population density, economic development, and the vulnerability and resilience of ecological, economic, and social systems (Schäfer et al., 2013b). In some scenarios, those geographically and economically most vulnerable to climate change, often living at the subsistence level, would be most likely to be negatively affected by uneven effects of SAI while having the lowest capacity to adapt to such effects, despite being least responsible for global warming (Olson, 2011, SRMGI, 2012; Carr et al., 2013; Preston, 2012). However, others have argued that SAI may also benefit some of the most vulnerable and poorest countries by reducing risks from climate change (Svoboda et al., 2011; Pongratz et al., 2012; Svoboda and Irvine, 2014). The weighing of risks is also an important topic in the context of “lesser evil” arguments, often taken to justify the further engagement in research and the possible deployment of SAI (see Box 3.7).

SAI as the “lesser evil”?

“Lesser evil arguments” are based on the assumption that if no substantial progress on emission reductions is made soon, then at some point in the future a choice would need to be made between allowing certain catastrophic impacts of climate change to occur versus engaging in SAI or another form of albedo modification that might prevent or reduce those impacts but that might also introduce novel risks (Gardiner, 2010; Markusson et al., 2014). In the case of a climate emergency, the argument suggests that the possible negative side effects of a direct intervention in the climate system via a technique such as SAI may be less worrisome than unmitigated climate change (Virgoe, 2009, Preston, 2013; Irvine et al., 2014b). However, in the face of uncertain consequences and unknown side effects of SAI, such claims are debatable. It cannot be ruled out that direct interventions in the climate could worsen some of the harmful consequences of climate change, even if it succeeds in alleviating others (Hegerl and Solomon, 2009, Matthews and Turner, 2009; Rickels et al., 2010).

From an intergenerational justice viewpoint, the distribution of effects of SAI also seems problematic. Based on the assumption that the present generation has a duty to protect the basic interests and rights of future generations (Meyer, 2008), it is widely discussed in the literature that SAI could exacerbate inequalities between generations, as it may allow risks and costs to be deferred (Gardiner, 2010; Burns, 2011; Gardiner, 2011; Goes et al., 2011; Svoboda et al., 2011; Ott, 2012; Smith, 2012). Such deferral of risks and costs would not be unique to climate engineering, as it also applies to the use of fossil fuels and many other activities of modern society. In general, there is a lack of reciprocity between generations of people who are not contemporaries, and an asymmetry in “power”, because current behaviour influences future people whereas they have no possibility to influence the present generation. This can lead to the externalisation of costs and risks over space and time (Ralston, 2009, Gardiner, 2011, Lin, 2012).

In an early analysis, Jamieson (1996) argued that, by deploying SAI, one generation would be choosing a specific climate path for future generations that may be irreversible or only changeable at high costs. Shifting the focus to the generation that would be laying the groundwork for a future SAI implementation through research and development, Gardiner (2010) argued that it is morally questionable to provide

future generations with the possibility of implementing a technique like SAI for their “self-defence” against climate change emergencies and, by doing so, compensating them for a crisis that could have been prevented through more benign options that are still available, such as increased global mitigation efforts (Gardiner, 2010).

In the case of a decision to implement SAI, any subsequent failure to maintain the aerosol forcing to counteract greenhouse gas forcing could result in a rapid and therefore potentially very damaging warming, depending on the scale of the intervention up to that point in time and how abruptly the SAI forcing would be ended (see Section 2.2.7). It has therefore been argued that deploying albedo modification techniques may reduce or foreclose options for future generations to a greater degree than other climate policies (Smith, 2012), thereby impairing or violating their right to autonomous self-determination (Ott, 2012, Smith, 2012) or leading to morally tragic, dilemmatic, or hazardous situations in which agents are compelled to act in a way that is morally reprehensible in at least some sense (Gardiner, 2010, Gardiner, 2011). Generally, intergenerational justice is one of several justice perspectives that can be brought to bear on assessments of the justice aspects of SAI. Others, as discussed by Tuana (2013), include corrective justice, ecological justice, distributive justice, and procedural justice.

Similarly to SAI, the environmental side effects of OIF will likely affect large regions, as well as future generations, particularly in terms of irreversible effects on ecosystems and biodiversity. OIF in particular raises questions of ecological justice, in terms of considering adverse effects on non-human life and on ecosystem sustainability in the context of normative evaluations, as well as reflecting upon our responsibilities towards non-human nature (Morrow et al., 2009, Ralston, 2009).

BECCS, despite at first glance perhaps appearing less problematic in terms of distributional effects on the global and intergenerational levels, could still cause harms via land use changes and effects on biodiversity, as a result of the extensive cultivation of monocultures. Due to the need for an adequate feedstock supply, higher levels of deployment would require vast conversion of land. This could decrease the land area available for agriculture and lead to increased food prices.

Box 3.8

Climate engineering deployment as a question of justice

Problems of distribution as well as of compensation and decision making can also be addressed from a justice perspective. On a general level, issues of justice are often based on certain assumptions about obligations towards others, their rights to certain goods, or the representation of their interests in decisions that could affect their wellbeing. A range of different issues is treated within various subdomains of justice, differentiated by the questions that they address as well as whose interests are foremost. Most relevant for the normative evaluation of the possible deployment of climate engineering techniques are:

- *Distributive justice*, reflecting upon the question of how benefits and costs should be distributed according to certain principles or criteria (such as maximisation, the priority view, egalitarianism, or sufficientarianism);
- *Redistributive justice*, aiming to redress undeserved benefits or harms;
- *Compensatory justice*, based on the idea that wrongdoers or the beneficiaries of wrongful actions must compensate, in some form, those who were harmed;
- *Procedural justice*, concerned with the fairness and transparency of the processes by which decisions are made;
- *Global justice*, dealing with principles that should guide one state in its dealings with other states, as well as with questions of the legitimacy (or lack thereof) of international institutions;
- *Intergenerational justice*, asking what current generations owe to future generations; and of the normative significance of past generations' actions;
- *Environmental justice*, reflecting upon the possibilities and mechanisms to include non-human life and ecosystem sustainability in normative evaluations; and how to understand human responsibilities toward non-human nature.

3.2.4 Compensation

The potential for some to suffer from the deployment of climate engineering techniques raises questions concerning compensation for possible harms. Three basic questions can be distinguished for these compensation issues:

- Who should compensate?
- Whom should they compensate?
- What should be compensated?

The question of “who should compensate” links back to the more general debate concerning the main principles for compensation for climate change impacts (Moellendorf, 2002, Page, 2006). The most prominent of these are the “polluter pays” principle (PPP), the “ability to pay” principle (ATP) and the “beneficiary pays” principle (BPP) (Page, 2012). As pointed out by Svoboda and Irvine (2014) as well as Wong et al. (2014), applying one of these principles as the sole governing principle for compensating SAI-induced harms can produce counter-intuitive results. This is often due to the neglect of considerations invoked by the other principles (Wong et al., 2014). Some concerns of applying those principles may be abated if a combination of principles is adopted, as has been suggested more generally for negative effects of anthropogenic climate change (e.g., Page, 2008, Caney, 2010). Combining these guiding principles, especially in relation to potential harms associated with SAI, would not necessarily lead to conflicts between principles, since the principles are not mutually exclusive and can often suggest similar courses of action and similar responsible parties. For example, the countries that would be able to deploy certain kinds of climate engineering techniques over longer periods of time, which would indicate causal responsibility for them in the context of the PPP, would also be those who would most likely gain the greatest benefits, since the form and scale of implementation would tend to reflect their interests (BPP). Furthermore, these would be the countries that would be most able to pay (at least to some extent) for the resulting negative consequences (ATP), and would also be those responsible for most of the historical and/or contemporary emissions (historical responsibility).

It is an open question whether such compensation should be based on the wrongfulness or culpability of the act, which would place it within the domain of compensatory justice; or based on the need to redress undeserved benefits or harms, which would then be a question of (re)distributive justice (see Box 3.8).

The answer to the question of “who should be compensated” is often less clear than might initially be expected. Different climate engineering techniques may harm different countries in different ways, making them possibly worse off than they would be under global warming alone. The question then is whether all countries would deserve equal compensation, based on the harms caused. Even if different countries faced similar overall losses, there may still be justification for unequal compensation, based on the type of loss, the vulnerability and ability to adapt, the responsibility for global warming, and the gains from it (Bunzl, 2011). Furthermore, an individual nation may simultaneously experience various forms of harm (e.g., increased drought) and benefit (e.g., reduced warming); the balance of these can be very different from one nation to another, adding further complexity to the assessment of who should be compensated.

A third crucial question is “what should be compensated, and to what extent”. Different normative approaches put limits on the kinds of harm that can be compensated. It might be considered impossible to compensate for actions or outcomes that compromise basic human rights or result in the loss of culturally significant ways of life or of statehood. Even for harms that in principle allow for compensation, attributing monetary values may be difficult. The baseline for compensation is also open for debate (Maas and Scheffran, 2012, Preston, 2013, Svoboda and Irvine, 2014). Should compensation claims include adverse effects of past climate change that might worsen or be reduced through climate engineering deployment, or should all compensation claims start from the beginning of the climate engineering activity? Furthermore, on a case-by-case level, it would be challenging to robustly attribute specific harmful impacts, e.g., prolonged drought or flooding, to any form of climate engineering deployment (Allen, 2003; Stott et al., 2004).

Compensation issues are of great importance for SAI. Due to the large effects that an implementation of SAI would be expected to produce, it is likely that not all states would be willing to accept such a course of action without some form of compensation. However, as concluded by Reichwein et al. (2015 in review): “although it is not entirely hopeless, there would be several hurdles in ensuring legal accountability for the risk of environmental harm from SAI under international law”. This is partly because of the inherent non-linearity and complexity of the climate system, which makes the detection of changes that would be caused by SAI and their attribution to the specific intervention (as opposed to natural variability) highly challenging. This could become less prevalent over time as more data would become available during the decades after deployment (MacMynowski et al., 2011; Jarvis and Leedal, 2012). Additionally, it might be unnecessary to causally attribute an event to some single cause. An alternative option would be to calculate the increased likelihood of an event occurring due to the change in radiative forcing produced by the SAI deployment. However, even calculating the fraction of risk attributable to an event would require comparison of the observed climate with a hypothetical climate in which the climate-forcing activity of interest is excluded; such methodologies would thus rely entirely on model computations, with their associated uncertainties (Stott et al., 2004; Svoboda and Irvine, 2014; Horton et al., 2015; Reichwein et al., 2015 in review).

Compensation issues would also be complex in the case of OIF, and would be concentrated on damages in marine ecosystems, especially in coastal regions. There are various possible impacts for which compensation could be expected, including impacts on the oceanic food web and thus on fish populations and the viability of fisheries (Chisholm et al., 2001), as well as side effects on the atmosphere (Lawrence, 2002) due to various compounds produced by phytoplankton, for instance dimethylsulphide, which can influence aerosol particle concentrations and cloud properties. A further complexity would involve determining who could claim a right to be compensated for damages in international waters.

Possible compensation for negative impacts of BECCS would depend on where in the process the negative impacts occur. Questions of compensation could become especially important in the event of possible leakage problems. On the other hand, problems arising during the production of bio-energy could be addressed within existing compensation schemes, as they would most likely occur within the jurisdiction of single nation-states.

4. International regulation and governance

International law frequently uses broad terms to establish the applicability of its provisions. In the issue area of climate engineering, the term “geoengineering” has become established at the CBD, and “marine geoengineering activities” has become established at the LC/LP. In light of this broad terminology, this chapter does not attempt to differentiate clearly between the regulation of techniques for greenhouse gas removal and for modifying planetary albedo. Instead, the analysis in this chapter suggests the existence of three potential — and partly intertwined — regulatory approaches toward climate engineering, described in Box 4.1, which are slowly becoming apparent in different types of normative output at the international level.

The categorisation of regulatory approaches proposed here serves to illustrate how international and European law could react to the challenges arising out of research on climate engineering techniques and/or

their deployment. As such, this categorisation is not explicitly laid down in any binding or non-binding international instrument. That the three approaches discussed below cannot and should not be understood as being clearly distinct from each other becomes evident when taking into account the approach followed by the LC/LP, which is categorised here as being activities-oriented. The LC/LP pursues the aim of protecting the marine environment; any regulatory action taken under its auspices is thus also effect-based. That said, it cannot be denied that the LP, which is set to eventually replace the LC, is based on an entirely different regulatory approach (general prohibition of dumping, with few exceptions) than, for example, the broadly framed CBD. It is asserted that these differences not only legitimise the systematisation introduced here, but also that this systematisation is of key importance for understanding how an effective governance regime covering one or more climate engineering techniques could be designed in future.

Box 4.1

Three regulatory approaches for climate engineering

1. regulation of climate engineering based on its potential role as a situational response to various conditions in the overarching context of climate change (*context*);
2. regulation through risk management measures for individual climate engineering activities and technical processes at the operational level (*activities*);
3. regulation through scientific assessment of potential environmental effects of different climate engineering techniques (*effects*).

The analysis then considers how the regulatory approaches surrounding the context, activities, and effects of climate engineering might manifest at the regional level in light of existing sources of EU law, and discusses how the EU has gone about implementing international obligations that fall within these normative categories, which could potentially be applicable to climate engineering. It has already been observed elsewhere that there are shortcomings at the international level in the existing regulatory framework concerning climate engineering (Bodle, 2010; Zedalis, 2010; Rickels et al., 2011; Bodle, 2012; Proelss, 2012; Bodle, 2013). EU law provides, in part, stricter legal standards for environmental protection, and introduces legal innovations that strengthen the regional implementation of global international law and provide a basis for limiting potential climate engineering activities, including unilateral action. An examination of EU law may therefore provide a timely case study of how regulatory structures at the regional/supra-national level might be applicable to climate engineering techniques within a broader framework of multilevel governance.

The remainder of this section (4.1 and its subsections) analyses emerging elements of a potential climate engineering regime in the activities of international treaty bodies. It begins with an overview of relevant treaties and then focuses on three treaties that embody the regulatory approaches outlined above: the UNFCCC, the LC/LP and the CBD. Section 4.2 then contextualises the three regulatory approaches in light of EU law.

4.1 Emerging elements of a potential climate engineering regime in the activities of international treaty bodies

To date, discussion of the development of regulation for climate engineering has primarily taken place in the competent treaty bodies of the LC/LP and the CBD, although a number of other international treaties, in particular the UNFCCC, would be potentially applicable treaty bodies. Concerning techniques to reflect sunlight back into space, potentially applicable treaties include the Convention on Long-Range Transboundary Air Pollution (CLRTAP), the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques

(ENMOD), the Vienna Convention for the Protection of the Ozone Layer, and the Outer Space Treaty (OST; for an overview of relevant agreements, see Rickels et al., 2011).

Concerning the ENMOD Convention (which is often mentioned in regard to climate engineering), it was clearly stated in the “Understandings”, prepared during negotiation of the treaty, that the parties did not intend its content to be applicable beyond the context of armed conflict. Efforts by the UN Secretary-General to convene a COP at the end of 2013 were also unsuccessful due to a lack of interest among the parties. For these reasons, the ENMOD Convention is not examined further here.

In general, as described in Box 4.1, three nascent and partly interrelated approaches to the regulation of climate engineering are becoming apparent in the activities of the parties associated with the aforementioned treaties. Recapping, these three approaches — along with the treaties that are most closely associated with these approaches in the context of current discussions around regulation of climate engineering — are:

1. *context*: as a situational, or context-driven, response to climate change (UNFCCC);
2. *activities*: as an activity or technical process (LC/LP);
3. *effects*: based on its effects on the environment (CBD).

Note that the first point does not imply that the UNFCCC would have to be considered as an instrument that has taken account of climate engineering from the outset. The categorisation developed in this chapter solely aims to distinguish between the behavioural patterns on which the different international treaty regimes are based. It has thus been introduced for the sake of systematically approaching the relevant international instruments.

Of course, the aforementioned approaches would not, taken individually, ever be able to provide a comprehensive regulatory framework for climate engineering that would go beyond the regulation of specific climate engineering techniques. Instead, in order to develop an effective regulatory structure for the regu-

lation of climate engineering as such (assuming that such a development would be considered the ultimate objective), all three approaches would arguably have to be integrated. The underlying process could, in principle, occur: formally, at the international level, through a dedicated treaty or protocol; dynamically, by way of, for example, amending the relevant binding instruments in parallel; or informally, through the adoption of assessment frameworks concerning climate engineering research or conclusion of Memoranda of Understanding between the secretariats of the aforementioned treaties. Such joint assessment frameworks and Memoranda of Understanding provide weak forms of formal coupling between the respective treaties at the operational level by fostering the coordinated implementation of shared objectives. Catalytic and synergetic results can be seen in the Rotterdam, Basel, and Stockholm conventions, where treaty integration has virtually been achieved using this approach.

The fact that all relevant legal instruments are to some extent based on similar approaches (embodied, for example, in the precautionary principle) and thus reflect a common denominator facilitates their integration, whatever form that process might ultimately take. The following subsections discuss the three legal instruments and the regulatory approaches they pursue in their relevance to climate engineering.

4.1.1 UNFCCC — Climate engineering as a context-specific response to climate change?

Identifying climate change as a “common concern of mankind”, the UNFCCC — the most comprehensive regulatory instrument adopted by the international community in response to the challenge of climate change — sets out a very general context into which all efforts to protect the Earth’s climate can be placed. In order to achieve the objective of the Convention, which is set out in Article 2 as the “...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”, the UNFCCC provides for two mechanisms:

1. emissions reductions at source;
2. sink enhancement.

These are defined in Articles 1 (8) and 1 (9), respectively. Although no explicit reference is made to climate engineering in the UNFCCC, the definition of a “sink” as “any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere” arguably covers some greenhouse gas removal techniques and might suggest a potential role for such techniques within the UNFCCC (Proelss, 2012). Other treaty provisions such as Article 4 (1)(c) may also suggest a role for active removal of greenhouse gases from the atmosphere by setting out a duty to “promote and cooperate in the development, application and diffusion, including transfer, of technologies, practices, and processes that control, reduce or prevent anthropogenic emissions of greenhouse gases...”.

Given that the language of the UNFCCC does not provide an explicit legal basis for distinguishing greenhouse gas removal techniques from conventional mitigation, and taking into account that it does not prohibit such activities — but, quite to the contrary, contains references to mechanisms that the academic community now widely understands as a part of greenhouse gas removal — the UNFCCC cannot be interpreted as explicitly prohibiting these forms of climate engineering. At the same time, however, this cannot be expansively interpreted as a blanket authorisation for all greenhouse gas removal techniques.

In any case, the UNFCCC’s formulation of the precautionary principle in Article 3 (3) (Parties “should take precautionary measures to anticipate, prevent or minimise the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures...”) would require a comprehensive assessment of the risks associated with measures to combat climate change (on the basis of the customary duty to inform and the duty to prevent transboundary harm) before a decision on climate engineering research or deployment could be made. This would continue to place primacy on conventional mitigation strategies that emphasise the reduction and prevention of emissions. Further analysis of the relevance of the precautionary principle in the regulation of climate engineering can be found in Proelss (2010), Tedsen and Homann (2013), and Reynolds and Fleurke (2013).

Incentives for the sustainable development of BECCS as a greenhouse gas removal technique under the UNFCCC, should such development be regarded as desirable, would require as a first step that the net impacts of the technology on emissions be recognised in international reporting and accounting frameworks for greenhouse gases. International climate reporting guidelines, as they currently apply to Annex I (industrialised) Parties, only make passing reference to carbon capture and storage (CCS), and accounting guidelines relating to Kyoto Protocol commitments make no mention of CCS at all (IEA, 2011). In 2006, however, a revision of the IPCC guidelines on national greenhouse gas inventory reporting was proposed to recognise CCS. These guidelines make no distinction between CCS using fossil or biomass fuel sources, requiring only that any technology involved in the reduction of emissions satisfies the requirement of the UNFCCC regarding access and technology transfer, that such technologies be “environmentally sound”.

The revised guidelines are envisaged to become binding for greenhouse gas reporting from 2015 (IEA, 2011). Further consideration of CCS under the Clean Development Mechanism (CDM) is presented in Box 4.2.

The reporting of biomass related emissions already forms part of the requirements under UNFCCC reporting guidelines. Annex I Parties are required to report such emissions under the LULUCF sector (land use, land use change and forestry). However, while reporting may be comprehensive, the accounting for biomass impacts under the Kyoto Protocol may not be, as parties are able to opt into or out of accounting for certain LULUCF activities. This raises the possibility that the benefits of BECCS in terms of greenhouse gas removal may count toward Kyoto Protocol greenhouse gas commitments, but that the costs of using unsustainable biomass in BECCS may be ignored (IEA, 2011).

Box 4.2

CCS under the Clean Development Mechanism

Incorporating CCS under the CDM has been on the agenda of international climate negotiations for several years. At the sixth session of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol (CMP 6) in 2010, a decision was taken that CCS utilising geological formations should be eligible for inclusion as project activities under the CDM. However, that decision was provisional and requires that nine issues are “addressed and resolved in a satisfactory manner”:

- non-permanence, including long-term permanence;
- measuring, reporting, and verification;
- environmental impacts;
- project activity boundaries;
- international law;
- liability;
- the potential for perverse outcomes;
- safety;
- insurance coverage and compensation for damages caused due to seepage or leakage.

Capture and storage of CO₂ from biomass were not specifically addressed in the decision. In November 2011, the UNFCCC Secretariat released the Draft Modalities and Procedures (M&P) for CCS in CDM (Decision 10/CMP.7), which discuss how these nine issues should be addressed, and served as the basis for the negotiations of the Subsidiary Body for Scientific and Technological Advice (SBSTA) in Durban.

Conversely, techniques that aim to reflect sunlight away from Earth are not generally considered to fall within the definitions of “sink” or “emissions reduction at source”, as they do not target the “stabilization of greenhouse gas concentrations in the atmosphere” as required under the objectives of the UNFCCC (Winter, 2011). Potential attempts to subsume such albedo modification measures under adaptation measures rather than mitigation measures, in order to integrate this category of climate engineering into the climate regime, could be challenged on the basis that these activities do not represent conventional adaptation measures such as those provided for in Article 4 (1)(e) of the UNFCCC (“appropriate and integrated plans for coastal zone management, water resources and agriculture, and for the protection and rehabilitation of areas, particularly in Africa, affected by drought and desertification, as well as floods”). Although this list is non-exclusive, there is no indication that a broad interpretation of the term “adaptation” to include albedo modification techniques would be appropriate given the objectives of the UNFCCC contained in Article 2, to stabilise greenhouse gas concentrations in the atmosphere and allow ecosystems to adapt naturally to climate change, because albedo modification techniques fundamentally influence the conditions to which ecosystems would adapt.

4.1.2 LC/LP — Climate engineering as an activity or technical process?

The LC/LP was developed with the primary intention of regulating the dumping of harmful waste and other matter into the oceans. Unlike the UNFCCC and CBD, which enjoy quasi-universal legal status, LC/LP only has a limited international membership, and although most member states of the EU are Parties to the treaty, the EU itself cannot become so as it is not a “State” as required under Article 24 (1). Also in contrast to the UNFCCC, Parties to the LC/LP have actively initiated significant steps towards the regulation of certain ocean-related greenhouse gas removal and sub-seabed storage techniques. Such efforts have concentrated on the development of a risk management framework to regulate potential activities at the operational level, rather than attempting to address the larger contextual questions that climate engineering raises. As such, the LC/LP is a process-oriented instrument which seeks to articulate pathways

towards decision-making in situations involving potential pollution of the marine environment, typically through assessment frameworks and amendments to the treaty/protocol. Activity within the LC/LP COP with relevance for climate engineering was initiated in 2006 in regard to CCS (London Convention and Protocol, 2006), which involved the adoption of an amendment to annex I of the LP to regulate CCS in sub-sea geological formations and an accompanying assessment framework; and a subsequent amendment in 2009 (London Convention and Protocol, 2009), to allow cross-border transport of CO₂ for CCS purposes. Note, however, that the introduction of CO₂ streams into the water column is prohibited. In the context of climate engineering regulation this development deserves attention, as CCS is regarded as a “bridging technology” when associated with conventionally generated emissions but could arguably be defined as a greenhouse gas removal technique when conducted in direct connection with relevant activities, for example as part of a BECCS approach.

In 2008, the COP adopted a resolution (London Convention and Protocol, 2008) banning OIF (legally defined by Article 1.4.2.2 of the treaty as “placement of other matter”) for purposes other than legitimate scientific research. This was followed in 2010 by an assessment framework (London Convention and Protocol, 2010) through which national authorities can determine whether scientific research on OIF is “legitimate” and how to manage applications to conduct research as required under LP Articles 4.1.2 and 9. A further development, discussed in more detail below, was proposed in 2013. This initial approach to producing non-binding yet politically authoritative guidance for decision making was at the time the most specific regulatory tool regarding any form of climate engineering research or deployment in existence, yet its scope is limited to the marine environment and those atmospheric activities where direct interaction with the marine environment can be reasonably expected. During the course of these and further ongoing developments at the LP, several studies provided insight by examining the question of whether OIF is compatible with international law in general and with the LC/LP in particular (Rayfuse et al., 2008; Craik et al., 2013; Scott, 2013; Verlaan, 2009; Güssow et al., 2010; Markus and Ginzky, 2011).

The most important aspect of the LC/LP process as a potential role model for the future development of governance of climate engineering has been the consideration of risk assessment of potentially polluting activities as a mandatory component of the decision-making process, subject to the application of the precautionary principle. The LP mandates a precautionary approach to environmental protection that would be applicable to any form of greenhouse gas removal research or deployment in the marine environment, as well as to the introduction of matter into the marine environment for the purpose of enhancing the planetary albedo, requiring in Article 3 (1) that “appropriate preventative measures are taken when there is reason to believe that wastes or other matter introduced into the marine environment are likely to cause harm even when there is no conclusive evidence to prove a causal relation between inputs and their effects”. Waiving the need to provide conclusive evidence of causation helps to overcome one of the central problems in regulating climate engineering generally — that of scientific uncertainty concerning the effects of research and/or deployment. Under the LP, a state cannot lawfully justify a failure to take preventative measures by reference to a lack of evidence for a causal relationship between an activity and detectable harm to the marine environment. In this regard, the LP’s formulation of the precautionary principle could serve as a helpful interpretive aid within an inter-treaty regulatory structure where formulations of the precautionary principle differ. This is not meant to suggest that the LP’s formulation of the precautionary principle might prevail over other formulations in other treaties. Arguably, this formulation should nonetheless be taken into account as a component of other legal rules applicable between the parties, together with the context, according to Article 31 (3)(c) of the Vienna Convention on the Law of Treaties (VCLT), when interpreting any of the treaties forming part of an inter-treaty regulatory structure. The weighting given to a particular formulation, however, will depend on how the principle is employed in the facilitation of operational cooperation and on the formal recognition of common objectives between the treaties (i.e., within joint COP decisions and Memoranda of Understanding between treaties). Problematic in the case of the LC/LP is its less than universal membership, as noted above. That said, the notion of “global rules and standards” in terms of UNCLOS Article 210 (6)

(United Nations Convention on the Law of the Sea) is often interpreted as referring to the rules and procedures codified in and adopted under the LC/LP, which would result in their incorporation into the regime of that treaty (which is binding upon significantly more states, as well as the EU).

In 2013 an amendment to the LP (LP Resolution 4(8) of 18 October 2013) was proposed by Australia, Nigeria, and the Republic of Korea to extend the scope of the Protocol to regulate the placement of matter for ocean fertilisation and other marine geoengineering activities. This proposal, which may represent a major step forward in the development of regulation for climate engineering, was adopted by consensus in October 2013, and aims to provide a legally binding mechanism to regulate the placement of matter for OIF while at the same time “future-proofing” the LP so as to enable regulation of other marine geoengineering activities that fall within its scope. It constitutes the first binding regulation in international law explicitly referring to a climate engineering activity. However, this statement should not be interpreted as implying that no rules of international law — particularly customary international law and international environmental law — would have been applicable in the absence of this first binding regulation. At the same time, it should be kept in mind that the amendment first enters into force when two-thirds of the accepting parties have deposited an instrument of acceptance, and can be subject to reservations, provided these are compatible with the overarching objectives of the treaty. Parties to the LC/LP who do not accept the amendment are not bound by the amendment, but are nonetheless under the obligation to take its provisions into account given the continuing (although legally non-binding) applicability of the resolutions on the regulation of ocean fertilisation (London Convention and Protocol, 2008) and the assessment framework for scientific research involving ocean fertilisation (London Convention and Protocol, 2010) for all parties, in conjunction with the overarching duty to protect and preserve the marine environment derived from the UNCLOS, the LC/LP, and customary international law.

The new Article 1 No. 5 bis contains the first definition of marine geoengineering to be introduced into a binding international treaty. The amendment further-

more prescribes binding criteria to distinguish research from deployment. The amendment, should it enter into force, would not automatically render the Protocol applicable to all marine greenhouse gas removal techniques. Rather, the applicability of the Protocol depends on a decision by the States Parties to include the activity in question in a new Annex 4 to the Protocol. Concerning techniques that aim to modify the planetary albedo, while the definition of marine geoengineering also encompasses the introduction of matter into the marine environment in order to increase the brightness of clouds, seeding using sea-spray generated from ocean waters would arguably not fall under the regulation. Furthermore, a new Annex 5 transforms the aforementioned Assessment Framework into a legally binding text; it reflects a comparatively strict implementation of the precautionary approach by foreseeing, at several stages of the assessment, that permission should not be granted unless sufficient evidence can be provided that the activity is unlikely to adversely affect the marine environment. Article 6 bis of the Protocol generally prohibits the placement of matter for marine greenhouse gas removal activities unless a listing of the activities concerned provides that they may be authorised under a permit scheme. This process under the LP, of first adopting a non-binding COP decision and then proceeding to amend the treaty/protocol to create binding law, demonstrates a potential model for other legal regimes in regulating other forms of climate engineering research.

4.1.3 CBD — Climate engineering judged in light of its effects on the environment?

The CBD was created with the intended objective to conserve biodiversity. With reference to each state's sovereign right to sustainably use its natural resources and the duty to prevent transboundary harm as the two foundations for state action, the CBD sets out a regulatory framework to gauge potential harm to biodiversity and ecosystems stemming from human activities. The CBD has a near-universal membership among UN member states, with the sole, but significant, exception of the USA, which has signed but not ratified the treaty. Like the UNFCCC, the text of the CBD itself does not explicitly refer to climate engineering (however, it could be amended by way of a

Protocol, cf. CBD Article 28 should the parties decide to regulate climate engineering research and/or deployment in a binding manner). However, in contrast to the UNFCCC, the CBD is not dedicated to the specific context of climate change, and in contrast to the LC/LP it is not designed to regulate specific activities. Its potential role in the regulation of climate engineering is instead to identify normative categories and procedures by which the potential effects of climate engineering on biodiversity can be monitored, assessed, and evaluated, as well as establishing limits, which may not be exceeded, for the reduction or loss of biological diversity.

As set out in Article 3 of the CBD, states have the “responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction”. To this end, they are required to adopt measures to minimise the adverse impacts on biodiversity, as described in CBD Article 14(1). These measures include the duty to “introduce appropriate procedures requiring environmental impact assessment ... and, where appropriate, allow for public participation in such procedures”, as detailed in CBD Article 14 (1)(a). Read in conjunction with the eighth and ninth recitals of the preamble (“Noting that it is vital to anticipate, prevent and attack the causes of significant reduction or loss of biological diversity at source, [n]oting also that where there is a threat of significant reduction or loss of biological diversity, lack of full scientific certainty should not be used as a reason for postponing measures to avoid or minimize such a threat”), the CBD presents an ambiguous version of the precautionary principle that cannot be interpreted as either prohibiting or authorising climate engineering activities.

To date, the CBD COP has adopted two specific decisions explicitly concerning climate engineering (albeit using the term “geoengineering” and without differentiating between albedo modification and greenhouse gas removal techniques), at its tenth meeting in 2010 (Convention on Biological Diversity, 2010) and eleventh meeting in 2012 (Convention on Biological Diversity, 2012). Note that there have also been further CBD COP decisions referring specifically to OIF. The 2010 decision stipulates in Para. 8 (w) that:

“...in the absence of science-based, global, transparent and effective control and regulatory mechanisms for geo-engineering, and in accordance with the precautionary approach [...] no climate-related geo-engineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts, with the exception of small-scale scientific research studies that would be conducted in a controlled setting in accordance with Article 3 of the Convention, and only if they are justified by the need to gather specific scientific data and are subject to a thorough prior assessment of the potential impacts on the environment”.

Although this decision is legally non-binding, it constitutes a politically authoritative statement by the States Parties to the CBD and as such is to be taken into account when measuring climate engineering activities against the biodiversity protection-oriented requirements contained in the CBD.

Decision X/33 also provides a definition of geoengineering that refers to “...any technologies that deliberately reduce solar insolation or increase carbon sequestration from the atmosphere on a large scale that may affect biodiversity (excluding carbon capture and storage from fossil fuels when it captures carbon dioxide before it is released into the atmosphere)...”. It is clear that the CBD considers itself an appropriate treaty body for discussing both greenhouse gas removal and albedo modification techniques, in contrast to the UNFCCC, where the language of the treaty has so far been interpreted as restricting the discussion to greenhouse gas removal techniques (note, however, that the interpretation of the UNFCCC described here might change over time, subject to political will, given the flexible wording of the treaty provisions and the possibility for interpretation of a treaty to change as a result of subsequent agreement between the parties or subsequent practice concerning the application of its provisions, cf. Article 31 (3) lit. a and lit. b of the VCLT, 1155 UNTS 331). Decisions X/33 and XI/20 of the CBD COP are therefore particularly important in relation to albedo modification techniques, as the CBD is arguably at present the only treaty with near-universal legal status in which

albedo modification techniques might be considered as falling under its mandate.

Irrespective of the type of climate engineering under consideration, the CBD contains a general obligation to conduct environmental impact assessments (EIAs). The wording of Decision X/33 allows for small-scale scientific research on climate engineering in controlled settings under the condition that these studies are “justified by the need to gather specific scientific data”. Should such experiments take place, the CBD may therefore be under increasing pressure to serve as the framework within which an “adequate scientific basis” can be established “on which to justify such activities”. The nature of justification is different, however, between that required of scientists wishing to conduct small-scale climate engineering research and stakeholders calling for actual deployment.

4.1.4 Outlook: bringing together the regulatory approaches of context, activities and effects

It was noted in the preceding sections that, in order to develop an effective regulatory structure for climate engineering techniques, the three approaches to regulation identified in the activities of the UNFCCC, LC/LP and CBD would need to be integrated. Whether — and how — this could be achieved depends firstly on better defining the scope of the intended regulation in relation to the specific technical features, areas of application and intentions behind the activities concerned. These specificities have so far not been adequately addressed in international regulatory bodies, mirroring the lack of clarity in the general debate surrounding terms like climate engineering, geoengineering, albedo modification, and greenhouse gas removal (see Section 1.2). Because of the great differences between individual techniques, the prospects and desirability of a treaty that subsumes a wide range of techniques under the general term “climate engineering” and attempts to address the full range of aspects involved (i.e., going beyond specific aspects such as impacts on biodiversity) are clearly negative, taking into account: (1) the time it would take to negotiate such an instrument, (2) that “commons-based” and “territorial” climate engineering techniques raise different jurisdictional issues and would thus require different forms of international cooperation and deci-

sion making, and (3) that a clear sense is yet to emerge of what the interests of different actors might be. Shared understandings of technical features, areas of applications and intentions behind climate engineering activities will only emerge — if at all — in light of active, open research programmes and assessments. More fundamentally, the effectiveness of any potential regulatory structure depends on a clear understanding of its object and purpose. It is still premature to speculate on what purpose or purposes the regulation of climate engineering might have and what goals it might be intended to pursue. In the meantime, until a clearer consensus emerges to guide decisions on whether to develop more specific regulation, the alternative is to focus on bringing together the aforementioned regulatory approaches at the operational level (i.e., through parallel action, common assessment frameworks or Memoranda of Understanding) using the example of those climate engineering techniques that are most relevant to research and practice. In this respect, developments that have taken place within the legal framework of the LC/LP might serve as a model for other non-ocean-related climate engineering activities.

4.2 The EU law perspective: considering a potential regulatory strategy for climate engineering including application of the approaches of context, activities and effects

Due to climate engineering's inherent potential for significant transboundary environmental effects, the question of its overarching permissibility remains at the level of public international law. An exclusively “top-down” perspective, however, would fail to take into account the more heterogeneous processes by which international law is created and implemented, as well as the different yet interlinked normative planes necessary for a coherent and stable legal system. Regulatory structures that would be initially applicable to climate engineering research or deployment activities already exist at the national and supranational levels, and these could provide a structure for implementing a new international legal regime within the dynamics of multilevel governance. Without a comprehensive international regulatory structure in place, EU law provides a “bottom-up” source of limitation on climate engineering for member states and

the EU itself. Although present EU law (the scope of which is limited to the territory of EU member states and to activities undertaken by EU citizens abroad) cannot be interpreted as generally prohibiting or authorising climate engineering, it serves to structure the decision-making process and provide essential provisions for environmental protection, which are in any case required to be implemented and enforced. EU law consists of both primary and secondary sources, with the former consisting of the multilateral treaties adopted by the member states defining the objectives and competences of the EU as an institution, and the latter consisting of the supranational legal mechanisms created by the EU itself for realising those objectives. In some cases such as the UNFCCC and CBD, the EU is also a party to multilateral treaties alongside its individual EU member states, which provides a further source of secondary law for the realisation of EU objectives. In other cases such as the LC/LP, the EU is not a party, meaning that member states are exclusively and independently responsible for implementing their obligations under this treaty, something which must nonetheless take place in compatibility with the framework of EU law. The EU is generally not precluded from enacting compatible (or even stricter) internal regulations, provided that the subject matter falls within its competences. However, it cannot exercise a formal coordinating role among the EU member states' positions within treaty bodies to which it is not a party. This fact considerably complicates the formation of a common EU position on a given topic “externally”, within the sphere of international relations, and therefore the influence that such a common position might have for the evolution of the treaty. This complex and continually evolving legal landscape on the one hand complicates an assessment of existing and emerging legal instruments at the international level, but on the other hand opens the analysis of new sources of law and provides an additional normative forum within which climate engineering can be subjected to more democratically legitimated legal scrutiny, at least within the EU, than at the level of international law alone.

4.2.1 EU Primary Law — An overarching context for climate engineering regulation and competences for its implementation within the EU

Questions regarding a regulatory strategy to determine a potential context within which research or deployment of climate engineering could be authorised or prohibited in the EU are best posed at the level of EU competences and objectives, i.e., against the provisions of EU primary law. The Treaty on European Union (TEU) (The Member States of the European Union, 2012a) sets out the organisational structure and objectives of the European Union that are relevant for potential EU action in the field of climate engineering. The Treaty on the Functioning of the European Union (TFEU) (The Member States of the European Union, 2012b) sets out in more detail the nature of competences between the Union and the member states, including the environment, energy, and common safety under TFEU Article 4 (2). TFEU Article 4 (3) adds that “[i]n areas of research, technological development and space, the Union shall have competence to carry out activities, in particular to define and implement programmes; however, the exercise of that competence shall not result in Member States being prevented from exercising theirs”. Because action concerning environmental protection on the one hand and research on the other hand is subject to shared competences under EU law, both national and supranational activity in climate engineering research and deployment are possible at present. As evidenced by the developments concerning CCS, this could potentially mean that both the EU and some member states engage in research and technological development of climate engineering methods, while other member states, despite not being in the position to veto EU-level research and development following the adoption of the CCS Directive, find themselves unable to promote such activities domestically due to public opposition of the kind witnessed in Germany over CCS (for an overview on the state of implementation of the CCS Directive and the divergent positions taken by EU member states, see COM(2014) 99 final). With regard to environmental competence, it should be noted, though, that according to TFEU Article 2 (2) the member states may only “exercise their competence to the extent that the Union has not exercised its competence. The Member

States shall again exercise their competence to the extent that the Union has decided to cease exercising its competence”. Were the EU to enact a moratorium, prohibition or authorisation of climate engineering in general or for individual climate engineering techniques, this would either need to be set out in an international treaty to which it is a party, which would then be transposed into EU secondary law, or by making use of its environmental competence codified in TFEU Article 192 (2), on the basis of a Commission proposal through the standard legislative process.

Regarding the Union policy on the environment, TFEU Article 191 (1) sets out the primary objectives, including “preserving, protecting and improving the quality of the environment, protecting human health, prudent and rational utilisation of natural resources, promoting measures at the international level to deal with regional or worldwide environmental problems, and in particular combating climate change”. As the central guiding provision of EU primary law with relevance for climate engineering, TFEU Article 191 (2) expressly requires that environmental policy “shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damages should as a priority be rectified at source and that the polluter should pay”. On this basis, all climate engineering activities would be judged against the precautionary principle as a binding rule of law, as well as the duty of preventive action against emissions and the mitigation of emissions at source, as opposed to either their dispersal or sequestration via other environmental media as intended by greenhouse gas removal techniques, or the management of solar radiation as targeted by albedo modification techniques. In accordance with TFEU Article 191 (3), the Union is also required to take account of available scientific and technical data in preparing environmental policy, as well as of the potential benefits and costs of action or lack of action, taking into account the enormous degree of scientific uncertainty concerning climate engineering.

Given these principles and standards of care for interaction with the environment, it is unlikely that most climate engineering methods would satisfy the principle of preventive and precautionary action. At the same time, as far as greenhouse gas removal is concerned, the distance between the source of emissions

and their point of sequestration would be a decisive factor in determining whether a certain activity can be seen as sufficiently rectifying emissions “at source” as required by EU law. Finally, the overarching objective of EU environmental policy of “improving” the quality of the environment and rationally using natural resources could be threatened by the prospect of climate engineering. Despite the prominent position given to combating climate change within EU environmental objectives and the clear intention behind climate engineering to contribute to such ends, in order to be consistent with EU policy climate engineering techniques would nonetheless need to be judged on their capacity to satisfy all objectives of EU environmental policy simultaneously, rather than merely as a second-order measure to satisfy one individual objective.

4.2.2 EU Secondary Law

To date, no act of EU secondary law has sought to explicitly regulate climate engineering research and/or deployment. That said, examples of EU secondary law, both procedural and substantive, can be identified that could potentially be triggered, subject to more detailed assessment, in the context of climate engineering research or deployment of climate engineering techniques.

Regarding the regulation of activities as one of the three approaches to a potential regulatory strategy for climate engineering, EU secondary law on environmental procedures is of central importance as it gives insights into the potential legitimisation of climate engineering activities and corresponding liability mechanisms. Regulation can perform specific legitimising functions, for instance by articulating procedural mechanisms by which the public can be included in decision-making processes on whether or not to pursue climate engineering, and by which liability for potential environmental damages ensuing from such techniques can be at least partially attributed. Procedural approaches to the legal questions surrounding climate engineering provide safeguards at the operational level, which are applicable to all potential forms of climate engineering and to both state and non-state actors at regional, national, and sub-national levels. The EIA Directive (Directive, 2011/92/EU) and the Environmental Liability Directive (ELD) (Directive,

2004/35/CE) are central examples of this category of EU secondary law.

Regarding potential regulatory strategies to address the potential environmental effects of climate engineering, there are several relevant EU substantive directives in the form of legislative acts, including the Air Quality Directive (Directive, 2008/50/EC), the Water Framework Directive (Directive, 2000/60/EC), the Habitats Directive (Council, Directive 92/43/EEC), the Birds Directive (EU-Directive, 2009/147/EC), and the Environmental Noise Directive (Directive, 2002/49/EC). Particularly relevant for the special case of CCS is the CCS Directive (EU-Directive, 2009/31/EC). This family of directives uses similar types of measures for avoiding, preventing, or reducing harmful effects on specific environmental components, as well as on human health and the environment as a whole, in line with the objectives and relevant provisions of EU primary law. At the same time, they also include provisions allowing exceptions from envisaged levels of protection under certain conditions (e.g., when compliance costs are judged excessive, or when overriding public interest or wider sustainable development concerns require exceptions from the protection standards established by these instruments). Directives are binding upon member states in their objectives but not in the manner in which they are transposed and implemented in national law by member states. As such, the transposition and implementation of EU secondary law, binding for EU member states, also provides an important demonstration of commitment to international treaty obligations as well as a source of state practice contributing to the formation of customary international law, as member states are parties to the treaties and at the same time independent actors in the broader practice of international relations. Thus, the standard of protection and care mandated by EU primary law and further developed through EU secondary law, sometimes implemented to an even higher standard by member states, contributes to international understanding and consensus-building as to how international law on a given topic is to be interpreted and implemented by other parties.

4.2.3 Taking a regional perspective on climate engineering

Notwithstanding some scepticism concerning EU unilateralism in fields such as shipping and emissions trading (Proelss, 2013), it has often been noted that legal developments at the EU level have clear and often very constructive feedbacks into international processes — particularly in relationship to environmental concerns. By approaching these existing tools as regional contributions to the completion of the international legal regime applicable to climate engineering, the international community may be able to harness a dynamic model for future regime-building beyond classic “top-down” multilateral treaty approaches. It is widely recognised that a joint course of regulatory action is often easier at the regional level than at the international level, and it may thus be appropriate to transpose the analytical approach currently being taken toward the dilemmas posed by climate engineering to a different scale. The adoption of a new perspective might highlight considerable opportunities and insights available for climate engineering regulation, by better grasping the interrelationships between legal regimes, both laterally at the international level and subsidiarily through the perspectives of multi-level governance.

As presented here, EU law contains a wide variety of provisions potentially applicable to both climate engineering research and deployment. Although these provisions do not, in themselves, provide an all-encompassing regulatory regime for climate engineering, their structure and relationship to emerging dynamics at the international level suggest pathways forward on different elements of climate engineering regulation and may help in the substantiation of a legal regime at the international level. What they do contribute is a notably high level of environmental protection and, most prominently, the central objective of improving the quality of the environment rather than merely maintaining it. Given this basic foundation, it can safely be said that EU law provides a further and, compared to the requirements of public international law, more stringent scrutiny of potential climate engineering activities. Moreover, it does so at a level closer to the sources of those activities, with well-established mechanisms to ensure public participation, access to justice, and legitimisation of decision making. Having these provisions at the EU level rather than merely at the level of the individual member states, where further implementing legislation exists, also provides an important coordinative function that might serve to effectively limit the scope for national decision makers to unilaterally undertake any form of climate engineering. Ultimately, however, EU law demonstrates the same types of deficits that are becoming apparent in international legal efforts to regulate climate engineering, suggesting that initiatives beyond formal legal approaches will be necessary to govern climate engineering.

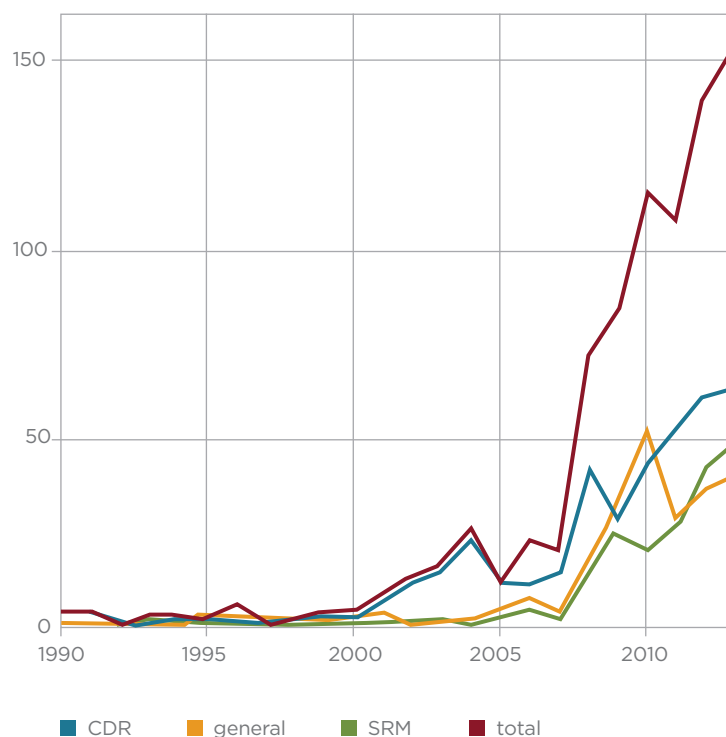
5. Research options

5.1 Background

Over the past decades, there has been a substantial increase in the general interest in the various proposed climate engineering techniques. This growing interest has been accompanied by an increase in research on the range of climate engineering techniques, as shown in Figure 5.1. Within this context, there are notable differences in the growth of research on planetary albedo modification and on greenhouse gas removal, as well as differences in the framing and perception of each within the research community and among associated funding bodies.

For planetary albedo modification, high-level discussions and preliminary research date back to at least the early 1960s (Keith, 2000, Fleming, 2010). However, prior to the early 2000s, serious research on such techniques was being conducted by only a limited number of researchers worldwide. This changed in the mid-2000s, particularly following the publication of an article by Crutzen (2006), revisiting the idea of SAI, which had originally been published in the mid-1970s (Budyko, 1974). The subsequent rapid growth in peer-reviewed research articles on this sub-

ject is depicted in Figure 5.1. Five commentaries were published together with the Crutzen (2006) article, all of which cautioned about the risks of steps toward implementation of any form of albedo modification, but at the same time generally supported “breaking the taboo” and encouraged basic research on albedo modification (Cicerone, 2006, MacCracken, 2006, Bengtsson, 2006, Kiehl, 2006, Lawrence, 2006). Research and scientific publications on the topic have since proliferated, including the development of several international projects such as GeoMIP (Kravitz et al., 2011), IMPLICC (Schmidt et al., 2012b), SRMGI (SRMGI, 2012) and EuTRACE. The article by Crutzen (2006) was quickly followed by the first major assessment report, conducted by the Royal Society (Shepherd et al., 2009), as well as by several other assessments (Blackstock et al., 2009; Rickels et al., 2011; Bodle et al., 2013; Edenhofer et al., 2011, McNutt et al., 2015a; McNutt et al., 2015b; Ginzky et al., 2011; UK House of Commons Science and Technology Committee, 2010; Gordon, 2010; Caviezel and Revermann, 2014). The topic has also been addressed in the IPCC’s Fifth Assessment Report, in all three Working Groups (IPCC, 2013a, IPCC, 2014a, IPCC, 2014b).

**Figure 5.1:**

Main trends in scientific publications on climate engineering (number of publications per year, indexed in Web of Science).

Source:

Oldham et al. (2014).

For greenhouse gas removal, interest has grown more gradually over a longer period of time. In the case of OIF, numerous research articles were already published by the mid-1990s. Prominent publications on other techniques to remove greenhouse gases also started appearing in the mid-1990s (e.g., Lackner et al., 1995). With the key exception of OIF, attitudes within the scientific community were less resistant to investigating these approaches than to planetary albedo modification. Even though OIF was and remains heavily criticised by many within the scientific and stakeholder communities, research was not as limited by the sense of “taboo” as it was for albedo modification, as evidenced by the 13 open-ocean field experiments testing various aspects of OIF that were conducted between 1992 and 2009. This may be at least partly due to the circumstance that several of these experiments were primarily aimed at investigating the fundamental nutrient uptake and cycling processes in the oceans, with a combined interest in the potential applications for enhancing CO₂ removal from the atmosphere.

This multi-purpose nature of knowledge production, described above for the case of OIF, also exists for research on albedo modification techniques. For example, perturbative field experiments examining cloud-aerosol interactions would simultaneously produce knowledge about one of the key uncertainties in contemporary climate models and about potential climate engineering strategies through cloud brightening. It remains to be seen what kind of effect the multi-purpose nature of knowledge production will have for research on climate engineering, e.g., facilitating, leading to a normalisation of albedo modification research, or alternately disruptive, leading to a contestation of fundamental atmospheric and climate research that is interpreted as being related in purpose to albedo modification research.

Currently, research on both types of climate engineering is extensive compared to 20 years ago, although it is — appropriately, from the standpoint of this consortium — far less extensive and attracts less funding support than research on mitigation and adaptation (including both technical and non-technical measures). Nevertheless, there is an extensive dialogue amongst and between researchers and key stakeholders (in particular funding agencies, policy makers, and NGOs) about whether this level of research is appropriate, whether public funding for research on intentional interventions into the climate system in general should be stopped, continued or intensified, and how research should be governed. Although decisions for or against research on different techniques are commonly made at the national level, there is a need at the international level to reflect on governance issues, a topic that has been intensified recently by the publication of proposed experimental designs for open-atmosphere field experiments for albedo modification, especially stratospheric aerosol injections (Dykema et al., 2014; Keith et al., 2014).

This chapter considers the current perspectives on climate engineering research and the options for funding and governing research, which the European Commission and other governing bodies may wish to take into consideration. In the next section, numerous arguments for and against research on greenhouse gas removal and albedo modification are considered, which have been prominently raised thus far. Section 5.3 then outlines the key knowledge gaps that have become evident throughout the body of this assessment.

5.2 Arguments for and concerns with climate engineering research

5.2.1 Arguments in favour of climate engineering research

A wide variety of arguments has been made in favour of conducting research on both greenhouse gas removal and albedo modification, although often in different ways and frequently differentiated between individual techniques. The main arguments in the current discourse are:

Information requirements: This argument suggests that climate change negotiations and policy making require a breadth of information, and since the IPCC has now taken up discussions of both greenhouse gas removal and albedo modification in its Fifth Assessment Report, the requirements are becoming more significant for information on related issues, for both types of climate engineering techniques, as a basis for supporting international policy development. The need for direct advice of policy-making organisations has driven, directly or indirectly, several of the assessments carried out to date, including those of the UK Royal Society (Shepherd et al., 2009), the US House of Representatives (Gordon, 2010), the UK House of Commons (UK House of Commons Science and Technology Committee, 2010), the German Ministry for Education and Research (Rickels et al., 2011), the German Federal Environment Agency (Ginzky et al., 2011), the report of the German Office of Technology Assessment (Caviezel and Revermann, 2014), the Working Group I, II and III contributions to the IPCC Fifth Assessment Report (IPCC, 2013a, IPCC, 2014a, IPCC, 2014b), the reports of the US National Research Council (McNutt et al., 2015a; McNutt et al., 2015b), and of course the EuTRACE project commissioned by the European Commission.

Knowledge provision: In addition to the formalised discussions in the context of the IPCC and climate change negotiations, there is also already a broader discussion about greenhouse gas removal and albedo modification among the international scientific, policy, and civil society communities and in parts of the broader public. Many researchers have indicated feeling a responsibility to provide knowledge that is scientifically sound as a basis for further discussion and decision making.

Deployment readiness: The argument has been made that the readiness with which different techniques can be deployed should be increased in order to allow for “buying time” for the implementation of mitigation measures, or to “be prepared” for the implementation of various forms of climate engineering if future environmental conditions worsen dramatically as a result of climate change (MacMartin et al., 2014; Blackstock et al., 2009; Swart and Marinova, 2010).

Premature implementation avoidance: It has been argued that research can provide decision makers with sound scientific information as a basis for determining courses of action, helping to avoid premature implementation of high-risk and highly uncertain techniques (Lawrence, 2006; Keith et al., 2010; Caldeira and Keith, 2010; Morgan et al., 2013). In particular, it is contended that limiting research would not necessarily reduce the probability of greenhouse gas removal and albedo modification techniques ultimately being deployed, but instead that limiting research could increase the likelihood of a technique being deployed without sufficient knowledge concerning effects and side effects (Rayner et al., 2013; Morgan and Ricke, 2010; SRMGI, 2012; Robock, 2012). This argument is primarily raised in discussions of albedo modification techniques but also applies to greenhouse gas removal.

Proposals elimination: It has also been suggested that research can help to weed out “bad” proposals, classified as those that are cost-ineffective or unrealistic, thereby determining which ideas should not be pursued further (Lawrence, 2006, Cicerone, 2006). This applies equally to greenhouse gas removal and albedo modification techniques, given that both can have substantial adverse side effects which might outweigh their potential benefits. As an example, prominent researchers have contended that past research has already made it clear that OIF should not be pursued further (Strong et al., 2009b).

National preparedness: States may want to know what other nations or groups of nations might be considering, what kinds of impacts and side effects to expect in case of implementation by third parties, and what to monitor in order to detect possible “covert” implementations (Lawrence, 2006; Seidel et al., 2014). This applies generally to direct interventions in the climate system by albedo modification, as well as to any greenhouse gas removal techniques for which potential large-scale side effects are expected, such as for marine biology as a result of OIF, or for crop prices due to BECCS.

Scientific freedom: Scientific curiosity and scientific freedom are occasionally cited as arguments in favour of research, particularly since such research not only contributes to a better understanding of greenhouse

gas removal and albedo modification techniques, but also often improves the general understanding of the Earth system. This applies both to albedo modification, whereby the model simulations provide additional insights into the behaviour of the climate system under various perturbation scenarios, and to greenhouse gas removal techniques, whereby research on, for example, OIF or BECCS would be expected to inform ecosystem management and improve our knowledge of biogeochemical cycles.

5.2.2 Concerns with climate engineering research

A wide variety of arguments has also been made against conducting research on both greenhouse gas removal and albedo modification, noting, however, that arguments against research often apply in different ways for the two classes of techniques. The arguments noted below generally apply either primarily to research into direct interventions in the climate system by albedo modification, or similarly to both classes of techniques.

The “moral hazard” argument: As described in Section 3.1.1, the moral hazard argument posits that research on climate engineering may weaken society’s willingness to reduce greenhouse gas emissions and adapt to climate change, either now or in the future. This applies similarly to both greenhouse gas removal, especially when aiming for large-scale deployment, and to albedo modification.

Allocation of resources for research: This argument partially applies to greenhouse gas removal, but is most relevant to albedo modification techniques. It rests on the competition for financial resources, infrastructure, and expertise between research on such techniques and research on other topics (Gardiner, 2010, Jamieson, 1996). One concern is that research may divert crucial investments away from energy-efficient technologies, the renewable energy sector, or even from studies to better understand the causes and effects of climate change (Robock, 2011). Such apprehensions often contend that the appeal to a possible “climate emergency” may particularly privilege climate engineering research and shield it from normal competition for funding (Gardiner, 2013, Ott, 2012).

Slippery slope: The concern is often raised that research into climate engineering may render its ultimate deployment inevitable, sitting at the top of a “slippery slope” toward deployment (Hulme, 2014; Morrow et al., 2009; Bracmort and Lattanzio, 2013). These arguments refer to path dependency and potential scientific or financial lock-in effects in the area of technological developments, emphasising that the step from research to deployment cannot always be easily controlled (Collingridge, 1980; Arthur, 2007), and that research cannot be easily separated from its potential application as technology (Jamieson, 1996; Morrow et al., 2009; Gardiner, 2010; Ott, 2012). These assumptions also play a role in the so-called “on the shelf” argument, which posits that technologies, once developed, tend to be used. Even though these arguments are primarily directed against albedo modification techniques, similar concerns can be raised for greenhouse gas removal techniques, which could hinder long-term major societal transformations toward more sustainable societies, for example by extending the lifetime of fossil-fuel-based production and consumption.

Concerns about large-scale field tests: Large-scale field tests could have direct and widespread impacts on both human populations and the biosphere. It is not clear how large a field test of albedo modification would need to be in order to establish confidence in the effectiveness of a proposed technique. It has been argued that only testing on a large (perhaps even planetary) scale and over longer periods of time could establish confidence in effects and side effects (Robock et al., 2010; Seidel et al., 2014), although proposals for more limited testing have also been made (Dykema et al., 2014; Keith et al., 2014; MacMynowski et al., 2011). It has been argued that albedo modification field tests of sufficient scale to produce measurable climate effects for a specific technique would be tantamount to full-fledged deployment (Robock et al., 2010), since small- and medium-scale field tests would be insufficient to characterise the climate response (Tuana et al., 2012; Blackstock et al., 2009).

Backlash against research: Concerns have been voiced that a strong civil society and public backlash against perturbative climate engineering field tests might generally hinder future research on greenhouse gas removal and albedo modification techniques, and furthermore that such a backlash might also affect the

ability of investigators to carry out fundamental scientific research that increases the level of understanding of the Earth system, which can support climate policy development (Schäfer et al., 2013a).

5.3 Knowledge gaps and key research questions

There are very many open research questions on climate engineering, ranging from natural science and technological aspects to social sciences, humanities, and legal issues. Here the results of the previous chapters of this assessment are used to identify important knowledge-gaps and to draw up a list of pertinent research questions. This list is intended to give an overview of a range of issues that would benefit from further investigation for various purposes, e.g., in order to provide a better basis for stakeholder groups, including policy makers, to develop positions on various issues associated with climate engineering. However, no attempt is made to prioritise the questions, e.g., for direct use in guiding research funding program developments. Such prioritisations are necessarily heavily context-dependent, and are thus likely to differ for different stakeholder groups (e.g., researchers of various disciplines, national policy makers, international policy makers, representatives of civil society, etc.). This is the first known compilation of this breadth of research questions on climate engineering, and can serve as a basis for follow-up developments of prioritised sets of research questions based on the individual needs and values of various stakeholder groups.

The questions are grouped into the following areas:

- natural sciences and engineering;
- public awareness and perception;
- ethical, political, and societal aspects;
- governance and regulation.

Here, the umbrella term “climate engineering” is employed; however, the issues relevant to individual techniques or to broader categories are carefully differentiated, and the umbrella term is only applied where appropriate.

1) Natural sciences and engineering

Questions regarding potential consequences, risks, and technological feasibility differ between techniques, although some questions concern many or all techniques simultaneously. Hence, general questions are considered first, followed by those specific to greenhouse gas removal and albedo modification.

General: In recognition of the finite nature of research funding, one option for posing questions is to start by identifying the most promising techniques and to focus funding upon those, and to then proceed by asking about the potential combination of remaining techniques:

- *Which proposed techniques currently appear to be the most promising, and according to which criteria can this be assessed?*
- *Are there any proposed techniques for which it can be confidently said that further research is, at this point in time, not a prudent investment, due to physical limitations or significant side effects of the technique uncovered by initial research?*
- *If a set of climate engineering techniques were to be deployed, is there an “optimal” configuration of one technique or combination of techniques for achieving specific climate goals, noting that goals are stakeholder-dependent?*

To help in evaluating different climate engineering techniques, it is useful to ask a range of questions that apply to the full portfolio of techniques under consideration:

- *Is the technique technically and economically feasible and scalable to have a significant effect on the climate?*
- *As many climate engineering techniques are little more than hypothetical proposals, what scientific uncertainties or technical challenges would need to be resolved before a given technique could be regarded as practicable?*
- *Many of the proposed techniques, if deployed at large scale, would have substantial resource requirements in terms of land area, raw materials, etc., and could also have significant side effects; what might be the associated broader environmental and economic consequences of fulfilling these input requirements?*

To support the development of effective climate policy, an understanding of the timescales required to develop the various climate engineering techniques may be important:

- *If the decision were made to implement a given climate engineering technique, how long would it take to develop the technology and necessary infrastructure? How would various factors, for example the desired scale of deployment, affect this development?*
- *Is it possible to postpone specific kinds of research on a given technique (for example, field experiments and the development of prototypes) while retaining the possibility of timely future deployment if broadly desired; if so, for how long could that research be delayed?*

Greenhouse gas removal: Greenhouse gas removal raises a number of specific research questions regarding its capacity and potential benefits, measurements, and monitoring, relationships to socioeconomic scenarios and potential drawbacks:

- *What are the physical, technological, and economic potentials of various techniques to remove greenhouse gases, taken individually or in combination, and how do these compare to available mitigation technologies?*
- *What monitoring, reporting, and verification programmes would be needed?*
- *For each technique, how does it relate to various socioeconomic scenarios (e.g., the mitigation pathways that underlie the RCP scenarios)?*
- *What would be the implications of deploying land-based, biological techniques at a large scale, given the existing demands on land and natural resources?*
- *What limits and trade-offs would such techniques face?*
- *What would be the long-term fate of carbon captured by these techniques? How can this be accounted for?*
- *What would be the long-term implications of employing techniques like OIF, which are expected to eventually release the carbon back to the atmosphere?*

Broadening the scope to the removal of greenhouse gases besides carbon dioxide:

■ *Are there practical techniques that would make it possible to remove non-CO₂ greenhouse gases from the atmosphere, or to increase their rate of destruction in the atmosphere?*

Albedo modification: Evaluating proposals to modify planetary albedo would require research into the fundamental capacity of the techniques, their various impacts, and potential side effects.

■ *How would the climate that results from a specific implementation of an albedo modification technique differ from that predicted without such intervention, as well as from the previously known (e.g., present-day and pre-industrial) states of the climate?*

■ *Cloud and aerosol processes are critical in shaping the way many albedo modification techniques would affect the climate, but many aspects of these processes are poorly represented in global climate models. What are the implications of these shortcomings for our confidence in the climate response to these techniques?*

■ *Given that many albedo modification techniques would allow some control over the spatial pattern of their climate forcing, would it be possible to “optimise” the climate response, and what would be the limitations and implications of such an endeavour?*

■ *How well can research into the climate impacts of albedo modification techniques provide the information necessary to judge whether the benefits of a given deployment strategy would outweigh the risks?*

■ *The climate is highly variable on a timescale of years to decades, and as such it will prove challenging to detect and attribute, and hence perhaps to control, the climatic response to albedo modification. What monitoring and control strategies would be needed to verify and manage a large-scale deployment of albedo modification?*

■ *Given the rapid and potentially disastrous warming that would follow from an abrupt termination of large-scale albedo modification, what “exit strategies” exist and what would their implications be for long-term climate policy?*

SAI and marine cloud brightening seem to be the most feasible albedo modification techniques, based on current knowledge, but there are many unanswered questions relating to their feasibility, including:

■ *Could technologically-robust and cost-effective spraying methods be developed for the purpose of SAI and marine cloud brightening?*

■ *Could millions of tonnes of material annually be affordably and safely lofted and released at altitudes of 20–25 km in the tropics, where research indicates that injections would be most effective?*

More general questions to inform governance developments include:

■ *What scales of field experiments would be required in order to develop a sufficient understanding of the relevant processes and responses to the various albedo modification techniques?*

■ *Attributing the consequences of albedo modification to the implemented techniques would pose many challenges, and would require long timescales before the control of these schemes could be verified; what are the implications of this?*

2) Public awareness and perception

Public awareness of climate engineering techniques remains low at present, yet the public is likely to play a key role in determining whether deployment of such techniques ever occurs, and prior to that, how much is invested into research on the technological and natural science aspects of the technique. Hence research is warranted into the questions:

■ *To what extent is the public aware of different greenhouse gas removal and albedo modification techniques, and how do attitudes and responses to these ideas vary?*

■ *Can the different scales and types of climate engineering research (modelling, study of analogues, field experiments, test bed demonstrations, prototypes, development, and deployment) be unambiguously defined and agreed between stakeholders; what purposes would such a definition serve; and what might be the implications of choosing specific definitions and distinctions between activities?*

- *What are the differences in awareness, attitude, and acceptance of theoretical and laboratory research, field tests, and potential deployment at different scales for different forms of greenhouse gas removal and albedo modification?*

- *What factors shape public awareness, and which are most influential for the development of public attitudes toward different techniques?*

- *How do stakeholders respond to information about climate engineering techniques? How does this depend on the context and style in which the information is presented?*

3) Ethical, political, and societal aspects

The possibilities of albedo modification and greenhouse gas removal raise many ethical, political, and legal issues, as discussed in Chapters 3 and 4. At a fundamental level, research needs to address:

- *What is the relationship between individual climate engineering techniques and human rights?*

Furthermore, the severe uncertainties about the consequences, side effects, and future development of different techniques present challenges that can be examined in various ways, for example through the development of risk ethics and by putting forward challenging normative questions such as:

- *How can the risks of certain techniques be weighed against those of severe climate change or climate tipping points?*

- *How can the difference between unintentional and intentional interventions in the climate and the moral properties associated with such interventions be better understood, and what do these differences mean for the development of standpoints on the various proposed techniques in different stakeholder contexts?*

- *Could certain techniques transfer risks and costs to future generations, and how are they to be evaluated based on different assumptions about our duties towards them?*

Historical research could add to this by addressing:

- *What can be learned from other multi-generational projects (for example, radioactive waste treatment and storage) that can be applied to analysing the risks and potential success (or lack thereof) of greenhouse gas removal and albedo modification techniques?*

Climate engineering also brings forward interesting economic, societal, and political research questions, such as:

- *How would the application of different techniques affect financial systems, particularly with respect to fossil-fuel and resource markets, and the carbon markets?*

- *How would the implications differ if specific techniques were to be applied in a centralised or decentralised way?*

- *How does the perception of different techniques by different stakeholders influence the further development of these techniques?*

- *How does the emergence of the proposition of climate engineering, and the possible emergence of specific climate engineering techniques, change societies and social behaviour?*

- *How might climate engineering techniques themselves be shaped by the societal context from which they emerge?*

Finally, climate engineering raises questions at the very foundation of our understanding of the role of humanity in the world, particularly in light of the recent development of the concept of the Anthropocene:

- *How does our understanding of the degree to which humanity has the “right” to intentionally intervene in the global Earth system vary across cultures, political backgrounds, and beliefs held by the various religious traditions around the world?*

- *How does the prospect of climate engineering impact our understanding of what it means to be human in the Anthropocene?*

- *Similar to considerations of the deeper meanings surrounding the possibilities presented by control over the human genome, what is the deeper meaning of contemplating the coordinated control of the Earth system on a global scale?*

4) Governance and regulation

Some of the research questions on governance and regulation relate directly to the policy options that are presented in Chapter 6, highlighting that these should be seen as evolving options, whose prioritisation will vary over time and as a function of stakeholder perspectives. Questions on governance and regulation of the variety of proposed techniques for climate engineering have mostly only recently started to emerge, and it is unclear what the advantages and disadvantages are in distinguishing between governance for research and governance for deployment. Thus, future research must articulate questions like:

- *What (if any) are the differing requirements for political processes considering research and deployment of different greenhouse gas removal and albedo modification techniques?*
- *Is it more sensible for the governance of various types and scales of research to be distinct, or to be a component of the overall governance of climate engineering implementation?*

With regard to governance of research, several questions arise:

- *Which actors should be responsible for monitoring, authorising, and/or prohibiting research of various types into the different climate engineering techniques?*
- *Should the public be engaged in developing governance for research, and if so, in what ways?*
- *How differentiated should governance be for different albedo modification and greenhouse gas removal techniques?*

Also important is the issue of who owns such techniques:

- *What could an intellectual property rights regime look like, specifically for climate engineering techniques?*
- *Should private investment in techniques for planetary-scale interventions be allowed, or should some or all techniques be government-owned?*

■ *Further questions in the domain of legal research are: How might a future liability regime for damages arising out of experiments and potential future deployment be structured?*

■ *Would the deployment of some techniques require new compensation schemes? How would those relate to existing liability schemes?*

■ *How are the precautionary principle and the preventive principle, and the different interpretations of each, relevant for regulating research on, and potential deployment of, individual climate engineering techniques?*

At the international level, research needs to clarify:

■ *How do different climate engineering techniques relate to the three existing Rio Conventions (UNFCCC, CBD, and the United Nations Convention to Combat Desertification, UNCCD) and other existing legal regimes?*

■ *How are the goals of each convention affected by the prospect of climate engineering, and how would they be affected by an actual large-scale implementation of various forms of climate engineering?*

■ *Are there greenhouse gas removal activities that fit within the flexible mechanisms of a potential post-Kyoto Protocol?*

■ *How do greenhouse gas removal and albedo modification techniques and their potential effects relate to the current Millennium Development Goals and the anticipated Sustainable Development Goals?*

6. Policy development for climate engineering

The complex socio-technical context within which discussions of climate engineering are emerging necessitates careful engagement with scientific, legal, political, economic, and ethical aspects of climate engineering as a basis for sound decision making. As outlined in the previous chapters of this report, questions arise about technological feasibility, global fairness, international cooperation, distribution of costs and benefits, and social acceptability. Decision makers will thus face complex choices and trade-offs. While many general principles that can guide policy development are likely to apply to most or all climate engineering techniques, the differing stages of development and discourse about the various techniques subsumed under the umbrella term “climate engineering” need to be taken into account when assessing policy options and pathways. In this sense, cases in which policy development is comparatively advanced (for example, OIF) may inform the policy development for emerging techniques such as SAI.

This chapter first outlines the policy context within which discussions of climate engineering are emerging (Section 6.1), with a special focus on the EU. Section 6.2 proceeds to examine general policy considerations, first at an abstract level and then more specifically for climate engineering research governance and the international governance of climate engineering. Section 6.3 discusses technique-specific policy considerations for BECCS, OIF, and SAI. Section 6.4 concludes by summarising the discussion of policy options, discusses the difficulties of policy making in this area, and reflects on some of the broader questions that result for science and society.

6.1 Policy context

The discussion of climate engineering techniques is emerging within the broader context of responses to climate change, and thus alongside existing and potential strategies for mitigation and adaptation. These mitigation and adaptation strategies cannot be expected to remain unaffected should discussions of climate engineering emerge significantly onto national and international political agendas. There is much concern in the climate engineering research community and among other stakeholder groups engaging with the topic, that the emergence of the climate engineering discourse might reduce overall willingness to invest in mitigation efforts, including diverting attention or reducing incentives for international emission reduction commitments (see also section 3.1).

For the past two decades, the EU has championed the internationally agreed target of limiting global warming to a 2°C increase in global mean surface temperature compared to pre-industrial levels. The EU has committed to reducing its emissions by 80–95% compared to 1990 levels by 2050 as its declared contribution under the Durban Platform process. It has also committed to reducing emissions by 20%, deriving 20% of its power from renewable sources, and to improving energy efficiency by 20% by 2020, also relative to 1990 (the so-called 20–20–20 targets, whereby it should be noted that only the first two are binding). However, even if the EU successfully reduces its own emissions, it represents only a comparatively small and declining (currently around 11%) proportion of global emissions. All other major emitters would need to achieve similar reductions in order to actually limit global warming to less than 2°C. Model simulations

indicate that even the most optimistic IPCC scenario, RCP 2.6, is “likely” — but far from certain — to limit average warming to less than 2°C by the end of the 21st century. Moreover, Fuss et al. (2014) found that the majority of the scenarios that would limit global warming to below 2°C require global net negative emissions, i.e., implementation of some form of climate engineering by greenhouse gas removal, and generally already by the second half of this century. Despite widespread recognition of this situation, emissions have nevertheless increased more rapidly in the past few years than envisioned even in the most pessimistic IPCC scenario, RCP 8.5. It remains an open question whether fixed temperature thresholds like the 2°C target might increase political pressure to actively deploy climate engineering techniques on a scale that would affect the global climate — either greenhouse gas removal techniques, as envisioned in the “vast majority” (IPCC, 2014d, p. 83) of scenarios that underlie RCP 2.6, or albedo modification and related techniques.

Of course, there are still opportunities to develop meaningful international agreements on emission reduction targets, for example at the international climate negotiations in Paris in late 2015. However, even though recent negotiations in Lima showed less pronounced differences between developed and developing countries than previous negotiations, no breakthroughs have been achieved yet. Nevertheless, individual actions by states and bilateral agreements, as well as new initiatives such as the Climate and Clean Air Coalition (CCAC), have raised hopes that meaningful reductions in greenhouse gas emissions (including non-CO₂ greenhouse gases) are still achievable.

It is from this context that discussions around climate engineering techniques have been emerging onto scientific and (albeit less so) political agendas, although overall research funding and political interest in pursuing climate engineering currently remain low. It will be important for the EU and its member states to develop a common understanding of — and shared perspective on — climate engineering techniques in order to respond to and, if desired, shape potential future developments in this area. In this process, the vast differences between the various climate engineering techniques need to be carefully accounted for

and situated within the broader landscape of climate action processes and initiatives.

Sustainable development and protection and improvement of the quality of the environment (Lisbon Treaty Article 2) are key objectives of EU policy. In these policy areas, the EU has established processes for ensuring comparatively high standards of environmental and social protection that can be built upon when devising governance for climate engineering. Should the EU decide to act as a global leader on climate engineering research, it could draw on this body of policies and principles to develop farther-reaching propositions for the governance and regulation of both climate engineering research and deployment, with the goal of informing and guiding international discussions.

Discussions of climate engineering governance are not emerging in a legal void (see Chapter 4). Customary international law includes established principles such as the duty to inform and the duty to prevent transboundary harm. National laws equally apply, for example the obligation to conduct environmental impact assessments, depending on the jurisdiction in question. Furthermore, provisions established to govern scientific research, such as peer review and ethics boards, also apply to climate engineering research. The developments at the CBD and LC/LP represent the first steps specific to the international governance of climate engineering techniques. The LC/LP in particular has been instrumental in providing legally binding rules on the testing and deployment of ocean iron fertilisation and has laid the groundwork for regulating other marine geoengineering activities that fall within its scope (see Section 4.1.2). At the level of bottom-up norm generation, attempts have been made to formulate principles that might contribute to the emergence of a collective understanding of what constitutes “appropriate behaviour” (March and Olsen, 1998) in the emerging field of climate engineering. This is particularly relevant at the current early stages of research, during which positions are not yet hardened and perceptions of appropriateness remain malleable. Sets of suggestions are contained in the “Oxford Principles” (Rayner et al., 2013), which also provided the basis for principles derived at the Asilomar International Conference on Climate Intervention Technologies in 2010 (MacCracken et al., 2010),

and recommendations governing the conduct of the SPICE project test bed (Stilgoe et al., 2013).

There is no directly applicable governance in place for perturbative albedo modification experiments in the open environment, beyond existing mechanisms such as: peer review; requisite conditions for receiving funding; and EIAs in cases where specified thresholds of environmental harm may be crossed. Although research principles and frameworks are being broadly discussed or implemented in specific projects (such as in the case of SPICE, see Box 3.5), there is neither coherence nor consensus on their value for all field experiments. This gap would need to be filled by further actions taken at (inter)governmental levels (this could be initiated through ministries or by international collaborations between research organisations, as well as through regional, supranational, and international organisations) and within the research community, to ensure the prevention of environmental harm and to provide sufficient legitimacy and accountability (Schäfer et al., 2013a; Schäfer and Low, 2014).

6.2 General policy considerations for climate engineering

Building upon the assessment of the legal landscape in Chapter 4 and upon the state of research in Chapter 5, this section provides some considerations on developing climate engineering policy in the EU. Choosing whether or not to support research on climate engineering — and if so, at what level to support the research and how to fund and govern it — will involve significant value judgments. Thus, the EuTRACE project can only provide guidance on setting priorities and developing policies from the perspective of the consortium, but will avoid being specifically prescriptive for the European Commission or other bodies. This sub-section focuses on general considerations that could be applied to developing policy on climate engineering. It begins with a discussion of factors that should be considered in forming a position on climate engineering research — the urgency of such research, possible sequences in which the research might be conducted, and the multiple uses for which climate engineering may create relevant knowledge (section 6.2.1). It proceeds to discuss policy considerations in developing principles for climate engineering governance (section 6.2.2) and strategies based on these prin-

ciples (section 6.2.3). Finally, section 6.2.4 discusses considerations specific to the international governance of climate engineering.

6.2.1 Urgency, sequencing, and multiple uses of climate engineering research

There are several considerations that need to be applied to the formation of a position on research on greenhouse gas removal and albedo modification. This section will discuss three key considerations:

- urgency/timeliness
- sequential versus parallel research approaches
- connection to other research.

6.2.1.1 Urgency and timeliness of climate engineering research

Various arguments can be made about the urgency of conducting research on albedo modification. On the one hand, one could argue that research should only be initiated or scaled up when it is demonstrated that there is insufficient time left to achieve climate targets via mitigation alone. Conversely, one could also argue that research on climate engineering should be initiated or scaled up as long as it is not demonstrated that there is sufficient time left to achieve climate targets via mitigation alone. Independent of whether long-term climate targets can be achieved, it can be argued that albedo modification represents the only potential method for reducing the near-term impacts of climate change and should therefore be researched independent of successes or failures in mitigation efforts. Various other intermediate perspectives could be considered, for instance a scenario in which it would only be possible to achieve climate targets through mitigation combined with the removal of greenhouse gases. Another possible argument is that research should mainly focus on key issues that will likely require the most time to resolve. A broad range of similar arguments is being applied to research on climate engineering in general, and a particularly critical debate in the literature presently concerns field experiments for albedo modification techniques. Example applications of these and other arguments for and against field testing of albedo modification are outlined in Box 6.1.

Summary of arguments in support of or against field tests of albedo modification

In favour

- There is a widely accepted urgency to halt or slow climate change before it reaches levels associated with large-scale dangerous consequences (which current knowledge suggests increases significantly in probability when global warming exceeds 2°C).
- Specific knowledge gaps (for example, on environmental impacts of various techniques) can only be closed by conducting field tests. Some small-scale field experiments would have a negligible impact and could proceed without concern for environmental harm (applying a low threshold, for example, global average radiative forcing equivalent to less than 10^{-6} W/m² as suggested by Parson and Keith (2013)).
- Beyond climate impacts, robust examination of which would need very large-scale tests, many aspects of albedo modification techniques can be tested at small scales, such as aerosol particle and cloud microphysics, impacts on stratospheric ozone chemistry, etc. These may give early insights into whether it is sensible to pursue specific techniques.

Against

- There is currently insufficient justification for small-scale field tests of albedo modification techniques until further modelling and laboratory work have sufficiently developed our basic understanding of the techniques and their impacts.
- Regulatory backlash and/or public contestation due to a real or perceived lack of legitimacy might endanger other important research efforts, particularly for related basic climate science (for example, understanding basic aerosol-cloud-climate interactions).
- Limited detectability of effects against the background of large natural variability means that field tests intended to examine climate impacts of albedo modification techniques would have to be conducted on a very large scale.

While concerns regarding field tests apply especially to albedo modification, some of these concerns also apply to higher-risk or higher-impact techniques for the removal of greenhouse gases, such as OIF.

6.2.1.2 Sequencing: Advantages and disadvantages of a parallel research approach

Some arguments call for a sequential approach to climate engineering research, in which it is usually suggested that one specific form of research should be conducted before any other. This may be natural scientific research, based on the assumption that if climate engineering is found to be technically infeasible, then investments in social science research and governance development specific to climate engineering techniques will have been wasted. It may also be social scientific research and governance development, based on the assumption that if climate engineering is socially unacceptable, opposed by the public and/or ungovernable, then investments in natural science research and engineering development specific to climate engineering techniques will have been wasted.

Conversely, it can be argued that governance is required to ensure that research, especially on albedo modification techniques, is equipped with an adequate degree of legitimacy, and that social scientific research can contribute to better understanding this. If a decision to invest in climate engineering research and to pursue the development of climate engineering options is to be based on a societal discussion on the desirability of such a course, then this discussion and related research would need to take place before such a decision is made. Once technologies have been developed to full scale, a discourse on their political and social desirability might then be too late to effectively contribute to guiding socio-political decisions. Lessons learned from other technologies, such as nanotechnologies and genetic modification, show that politics and decision making do not simply “follow the science”. In particular, field tests in the absence of what is perceived as appropriate governance would lack legitimacy (Schäfer et al., 2013a), which could result in extensive public opposition, in turn rendering investments in natural science wasted. Natural science experiments take place in a societal context

and can have spill-over effects and create conflicts. Social science research can help the community involved in the discourse around climate engineering to better understand the concerns associated with individual techniques and their development.

It is therefore emphasised that this consortium has followed the approach of parallel research, which is thus viewed favourably here, since the results allow consideration of how normative, social, and political factors would influence the potential development of climate engineering techniques; how these factors influence each other; and how the potential development of climate engineering techniques may impact the socio-political world. Future parallel research could involve studies on the public acceptance of climate engineering in more EU countries; for example, participatory governance programmes to elicit public values on climate engineering via a coordinated approach (e.g., deliberative focus groups, social media, etc.). The findings could systematically inform policy making and the investigation of governance structures intended to prevent moral hazard and “slippery slope” dynamics; simultaneously, natural science and engineering research could provide these studies with improved information on the potential physical characteristics of various designs for climate engineering techniques and their potential environmental impacts.

6.2.1.3 Multiple uses of knowledge: Connection to other research

It has been noted that climate engineering research and its broader discourse will be most valuable if it does not occur in isolation from other fields and topics, and particularly that it is valuable to place climate engineering research in the broader context of mitigation and adaptation (Bellamy et al., 2013).

Furthermore, a more specific connection can be made between climate engineering research and other research topics. It is not always easy or even possible to distinguish climate engineering research from basic research on the climate system and its components, which is not aimed at generating knowledge for climate engineering. Findings in atmospheric physics and chemistry, the ocean system, and other research topics may also yield insights into climate engineering, and vice versa. Climate engineering builds on a

large body of research, for example on climate change mitigation (for greenhouse gas removal techniques, especially BECCS), climate and climate change modelling (especially for albedo modification techniques), and biogeochemistry (especially for ocean fertilisation). Analogues for climate engineering (such as volcanic eruptions and natural ocean fertilisation events) have been studied extensively, independent of any specific interest in climate engineering applications. Research on greenhouse gas removal and albedo modification not only depends on the knowledge base established through research in related fields, but also provides benefits by feeding back into the broader topics of climatic and Earth system research. The same holds for technological research, which may find applications outside the field of climate engineering (for example, gas separation techniques and spraying techniques). Climate engineering research could therefore create synergies with other scientific issues, and may create valuable knowledge wholly independent of whether or not any climate engineering techniques are ultimately deployed. Similarly, social science research can develop insights from investigating the debate and dynamics around climate engineering that will remain valuable even if climate engineering itself were never to be pursued any further. Thus, if a decision is made that climate engineering research is justified, then from the perspective of efficient use of resources it is sensible to look for opportunities to maximise synergies such as those described here, but without masking the intention of creating knowledge for climate engineering.

6.2.1.4 Outlook: a challenge and opportunity

Various arguments for and against climate engineering research, based on different assumptions, have been applied to inform the international debate (see Section 5.2). Against the background of increasing research funding, also in several EU member states, a detailed analysis of the range of arguments, including those about how and under which conditions to pursue research on greenhouse gas removal and albedo modification techniques, could help to inform societal debate and political decision making. The previous chapter (see Section 5.3) provided guidance on the questions that such an analysis might address, summarised in the form of important research questions

for different fields of interest such as the natural sciences, public awareness, ethical, political, and social aspects, as well as governance and regulation. As one conclusion of the interdisciplinary EuTRACE project, the consortium advocates a parallel research approach that simultaneously addresses questions of natural scientific and social scientific interest, without prioritising one to be carried out before the other.

A great challenge remains for funding agencies and governing bodies, and also for research institutes and individual researchers, to weigh the arguments that speak in favour of and against research into climate engineering (Section 5.2). It is not possible to provide blanket answers and judgments about the relative weighting of these arguments for all the individual techniques discussed in this report, since such weightings are strongly dependent on values and stakeholder perspectives. Below, in Section 6.3, guiding principles are distilled and provided, with an interest in providing support to the European Commission and the broader policy and research community. A conscientious application of these principles in accordance with the continuously developing knowledge base on climate engineering may facilitate the development of European policies on research and on the potential implementation of climate engineering techniques that are coherent and consistent with the basic principles upon which broader European research and environmental policy are built.

6.2.2 Policy considerations in developing principles for climate engineering governance

Given the strong arguments outlined above (Section 5.2) both for and against research, there is a considerable debate about whether research into greenhouse gas removal and albedo modification should take place in the first place; if so, what forms it should take; and on the need for, and possible forms of, governance for the differing techniques during the various stages of their research and development trajectories. In order to guide the scientific community and policy makers in this debate, several principles have been derived for this report, and are presented in this section. These principles have been distilled from existing provisions in EU primary law, supplemented by international law and the development of climate

engineering governance through the CBD and LC/LP, as well as principles from the academic literature (Rayner et al., 2013; Morrow, 2009)

The set of principles below may guide policy development for a very broad range of techniques throughout their respective technological development trajectories. Intentionally remaining at an abstract level, they lay down basic normative parameters that can guide decision making in the area of climate engineering. Decision making will necessarily require the balancing of different values; specific policy options will therefore embody the values of one or more of the principles to various extents, and in their application may conflict with each other.

The principles and their implications for climate engineering techniques are as follows:

The **minimisation of harm**: The risk of individuals being exposed to harm from climate engineering, the number of people exposed to risks, and the magnitude of the potential harm should all be kept as low as possible, and serious and irreversible harm should be avoided. A stricter reading of this principle may conclude that there is an obligation to not cause environmental harm, as well as a duty of prevention as a matter of due diligence.

The **precautionary principle** (see also Sections 4.1.1–4.1.3, 4.2.1): The precautionary principle is to be applied in situations of scientific uncertainty. It demands preventive measures against plausible environmental and human health threats that are serious or irreversible. Necessary and appropriate precautionary measures may be permitted or even required, depending on the formulation of the principle, when the best available scientific and technical data indicate the existence of risks. In order to decide on appropriate precautionary measures, policy makers need to define the appropriate level of protection to be applied, and the severity, persistence, and reversibility of the potential impact, were a threat to transpire. It is important to note, however, that some have drawn a different interpretation from the application of the precautionary principle: an obligation to conduct research, as it represents a possible measure for preventing damage and harm associated with climate change (Bodansky, 1996, Bodansky, 2012, Reichwein, 2012, Ralston, 2009).

■ Origin: TFEU Article 191 (2) – “Union policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Union. It shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source and that the polluter should pay”.

The **principle of transparency**: The principle of transparency calls for the open distribution of relevant information about research activities. The background for this is that, in order to adequately judge whether such activities should be supported, tolerated (allowed), or opposed (banned), the scientific, civil society, and policy communities have a need for information on research activities related to climate engineering. Transparency can also be considered to be of instrumental value, as it can foster future scientific research by reassuring the public of the integrity of the research process (Rayner et al., 2013). Transparency thus serves both substantive and procedural ends, and mechanisms that establish transparency will need to take this dual purpose into account (Craik and Moore, 2014).

■ Origin: TEU Article 11 (2) provides that “the institutions shall maintain an open, transparent and regular dialogue with representative associations and civil society” while Article 11 (3) provides that the Commission “shall carry out broad consultations with parties concerned in order to ensure that the Union’s actions are coherent and transparent”.

The **principle of international cooperation** requires action to be undertaken involving the international community as far as possible, in order to build global legitimacy and peaceful resolution of possible conflicts of interest and legal disputes. It does not follow from this whether climate engineering constitutes a task flowing from the treaties, and it would first need to be determined whether climate engineering reflects the values of the Union. In international law, it is derived from the principle of “good neighbourliness”, which is normally extended given the concepts applied in states’ agreements. Thus the content and scope of cooperation are derived from the text of the agreements themselves and may normally include a commitment to further develop a legal

regime. Also, as a principle, it encompasses many other stand-alone legal obligations, both procedural and substantive, including information sharing, participation in decision making, EIA, information exchange, consultation and notification, provision of emergency information, and transboundary enforcement of environmental standards.

■ **Origin:** TEU Article 4 (4) provides that “the Union and the Member States shall, in full mutual respect, assist each other in carrying out tasks which flow from the Treaties”. TEU Article 8 (1) provides for cooperation with neighbouring countries “founded on the values of the Union”.

Greenhouse gas removal and albedo modification — or at least some of the techniques — may be understood as **public goods**, allowing for the regulation of such techniques in the public interest (Rayner et al., 2013). The view of both forms of techniques as a public good is based on concerns about the future orientation of research and the role of private enterprises and commercial interests. These concerns are often based on the profit orientation of the private sector, the possible limitation of accessibility if such techniques would be commercialised, and the potential bypassing or neglect of the socio-economic, environmental, regulatory, and humanitarian dimensions of certain climate engineering techniques by private enterprises (Robock, 2008; Blackstock and Long, 2010; Shepherd et al., 2009).

6.2.3 Strategies based on principles

Based on these principles, different strategies have been proposed that could be applied across all climate engineering approaches, including:

Early public engagement: The demand for early public engagement in research and development of albedo modification and greenhouse gas removal techniques can be grounded in reflections upon procedural justice (see Section 3.1.3). It is also instrumental in building trust in scientific activities (Bodansky, 2012) and in improving the quality of socially robust scientific and technological solutions, especially in situations of uncertainty (Stirling, 2008; Carr et al., 2013; Corner and Pidgeon, 2010; Stilgoe et al., 2013).

Independent assessment: An important instrument for achieving transparency as well as for the minimisation of harm is the independent assessment of possible environmental impacts and other impacts of research activities involving greenhouse gas removal and albedo modification field tests. Particularly in the case of expected transboundary impacts, such assessments will be most respected if they are carried out through independent regional bodies, international bodies, or both (Rayner et al., 2013; Morrow, 2009).

Disclosure mechanisms and transparency: Craik and Moore (2014) explore the multiple functions that transparency may have as a mode of governance for climate engineering research. They identify two overarching purposes in this regard: 1) minimisation of risks associated with research through disclosure of information, which allows regulators, proponents, opponents, and other actors to understand the risk profile of research and thereby take action toward reduction of risks, and 2) trust-building through acknowledgement and operationalisation of the normative right to know about activities that may be of interest. Together, these dual roles should help to situate climate engineering research as a global public good in which all interested parties have a stake, are able to assess their interests, and to understand where opportunities occur for their engagement in decision making. Furthermore, Craik and Moore (2014) identify three procedural mechanisms which might be applied to serve these functions: environmental impact assessment (see also the previous point), research registries, and information clearinghouses. Particularly for the governance of field experiments into albedo modification techniques, they encourage regulatory bodies at the national and international levels to undertake actions toward the implementation of these procedural mechanisms.

International codes of conduct: Hubert and Reichwein (2015) explore a model of an informal, harmonising draft code of conduct to govern and regulate climate engineering, focusing on the near-term prospect of scientific research and development of these proposed techniques, and set against the background of advancing scientific, political, social, and economic discussions on this subject. Their analysis of a wide range of existing legal sources suggests that this topic is situated within a large body of evolving inter-

national norms established in other contexts, which even if they are not directly applicable can make an important contribution to the elaboration of guidance on the responsible conduct of climate engineering research at all levels. They also explore issues related to legal form, taking into account issues related to the high degree of regime interaction and normative overlap implied by the subject matter of climate engineering, and the need to develop and harmonise measures at various levels and involve different actors. This approach could serve as a possible flexible and adaptive governance approach to advance and coordinate the efforts of governments, existing or new international organisations and treaty bodies, and non-state actors such as NGOs, business, scientific academies, research institutes, and individual scientists in addressing this topic.

Responsible innovation and anticipatory governance: Stilgoe et al. (2013) develop a “framework for responsible innovation” in which an interactive process allows scientists to convene with stakeholders to exchange views on the (ethical) acceptability, sustainability, and societal desirability of their work (Stilgoe et al., 2013; citing Schomberg 2011). This can be situated alongside wider efforts toward anticipatory governance: a strategic approach to enabling early investigative and regulatory actions in emerging (technological) debates. A key tenet here is that precautionary or predictive approaches base action on reducing uncertainty and reacting as much as possible to a “known” future. Anticipatory practices seek to navigate uncertainty and to forestall technocratic management (prediction) or an indeterminate state of inaction (precaution) by integrating diverse bodies of knowledge from scientific and societal constituencies, and by pointing out key nodes and modes of interaction as context to decision making (Barben et al., 2008; Guston, 2014; Karinen and Guston, 2010; Foley et al., 2015 forthcoming).

This could enable early warnings, public scrutiny of science, public legitimacy and inclusiveness, and provide the flexibility and responsiveness necessary to respond to emerging knowledge and public contestation. In the context of climate engineering, with specific insights drawn from the SPICE project (see Section 3.1.4), the responsible innovation framework envisions an institutional review process (a “stage-

gate” process), set up by funding agencies, in which an expert panel assesses research along specific criteria. In Stilgoe et al. (2013), these are:

- risks identified, managed, and deemed acceptable;
- compliant with relevant regulations;
- clear communication of the nature and purpose of the project;
- applications and impacts described and mechanisms put in place to review these;
- mechanisms identified to understand public and stakeholder views.

The principles of transparency and participation may suggest establishing a platform for disclosure of relevant information regarding climate engineering-related research and/or deployment activities. Information could be provided on risks and opportunities associated with individual activities, as well as on the rationales for policy decisions. Transparency can also be aided through independent environmental and social impact assessments to generate relevant information for the public. Binding standards for reporting can assist comparability between individual activities.

The realisation of some of these principles, demands, and instruments, especially in the governance of small-scale field tests of albedo modification techniques, but also similarly for perturbative experiments such as open-ocean OIF experiments, requires adequate governance mechanisms and institutions at national and international levels that currently do not exist (Schäfer et al., 2013a); furthermore, it can be anticipated that new governance gaps may emerge, requiring the creation of new rules and institutions. On the other hand, some have expressed scepticism over whether international governance of research is necessary or even possible, given the present stage of development of many techniques (Victor et al., 2013; Morgan and Rieke, 2010; Parson and Keith, 2013).

6.2.4 Policy considerations for international governance of climate engineering

Taking into account the possible side effects and risks associated with different climate engineering techniques, the question arises: who can legitimately decide on climate engineering deployment or even research (especially field tests), and through what processes? Answers to this question can be derived from, or related to, principles of procedural justice, which deals with the idea of fairness in the processes that resolve disputes and allocate resources, benefits and costs. Claims of procedural justice are often based on the assumption that to be morally acceptable, all those affected by a decision must be notified and consulted and must have the ability to contribute to the process of decision making, or have their interests represented (Jamieson, 1996; Morrow et al., 2009; Rayner et al., 2009; Svoboda et al., 2011; Carr et al., 2013; Rayner et al., 2013). As climate engineering is designed to address a global problem and therefore

may, as a result, noticeably affect the global population, it has been argued that the scope of public engagement should therefore be global (Preston, 2012, Preston, 2013).

Democratic processes at the national level alone appear insufficient for decisions on deploying techniques that could have transboundary effects. Decisions affecting a shared natural resource and common heritage are often seen to require a cooperative legal framework in which the sovereignty and interests of all states are taken into account (Abelkop and Carlson, 2012). However, agreements involving the global commons that are acceptable to all parties may be impossible to reach due to significantly different interests that are grounded in geopolitical, economic, and related issues (Athanasίου and Baer, 2002, SRMGI, 2012). Furthermore, international decision-making structures often exclude or marginalise those who are especially vulnerable (Jamieson, 1996; Pogge, 2002; Corner and Pidgeon, 2010; Gardiner, 2011; Joronen et al., 2011). Procedural norms (see Box 6.2) provide guidance on how these difficulties and shortcomings can be overcome.

Box 6.2

Procedural norms

There are several procedural norms that could help facilitate and improve the quality and legitimacy of climate engineering decision making:

- notification and consultation of those affected as well as the wider public and other nations (Morrow et al., 2009; Svoboda et al., 2011; Carr et al., 2013; Rayner et al., 2013);
- fostering public engagement early in the research phase (Poumadère et al., 2011);
- open preparation and execution of environmental as well as societal impact assessments prior to conducting activities that can have significant environmental or other impacts (Abelkop and Carlson, 2012);
- transparency and public disclosure of the rationales for policy decisions on climate engineering techniques (Craik and Moore, 2014);
- providing a mechanism for appeal and revision to ensure fairness (Daniels and Sabin, 1997, Tuana, 2013).

Many possible variants for an institutionalisation of climate engineering governance have been set forth in the literature (Cicerone, 2006; Victor, 2008; Davies, 2009; Morrow et al., 2009; Virgoe, 2009; Benedick, 2011; Bodansky, 2011; Bodansky, 2012; Lloyd and Oppenheimer, 2011; Galaz, 2012; Dilling and Hauser, 2013; Morgan et al., 2013; Zürn and Schäfer, 2013; Barrett, 2008b). Currently, three institutional loci are at the centre of attention: the UNFCCC, the CBD, and the LC/LP. The following subsections will briefly review the state of discussions on climate engineering within these frameworks, highlight possible ways forward for international governance of SAI, OIF, and BECCS, and examine possible actions the EU could take.

6.2.4.1 The United Nations Framework Convention on Climate Change (UNFCCC)

To date, the UNFCCC Conferences of the Parties (COPs) have remained silent on climate engineering, which is of little surprise given that alternatives to conventional mitigation are frequently considered a source of moral hazard, threatening the premise of the current climate regime that is based on reducing emissions. Although the UNFCCC, with its explicit focus on climate change, could provide a viable framework for the climate engineering debate to unfold, the present provisions of the treaty only allow for consideration of techniques for greenhouse gas removal. No straightforward avenue is currently available for incorporating albedo modification techniques into the discussions. Principally this could be done by posing climate engineering as an additional response strategy to anthropogenic climate change; however, as noted, a widespread concern is that this could be detrimental to the negotiations around CO₂ reductions.

Beyond the treaty bodies, the only specific activity related to climate engineering within the broader UNFCCC regime is the inclusion of a brief discussion of climate engineering methods in the Fifth Assessment Report of the IPCC (IPCC, 2014c). However, since the IPCC has a purely scientific advisory function (to analyse existing science and identify priority needs for further research activities), this cannot be interpreted as having legal relevance, although it might contribute to a political dynamic that leads to

an uptake of climate engineering in future discussions at the UNFCCC. It also demonstrates the scientific and policy relevance of climate engineering to the problem of climate change. Whether the fact that climate engineering has been taken into account by the IPCC will lead to its inclusion in future UNFCCC COPs cannot be foreseen, but the visibility of the issue in general can be expected to increase.

6.2.4.2 The Convention on Biological Diversity (CBD)

Milestones in the development of climate engineering governance at the CBD were the COPs in the years 2008 (decision on ocean fertilisation), 2010 (decision on climate engineering more broadly), and 2012 (where several decisions were adopted that relate to climate engineering). This is of considerable relevance given the almost universal validity of the CBD, with the key exception of the USA, which is not a member state. While these decisions are not legally binding (as described by Proelss (2009) for the 2008 decision) and therefore far from providing a legally binding moratorium, the call for science-based, global, transparent, and effective control and regulatory mechanisms, adopted with consent by all parties, conveys a strong political will to engage in further discussion on and regulation of climate engineering at the international level. Notwithstanding its non-binding nature, the CBD Decision could provide guidance for future regulatory activities.

6.2.4.3 The London Convention and Protocol (LC/LP)

Parties to the LC/LP have developed governance for marine climate engineering activities at a comparatively rapid pace over recent years (as outlined in Section 4.1.2). As a well-developed legal instrument for the protection of the marine environment, the LC/LP provide a suitable institutional setting for comprehensively addressing marine climate engineering activities, with the major consideration that their scope remains specifically limited to the protection of the marine environment. It has also been pointed out that regulation of climate engineering within the LC/LP may impact not only research on climate engineering, but also basic research on the marine environment more generally (Hubert, 2011).

6.2.4.4 Possible future development of the emerging regime complex on climate engineering

This section provides an outlook on possible developments in climate engineering governance based on the preceding sections, and ties in the analysis of ethical, legal, and political considerations in the climate engineering discourse with that of past developments and current features of the existing climate engineering governance landscape, along with an analysis focusing on what an EU perspective on this might be.

The comparatively rapid development of international governance for climate engineering over the past couple of years at the CBD and the LC/LP suggest a willingness of states to cooperate on the issue of climate engineering. In the medium term, this might signal the emergence of a regime complex consisting of regulatory provisions that include the CBD and the LC/LP, as well as potentially the UNFCCC (given the considerations noted above), supported by strategies designed to manage interplay between these institutions and by scientific assessments from the IPCC (Zürn and Schäfer, 2013).

The concept of a regime complex describes a situation in which there is no “fully integrated [institution] that [imposes] regulation through comprehensive, hierarchical rules” (Keohane and Victor, 2011), but rather a set of separate, fragmented institutions that partly overlap and might complement or contradict each other. From the above discussion, it is clear that there is no single body that at present is likely to claim the authority to comprehensively govern climate engineering. Instead, there is evidence for the emergence of different forms of governance in different institutional settings, most notably the CBD and the LC/LP.

The limited focus of the UNFCCC on climate protection could potentially lead to a “blending-out” of the non-climatic effects of climate engineering activities, such as effects on ecosystems and biodiversity, if it became the main institution for handling the issue. These could, however, be accounted for by the CBD; here, the inverse problem occurs, as the CBD, with its limited applicability focusing on issues related to biodiversity, does not address the effects of climate engineering techniques outside of their relationship to

biodiversity. A functional linkage between the two institutions could potentially contribute to providing a more comprehensive regulatory approach, but this may be overshadowed by the potential for political and legal conflict between the individual elements of such a regulatory structure. The legal relationship between the CBD and UNFCCC is still a matter of discussion (see Wolfrum and Matz, 2003).

A possible way to prevent political and legal inter-institutional conflict could be seen in the conclusion of memoranda of understanding negotiated by the institutions’ secretariats and then submitted to the respective COPs. Specifically for the CBD and the LC/LP, given the apparent similarities between the two conventions’ views on climate engineering as evidenced by their consistent approaches as well as mutual references contained in their statements on the objectives and the future of climate engineering regulation, this seems to be an achievable near-term goal. That said, while the CBD can claim a large degree of input legitimacy for its decisions arising from its quasi-universal membership, it suffers from the general nature of its provisions, the legally non-binding character of its COP Decisions on climate engineering, and its limited focus on biodiversity. Similarly, the LC/LP is characterised by its limited focus on protection of the marine environment from the dumping of waste and other matter, and its impact is further reduced by the limited number of parties that have ratified or acceded to it. Finally, the normative strength of the UNFCCC must also be considered as being limited in light of its exclusive focus on the climate and its often cumbersome negotiation process.

These weaknesses of the emerging global regime raise the question of the potential role of regional supranational entities such as the EU in the future governance of climate engineering. While climate engineering governance at the EU level would not provide a solution to the deficiencies of governance at the global level, it has the potential to initiate a process of harmonisation across instruments and to substantiate and complement governance emerging at the international level.

6.3 Technique-specific policy considerations

The following discussion on the development of policy options examines the three individual techniques (BECCS, OIF, and SAI) that are focused on in this report. Each technique-specific section begins by summarising the state of the art of scientific knowledge (see Chapter 2 for more extensive discussion) and then goes on to consider the state of technological maturity.

This is followed by a brief discussion of the particular concerns associated with a given technique. However, it is also valuable to note a number of common concerns applicable to all three example techniques, including:

- siphoning resources away from research in other areas;
- decreasing overall willingness to invest in mitigation of greenhouse gas emissions;
- creating forms of socio-technical lock-in due to vested interests and institutional inertia;
- having resource demands that significantly exceed initial estimates;
- causing resistance to and contestation of scientific activities in the open environment that are technically related to climate engineering technologies but do not share its intents, especially if field research is conducted under conditions of insufficient accountability and legitimacy.

An example of the latter could be perturbative tests of cloud microphysics, where understanding would be advanced for both albedo modification approaches as well as for basic climate science (see Section 5.1).

Finally, each section examines the current state of legal and norm development before discussing the policy context and range of policy considerations. A number of cross-cutting options were discussed in Section 6.2 on pursuing research, deriving principles for governance and for enacting policy at the EU and international levels. Here the focus is placed on

options that are more uniquely suited to individual technologies.

6.3.1 Policy development for BECCS

Scientific state of the art and technological maturity: As described in section 2.1.2, the technologies involved in BECCS are not yet fully developed and it is currently unclear how effectively they might be scaled up to the sectoral-scale deployment required to have an impact on the global carbon cycle at the level classified as climate engineering. However, a substantial role for BECCS is envisaged in many of the scenarios that succeed in limiting temperature rise to 2°C in the 21st century. The “vast majority” (101 out of 116) of scenarios that underlie the IPCC’s RCP 2.6, the only scenario in which meeting the 2°C goal is considered “likely” (IPCC, 2014d), include some form of greenhouse gas removal, especially BECCs and afforestation. BECCS is also included in “many” (235 out of 653) of the scenarios that underlie RCP 4.5 (Fuss et al., 2014).

Early commercial-scale CCS projects are operational and CO₂ capture, transport, and storage technologies are proven (Scott et al., 2013) and are directly applicable to BECCS. CO₂ capture from pure biomass burning (or from fossil fuel and biomass co-firing in proportions capable of delivering a net CO₂ removal) can initially adapt CCS CO₂ capture technologies, but further research and development on capture technologies specific to biomass will be required to maximise efficiency (IEAGHG, 2011, Bracmort and Lattanzio, 2013).

Nevertheless, the possible scales and rates of deployment for BECCS are primarily technically limited by the availability of sustainably produced biomass and the availability of pre-existing CCS infrastructures for CO₂ transport and storage (IEA, 2011, see also Section 2.1.2 in this report).

Concerns associated with BECCS: Provided the required resources (biomass growth and processing facilities, CO₂ storage) are available, small-scale initial deployment of BECCS could take place largely within national jurisdictions, so that local and national authorities would be primarily responsible for managing any resulting local environmental effects and soci-

etal responses. However, BECCS on the scale considered in the IPCC RCP 2.6 scenario would very likely have noticeable transboundary environmental, economic, and societal impacts. These could be both positive (for example, CO₂ removal; biomass production creating long-term economic activity in rural regions) and negative (for example, biomass production displacing food crops and thereby reducing food security; reducing biodiversity; depleting water supplies). While these impacts could be further explored in theoretical and small-scale studies, practical experience at full operational scale would likely be necessary to generate an adequate level of understanding to make an informed decision about its large-scale implementation, as well as to inform the technical development of BECCS processes in terms of sustainability, CO₂ removal efficiency, and the characterisation and reduction of associated impacts.

Legal and norm development: From an EU perspective, at present there are several regulatory and policy regimes that set the contemporary context for BECCS, including:

- EU greenhouse gas emission reduction targets (the 20–20–20 targets, see Section 6.1);
- the EU emission trading scheme (EU ETS);
- the EU CCS Directive (Directive 2009/31/EC) and associated policies;
- the EU Renewable Energy Directive (Directive 2009/28/EC) and renewable policies;
- the Fuel Quality Directive (Directive 2009/30/EC); the CDM under the UNFCCC, particularly in the context of a broader international setting.

The recent European Council 2030 climate and energy conclusions agree to a binding target of a 40% reduction in greenhouse gas emissions, further aiming for an 80% reduction by 2050. The primary EU mechanism to drive this decarbonisation is the EU ETS. Under the ETS, accounting for and incentivising greenhouse gas removal is currently ineligible — a tonne of CO₂ (or equivalent) removed does not “create” a saleable equivalent emissions permit. The 2009 CCS Directive (under review in 2015) provides the legal

framework for the geological storage of CO₂ captured from large anthropogenic sources, and associated revision to the EU ETS recognises CCS as mitigation.

The 2009 Renewable Energy Directive (2009/28/EC) and Fuel Quality Directive (2009/30/EC) provide the background to current EU efforts to develop biomass as an energy resource. The Renewable Energy Directive requires that by 2020, 20% of all energy used in the EU must come from “renewable sources”, including biomass, bioliquids and biogas (translating into different targets for individual member states). The 2030 Council conclusions agree to an EU-level 27% target for 2030, but without binding contributions from individual member states. This growing incentive for biomass-derived energy has raised concerns over the risk of indirect land use change (ILUC), land conversions resulting from displacement of food crops that might counter the direct carbon saving.

At the international level, the 2011 UNFCCC COP adopted modalities and procedures for including CCS within the CDM (Dixon et al., 2013). The Decision does not explicitly distinguish between the storage of carbon from conventional uses in, for example, coal-fired power plants and the storage of carbon from bioenergy generation or biofuel production, but the eligibility of any specific proposed project is subject to agreement between the individual parties. After the 2011 Durban COP, the May 2012 meeting of the executive board of the CDM in Bonn released procedures for the submission and consideration of a new baseline and monitoring methodology for CCS CDM project activities, along with guidelines for project design.

BECCS policy context and considerations:

- EU policy attention to BECCS may be warranted for three reasons:
- the suggested importance of BECCS to achieving decarbonisation (IPCC 2013a, 2014a, 2014b);
- the experience that establishing deployment of technologies reliant on large resources and infrastructures requires many decades;

■ the opposition that is becoming evident in some European countries against proposals for developing BECCS.

Should the EU envisage a substantial role for BECCS in its domestic emissions reduction strategy, steps toward this would include research and technology development, infrastructure provision, market development and societal engagement. Research and development, would need to focus both on specific technologies and on analysis and development of assessment criteria to account for removed CO₂ across the full BECCS system (this could build on the current development of sustainability criteria for bioenergy).

As stated above, the rate and scale at which BECCS could be undertaken depends primarily on biomass supply, and on the provision of CCS infrastructures. The identification, assessment, and approval of large capacities of geological storage for CO₂ and the construction of CO₂ transportation networks have long (decadal) lead- and build times. Should substantial BECCS deployment be desired in the EU, the prior acceptance and deployment of CCS is likely to be a precondition.

With respect to market development, some proponents of BECCS suggest creating economic incentives for net carbon reductions through the inclusion of BECCS in carbon markets. It is argued that this would also accelerate technological development (IEAGHG, 2011, EASAC, 2013). Others argue the opposite: that BECCS should be excluded from carbon markets to avoid, among other effects, the displacement of other, perhaps more sustainable, mitigation options (McLaren, 2012). A possible approach to limiting this risk could be to set initial contribution quotas (analogous to those suggested for the contribution of first-generation bioenergy towards renewable energy targets, cf. EU COM (2012) 595 final) with specified review and assessment periods.

In relation to CCS, it has been argued that far-reaching policy interventions at an early stage of development can lead to overregulation that is arguably detrimental to research and development. However, given the concerns noted above, the following points emerge as potential policy interventions.

Given the public opposition to CCS in some European countries, it seems important to enhance the democratic legitimacy of decision making by allowing publics to voice their hopes and concerns about BECCS and to contribute to decision-making processes. This should particularly include decisions about the further development of BECCS and about potential sites for BECCS power plants and CO₂ storage sites.

Comprehensive lifecycle assessments appraise projects independently according to criteria for environmental effectiveness (this would need to incorporate all emissions generated by a BECCS project over its lifecycle), as well as their social and environmental sustainability (see Section 2.1.2 for details). Activity boundaries are critical when assessing the costs and benefits of individual projects (see Section 4.1.1), as are other aspects of how the lifecycle assessment is carried out, including the standards that are applied (and how they are set, monitored and enforced). Crucially, accounting for emission reductions through BECCS in the UNFCCC may not be comprehensive, as parties are presently able to opt in or out of accounting for certain activities under Land Use, Land-Use Change and Forestry (LULUCF; see section 4.1.2 and IEA, 2011). It would also be challenging to account for net emission reductions in Annex I countries, as the resources (such as biofuels) are often produced in other countries (among them non-Annex I Parties) that employ different accounting and reporting requirements (IEA, 2011).

Finally, based on these considerations, one option for policy development at the EU level would be to build on the European Commission's proposal for the introduction of EU-wide binding sustainability criteria for solid and gaseous biomass, thereby coordinating and establishing linkages between the existing frameworks for regulating biomass and CCS, e.g., the CCS Directive and the Renewable Energy Directive discussed above. This could, for example, take the form of an inter-agency panel consisting of members from different relevant EU agencies.

6.3.2 Policy development for OIF

Scientific state of the art and technological maturity:

As described in section 2.1.7, thirteen field experiments have examined OIF. The findings demonstrate potential for inducing significant plankton blooms that persist over several weeks in some regions of the oceans, but also that the actual increases in CO₂ uptake and drawdown are very uncertain (Boyd et al., 2007; Buesseler et al., 2008; Williamson et al., 2012b). Studies suggest a maximum potential uptake of about 3 Gt CO₂ per year for fertilisation of the entire Southern Ocean (Oschlies et al., 2010a), noting that storage of CO₂ would not be permanent, since it would mostly resurface after several centuries due to the thermohaline ocean circulation. The technique's effectiveness and feasibility as a carbon sequestration method remain highly uncertain. Due to this uncertainty, as well as controversies associated with its ecological and societal impacts, there has been relatively little work on issues of technical feasibility (e.g., sustained provision of sufficient amounts of soluble iron, effective delivery techniques, technical requirements for ships and the numbers of ships that would be needed, frequency and distribution of fertilisation, forecasting of particularly susceptible gyres, etc.).

Concerns associated with OIF: This technique would be highly environmentally disruptive if implemented at a scale sufficiently large to impact the global CO₂ budget. If deployed at large scale, OIF could have severe or irreversible side effects on marine ecosystems; for example, by disrupting the food web and affecting biodiversity (Chisholm et al., 2001; Strong et al., 2009a), as well as by influencing the atmosphere through the production of gases such as dimethylsulphide (DMS) and N₂O (Lawrence, 2002; Jin and Gruber, 2003; Liss et al., 2005). The complexity of the ocean system and the lack of scientific knowledge of its structure and functioning increase the uncertainties surrounding the effects of OIF.

Legal and norm development: The legislative history of marine climate engineering governance at the LC/LP dates back to 2008 with the adoption of a non-binding resolution that no ocean fertilisation activities other than “legitimate scientific research” should be allowed, given the present state of knowledge (London Convention and Protocol, 2008), and stating that

scientific research proposals should be assessed on a case-by-case basis using an assessment framework to be developed by the Scientific Groups responsible for providing scientific and technical advice. In 2010, an Ocean Fertilisation Assessment Framework (OFAF) was adopted by the LC/LP for determining whether proposed ocean fertilisation research represents “legitimate scientific research”, as well as a component on environmental assessment (London Convention and Protocol, 2010).

In October 2013, the Contracting Parties to the London Protocol adopted an amendment to the agreement, which provides a legally binding mechanism to regulate the placement of matter in the oceans for the purpose of OIF, and allows for the possible regulation of other “marine geoengineering” activities that fall within the scope of the Protocol in the future. The London Protocol has thus become the first international treaty that expressly addresses a particular climate engineering technique in a legally binding manner and, moreover, has worded its amendment to allow for expansion to a considerable number of climate engineering techniques. Ratification of these amendments by the Contracting Parties is still pending at the time of writing.

Membership of the LC and LP is not universal, and not all states that are parties to the LC are also parties to the LP. Although most member states of the EU are party to the LP, the EU itself cannot become a party because it is not a “State” as required under Article 24 (1) of the London Protocol. While the amendment thus only binds the States Parties to the LP, the notion of “global rules and standards” in terms of UNCLOS Article 210 (6) may be interpreted as referring to the rules and procedures codified in and adopted under the LC/LP, which would result in their incorporation into the UNCLOS regime (which is binding upon significantly more states, as well as the EU).

UNCLOS also applies to ocean fertilisation activities and includes the general obligation, set out in Article 192, to protect and preserve the marine environment, as well as a more specific obligation, in Article 194, to take all measures necessary to ensure that activities under a state's jurisdiction or control are conducted so as not to cause damage by pollution to other states and their environment.

OIF policy context and considerations: In October 2013, the Contracting Parties to the London Protocol adopted by consensus an amendment to provide a legally binding mechanism to regulate the placement of matter for ocean fertilisation. The amendment will enter into force 60 days after it is ratified by two-thirds of the Contracting Parties.

The EU has very successfully taken the role of an “enforcement organ” of the International Maritime Organization (IMO) in the shipping context. This is due to the fact that the EU has the power to enforce its legal measures by way of the “treaty infringement procedure”. This would require the EU to enact measures that correspond with the LP amendment or substantiate its provisions if, and to the extent to which, these establish minimum standards.

A central policy option for the EU would be for the European Commission to urge all LP member states to ratify the amendment and for all LC members to become parties to the LP. Recent developments in the governance of OIF arguably place this technique at the most advanced stage of legal and norm development among climate engineering techniques. As such, it might provide insights into overall developments in climate engineering governance and accordingly guidance for developing governance for other techniques. There are other instructive aspects of this case relating to precipitous commercial development and rogue private actors, protection of global commons areas, and the societal acceptability and public controversy associated with climate engineering.

In principle, EU member states could also be bound via incorporation of the standards to the LP by reference into UNCLOS (Art. 210(6) UNCLOS). Furthermore, the EU could enact binding measures consistent with the requirements set out in the amendment. Future measures could potentially aim to provide for the effective implementation of the LP.

6.3.3 Policy development for SAI

Scientific state of the art and technological maturity: The artificial injection of large amounts of aerosol particles or their precursor gases into the stratosphere (SAI) could produce a global cooling effect of up to several degrees Celsius, according to model

simulations (see section 2.2.1 for further details). Given the substantial risks known to be associated with continued global warming (IPCC 2013a, 2014a, 2014b), reducing the rate at which global mean temperatures are increasing would be expected to reduce some of the impacts of climate change, including sea level rise, heat waves, and the rate of sea ice decline. Modelling also indicates that the increase in the intensity of the hydrological cycle expected from global warming could be reduced by reducing global average temperatures; lessening the magnitude of changes to precipitation patterns, the intensity of floods and droughts, and changes to local weather (Kravitz et al., 2014b). However, modelling studies have shown that SAI cannot simultaneously restore both global mean temperature and global mean precipitation changes to an earlier state (Schmidt et al., 2012a; Tilmes et al., 2013), thereby necessitating some form of trade-off between these potential benefits.

Research has shown that there would also be numerous inequities, uncertainties, and risks associated with an implementation of SAI, including a non-homogeneous cooling (especially as a function of latitude) associated with various risks that include modifying large-scale weather patterns, the distribution of precipitation, and impacts on ozone (Kravitz et al.; 2014b, Ferraro et al., 2014; Tilmes et al., 2009; Heckendorn et al., 2009). The inability to simultaneously restore global mean temperature and precipitation patterns would mean that if global mean temperature were restored to some earlier state there would be substantial, novel hydrological changes that may prove detrimental to some regions.

Knowledge about the effectiveness and impacts of SAI originates primarily from a range of modelling studies. Early experimental designs for field tests have recently been set forth in the peer-reviewed literature (Dykema et al., 2014; Keith et al., 2014) but have not yet been conducted.

SAI is therefore at an early stage of development. Large uncertainties regarding the technical feasibility of this technique remain: for example, whether it would be possible to produce aerosol particles at the appropriate size and injection rate to avoid coagulation (larger particles may be less efficient at reflecting sunlight and fall out of the atmosphere more quickly),

or what the cost-effectiveness and technical capacity would be for various delivery methods (aircraft, tethered balloons, etc.) to inject particles at altitudes of 20 km or higher. Beyond theoretical and laboratory work, field experimentation may eventually be needed to adequately understand the technical requirements and limitations involved.

Concerns associated with SAI: Numerous technical and environmental uncertainties surround the deployment of SAI, including the appropriate system of delivery, as well as impacts on and feedbacks with ozone (Tilmes et al., 2008) and cirrus clouds (Kuebel et al., 2012) that complicate projections of the distribution of aerosols and wider climatic consequences.

Concerns also focus on the intertwined consequences of deployment for human societies and the natural world. For example, depletion of the ozone layer would also create health concerns, and although SAI may reduce the overall risks of climate change, regional impacts on temperature, precipitation, and weather patterns would be unevenly distributed, shifting the impacts and burdens of climate change (Kravitz et al., 2013a; Tilmes et al., 2013), potentially to those regions with the least capacity to accommodate them (Olson, 2011; SRMGI, 2012; Carr et al., 2013; Preston, 2012). An escalation in conflict potential could result from various factors, including: impacts on natural resources (e.g., water, agriculture or forestry); development of military applications for SAI; power plays; or inadequate compensation for those regions suffering from perceived negative side effects (Maas and Scheffran, 2012; Scheffran and Cannaday, 2013; Brzoska et al., 2012; Link et al., 2013). Moreover, there would be a “termination effect” if SAI were to be used to mask large amounts of warming and then abruptly stopped, which would subject ecosystems and the societies dependent on them to far greater rates of change than under a business-as-usual scenario (Jones et al., 2013).

Furthermore, reservations have been expressed about researching SAI or even discussing the subject with the public or policy makers, originating in various concerns, including: the risk of a “moral hazard” that would reduce the incentives and motivation to invest in mitigation (see, for example, Hale, 2012, Lin, 2013,

Preston, 2013); altering humanity’s relationship with, and sense of responsibility toward, the natural world (Buck, 2012, Tuana, 2013); difficulties in framing and conducting engagement with members or representatives of civil society (Corner et al., 2012); and the possibility of resistance to and contestation of related scientific activities in the open environment (Schäfer et al., 2013a; Parker, 2014).

Legal and norm development: At present, there are few international governance mechanisms that would directly apply to SAI and other planetary albedo modification research, even though international customary law and a number of existing regimes at the UN level may apply in piecemeal fashion or could conceivably incorporate SAI governance within their mandates (Bodansky, 1996; Virgoe, 2009; Lin, 2009; Reynolds, 2011; Bodle et al., 2013; Zürn and Schäfer, 2013). In addition to the lack of specific international regulation of SAI, law on the protection of the atmosphere is less developed than the law of the sea, where UNCLOS is often declared a “constitution of the oceans” that supplies a legal order for the study, use and protection of seas and oceans (UNCLOS, Preamble; for further discussion, see Hubert and Reichwein (2015)).

Expert opinions diverge regarding a suitable framework that could accommodate the governance of SAI research. Earlier legal assessments tended to address the applicability of existing legal regimes to manage the political issues surrounding SAI deployment. However, recent literature, corresponding to the emerging question of field tests, has started to assess capacities to additionally govern near-term, small-scale actions. Some argue that the UNFCCC is a natural platform for SAI governance at its earliest stages, as a regime with universal membership that could develop a holistic governance process and appropriate mechanisms for field tests and even deployment (should this be deemed necessary), based on an expansion of its existing mandate and funding, reporting, and decision-making mechanisms. The UNFCCC may also be able to incorporate deliberations on SAI more cohesively into wider developments in climate policy (Honegger et al., 2013; Lin, 2009; Zürn and Schäfer, 2013). Others note that the UNFCCC agenda may not be able to accommodate the entry of a debate whose objectives and management may distract from stated goals and activities surrounding mitigation and adaptation.

Other regimes may be applicable, and pursuing governance at one regime or another may present trade-offs due to their different mandates and capacities, as well as how these might address the currently indeterminate objectives for SAI research (Bodde et al., 2013). The CBD, as noted, has already taken non-binding decisions on research relating to all climate engineering approaches, and a number of others including ENMOD (the prohibition of hostile weather modification) and the Montreal Protocol under the Vienna Convention (the regulation of ozone-depleting materials) have loosely applicable mandates (Bodde et al., 2013).

On the other hand, a number of norms embodied by sets of principles are being discussed amongst the academic community as useful guidelines for more substantive governance processes and mechanisms in research and field tests (Rayner et al., 2013; MacCracken et al., 2010; Morgan et al., 2013), although these do not qualify as legal developments. A tangible example of how principles of responsible innovation can inform governance processes can be seen in the “stage-gate” for the SPICE project’s test bed (Stilgoe et al., 2013). Still, this constitutes a single example, and whether such a framework will be taken up more widely in the future — or whether it would be the appropriate framework to adopt in the first place — is an open question.

SAI policy context and considerations: The CBD is the only instrument that has directly addressed the issue of SAI, but only by generally referring to the umbrella term of “climate-related geoengineering”. SAI, however, presumptively falls within the regulatory and geographic scope of numerous multilateral instruments that apply to the atmosphere, including the UNFCCC and Vienna Ozone Convention. At the same time, given the extensive uncertainties surrounding SAI as a measure for partly counteracting climate change, it is not clear whether international legal bodies — particularly the UNFCCC — would be prepared to debate SAI technological development, or to develop appropriate governance for it. It may therefore be valuable, at least in the near term, for the EU to maintain an exploratory stance on SAI, supporting research programs that investigate its physical, political, legal, and societal implications, and that help to provide options for future actions (see Section 5.3 for

a list of outstanding research and policy questions arising from previous investigations) and that might be modelled on flagship projects akin to that currently conducted on the human brain, or Joint Programming Initiatives co-funded between the EC and national research budgets (see section 6.4).

SAI occupies a different policy space than BECCS and OIF: in contrast to the governance developments for BECCS and OIF, at present there are no clear international governance developments for SAI, so that one policy option for the EU would be, for now, to avoid taking concrete positions on international governance forms for SAI, especially any that may prove inflexible under changing conditions for itself and its member states. At the same time, the EU would likely benefit from closely observing the relevant developments in the CBD, LC/LP, and possibly the UNFCCC, particularly to determine whether any of these developments, e.g., for marine climate engineering activities, could serve as a template for SAI and other albedo modification techniques.

As discussed in detail in Section 6.2.1.1, one of the key challenges for SAI, and generally for albedo modification, is the governance of near-term outdoor experimentation. One option for the EU is to consider thresholds for the impacts of outdoor experiments on radiative forcing, as proposed by Morgan and Ricke (2010) and Parson and Keith (2013). However, it has also been pointed out (Schäfer et al., 2013a) that such thresholds only aim to address known environmental concerns associated with field tests of SAI, but not the wider concerns discussed earlier in this Chapter and in Chapter 3, which should be taken into account in developing effective governance. In this context, a further policy option for the EU would be to draw lessons, where possible, from prior and existing efforts to develop principles, criteria, and procedures for public engagement and risk assessment that explore and incorporate societal concerns (see for example, the stage-gate process for the SPICE test bed in Section 3.1.4, case study 4).

6.4 An EU perspective

With a focus on near-term governance and in light of the aforementioned, two perspectives need to be distinguished with regard to the EU: firstly, its positioning vis-à-vis climate engineering research; secondly, where the EU as a whole fits into the wider emerging regime complex. An explicit focus on research governance within the EU can provide an outlook on possible pathways that the EU might pursue in this area in the near term. The questions of where the EU as a whole fits into the wider emerging regime complex, and what the EU's possible courses of action are, then re-open the perspective, focusing on the governance of both research and deployment within a multilevel governance framework.

With regard to climate engineering research, the EU, through its seventh framework research programme (FP7), has already funded two projects that focus explicitly on climate engineering: Implications and Risks of Engineering Solar Radiation to Limit Climate Change (IMPLICC) and the project that produced this assessment report, the European Transdisciplinary Assessment of Climate Engineering (EuTRACE). IMPLICC was a modelling study focusing on albedo modification techniques, whereas EuTRACE was an assessment study, focusing on collecting and synergising existing information. There has been hardly any debate about climate engineering at the EU level, although of course the priorities of the framework programme, including its individual calls, are not decided upon by the European Commission alone, but are also influenced by the member states. Despite some changes, this procedure will continue in the future, i.e., for Horizon2020, the next framework programme.

The EU is currently financing two flagship projects set to run for ten years, one on new materials (graphene) and another on modelling the human brain, each receiving approximately one billion euros of funding (information available at <http://cordis.europa.eu/>). It is not implausible that a future flagship project, for example in the 2020s, may involve climate engineering or some aspects thereof (e.g., an individual technique such as BECCS or SAI). Such a large-scale project would naturally require substantial preparatory work. A different approach may be the new “Joint

Programming Initiatives”, which cover activities that are co-funded between the European Commission and national research budgets, or “Joint Technology Initiatives”, which are intended as joint public/private research endeavours. In the latter case, however, some concern has been expressed by the NGO community regarding undue industry influence, to the exclusion of broader societal concerns (CEO, 2011). Greater legitimacy could potentially be provided by wider adoption of the type of stage-gate approach adopted in the UK as a means to operationalise the concept of responsible innovation (see Section 6.2.3). Nevertheless, all these forms of research give the EU a quite flexible set of programming lines to engage in research.

With regard to the emerging regime complex, the EU is arguably in a unique position: On the one hand, its member states are all parties to both the UNFCCC and the CBD. In addition, the EU itself, being a supranational organisation equipped with the competence to effectively enforce proper application of its laws vis-à-vis its member states, is a party to both conventions. Therefore, EU member states could, in principle, agree on a common position to be proposed to both the UNFCCC and the CBD. So far, however, no specific EU perspective on climate engineering has been agreed upon. Leaving aside the fact that EU politics have naturally had to focus on the challenges arising from the economic and financial situation of certain member states, the current focus of environmental policy is primarily on the difficulties in achieving consensus over the EU's low-carbon “roadmap” and on achieving a binding global emissions reduction agreement in 2015. The political will to address climate engineering questions in this context is currently likely to remain very limited. Furthermore, the logic of European mitigation politics is not likely to directly apply to the climate engineering debate, since there are notable differences in the incentives and uncertainties involved in the two issues. Thus, taking into account its considerable political influence, the EU might one day contemplate leveraging and advancing a common position on climate engineering within the different regulatory settings, thereby — following internal negotiations — perhaps also contributing to the prevention of conflicts among its member states.

With regard to its institutional design, however, the EU is not a unified body: Its executive organ, the European Commission, is divided into 28 Directorate-Generals (DGs), with DG Environment responsible for the CBD, DG Climate responsible for the UNFCCC, and DG Research responsible for research programmes. The challenges present at the CBD, UNFCCC, and LC/LP are thus mirrored at the level of the European Commission, or the EU as a whole, and are furthermore reflected in the fragmentary nature of existing EU secondary law relevant to climate engineering. Conflict avoidance and capitalisation on the EU's unifying power would thus require an inter-service consultation within the Commission and subsequently a process of developing communication and a common strategy (or an EU-wide document) galvanising a common position on the issue. Any such action would have to be regarded as a comparatively cautious approach. It is worth adding in this respect that the European Parliament, as part of a wider 2011 resolution on the Rio+20 summit, rejected the idea that climate engineering should be discussed there.

The potential consequences of EU research activities and the adoption of a joint EU position on climate engineering research are worth considering. Interested or "third" states might respond by initiating their own research programmes, in particular, if any kind of future EU conduct were considered as unilateral action. The danger of such a "race for climate engineering research" could be addressed by way of open research frameworks, i.e., frameworks aiming at the integration of third-party actors in order to foster international cooperation. For example, the EU-China Near Zero Emissions Coal (NZEC) initiative aims to build demonstration plants in China to test the feasibility of CCS technology on an industrial scale. Similarly, climate engineering research coordinated at the European level could actively involve international partners in order to build trust through transparency and information sharing. Mobilisation and Mutual Learning (MML) Action Plans, which are designed to bring together a diverse set of stakeholders and may include participation from non-EU states, could provide a framework for this at the EU level. Examples include MMLs on synthetic biology with the involvement of the US, and on biometrics with the involvement of China. Any joint European involve-

ment in climate engineering research is likely to provoke comparable reactions from third-party actors. An alternative approach to this challenge might involve initiating negotiations on a global code of conduct for climate engineering research (Hubert and Reichwein, 2015). By incorporating criteria relating to general principles for promoting the responsible conduct of scientific research involving climate engineering, such a code could assist the responsible national authorities in the assessment of climate engineering research projects. It could also provide for transparency (e.g., by establishment of an open registry of relevant projects), and thereby not only foster cooperation between states but also contribute to the formation of trust between scientists on the one hand and trust in science on the other hand.

Politically, implementation of a European climate engineering research policy would influence the structure and content of the EU's climate change response portfolio as it stands today. The EU is a major advocate of the 2°C warming limit. Given that the IPCC indicates that in the "vast majority" of scenarios that limit warming to 2°C in the 21st century, some form of greenhouse gas removal is required (IPCC, 2014d), this commitment may have challenging implications for climate engineering policy in the EU. Seen from this perspective, research on greenhouse gas removal could become a significant component of developing and evaluating policy options for staying below the 2°C limit. Furthermore, given the currently slow progress on implementing mitigation measures, combined with the limitations of greenhouse gas removal techniques (in particular the technical uncertainties and the long timescales involved to significantly influence global atmospheric CO₂ concentrations), a strict commitment to the 2°C limit could eventually lead to a very difficult decision over whether to deploy albedo modification techniques in order to stay within a given temperature threshold (e.g., the 2°C limit) or, in recognition of the risks of such deployment, to allow the threshold to be crossed.

Legally, member states have equipped the EU with appropriate legislative competences which can be applied to climate engineering research and deployment. However, EU primary law also sets comparatively strict limits to activities that include the risk of significant adverse consequences for the environment

and for human life. The adoption of the CCS Directive can be regarded as a precedent in this context. While it can be argued that the link between CCS and conventional energy production is significantly closer than that between CCS and climate engineering, the CCS Directive also arguably constitutes a first step in the transformation of “traditional” climate policy approaches that aim to reduce emissions by increasing efficiency and reducing demand, into a climate policy framework that also includes reduction of emissions “at the tailpipe”, and consideration of the associated environmental consequences (e.g., issues around long-term storage), within which issues of intergenerational justice and the handling of risks and uncertainties will gain increasing importance.

7. Extended Summary

7.1 Introduction

There is a broad scientific consensus that humans are changing the composition of the atmosphere, and that this is leading to global climate change, as described by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report of 2013–14. However, the national and international mitigation efforts encouraged by this recognition have not yet been sufficient to reduce greenhouse gas emissions, or even to significantly slow their annual increase. Furthermore, steps toward adapting to climate change are proving difficult and often costly, and in some cases might not be possible, e.g., for small island states at risk of inundation by sea level rise, and for heavily populated coastal regions.

Against this background, various researchers, policy makers and other stakeholders have begun to consider and discuss responses to climate change that cannot easily be subsumed under the categories of mitigation and adaptation. The first question that is often raised is: Are there viable ways to remove large amounts of CO₂ and other greenhouse gases from the atmosphere? Many ideas have been proposed for doing so, which vary considerably in their approach, and include: combining biomass use for energy generation with carbon capture and storage (BECCS); large-scale afforestation; and fertilising the oceans in order to increase the growth and productivity of phytoplankton, thus increasing the uptake of CO₂ from the atmosphere and the sedimentation of dead carbon mass to the deep oceans.

Going beyond ideas for removing greenhouse gases, another question has also been raised: Are there possibilities for directly cooling the Earth? Several ideas have been proposed for doing so, mostly via increasing the planetary albedo, i.e., the amount of solar radiation that is reflected back to space (mostly by clouds or at the Earth's surface) and therefore not absorbed by the Earth. Techniques for albedo modification have been proposed that would act at a range of altitudes, including whitening surfaces, making clouds brighter, injecting aerosol particles into the stratosphere, and placing mirrors in space.

Taken together, ideas for greenhouse gas removal and for albedo modification are commonly referred to by the umbrella term “climate engineering” (or “geoengineering”, which is often used synonymously).

This summary gives an overview of the results of the assessment report prepared for the European Commission by EuTRACE (the European Transdisciplinary Assessment of Climate Engineering), a project funded by the European Union's 7th Framework Programme. The project assessed the current state of knowledge about the techniques subsumed under the umbrella term climate engineering and developed considerations for potential future research and policy development from a specifically European perspective. EuTRACE brought together academics from 14 partner institutions across Europe, with expertise in disciplines ranging from Earth sciences to economics, political science, law, and philosophy. Through the large and interdisciplinary composition of the EuTRACE project consortium, the assessment report is able to capture a broad range of perspectives across disciplines and to reflect on the field's development

through all of them. Thus, it should be of interest not only for the European Commission but also for the broader community of interested stakeholders.

This assessment report provides an overview of the individual techniques that have been proposed for greenhouse gas removal and albedo modification. The state of scientific understanding and technology development (including estimates of potential operational costs) is described, followed by an examination of key questions that arise in the social, ethical, legal, and political domains, such as: the possible influence of climate engineering techniques on mitigation and adaptation efforts; how these techniques are perceived by the public; as well as their conflict potential, economic aspects, distributional effects, and compensation issues. The current regulatory and governance landscapes are then assessed, along with potential avenues for future research and options for developing policy for climate engineering. While the report gives a broad overview of issues around climate engineering and the range of techniques involved, it also carefully distinguishes between the individual techniques wherever appropriate. Furthermore, in order to illustrate many of the key issues, three selected techniques are discussed in greater detail throughout the report, two for greenhouse gas removal — bioenergy with carbon capture and storage (BECCS) and ocean iron fertilisation (OIF) — and one for modifying the Earth's albedo — stratospheric aerosol injection (SAI). These techniques were chosen for several reasons: they are among the most discussed techniques; they include some of the most advanced governance discussions and developments (especially for OIF); two of the techniques (OIF and BECCS) have undergone dedicated field experimentation; they include one land-based, one ocean-based, and one atmosphere-based technique; they encompass techniques that could potentially be confined to small areas (BECCS) and others that are transboundary in nature (OIF and SAI); they are currently at very different stages of research and technological development; and their presumed levels of effectiveness and potential risks differ greatly.

This summary follows the overall structure of the assessment report in terms of the order of the chapters, although in order to facilitate reading in the form of a summary, the structure within the individual

chapters is not always followed. Nevertheless, the broad topics and headings within this summary correspond closely to the chapter contents, making it generally straightforward to locate further details in the main report corresponding to any points made in this summary. To further enhance readability, references are not included in this extended summary; for the original literature on which the various points are based, the reader is referred to the full report.

7.2 Characteristics of techniques to remove greenhouse gases or to modify the planetary albedo

7.2.1 Greenhouse gas removal

A wide range of techniques is discussed in the assessment report for the removal of CO₂ and other greenhouse gases from the atmosphere and sequestering them over long periods, including terrestrial and marine techniques, as well as biotically and chemically based techniques. Among the primarily terrestrial biotic techniques are afforestation, BECCS, biochar, as well as other biomass-based techniques; the main terrestrial chemical technique is direct air capture, while enhanced weathering is both terrestrial and marine; finally, two techniques are considered that would aim to increase the rate of carbon transfer to the deep ocean, with ocean fertilisation involving the “biological pump”, and artificial upwelling involving the “physical pump”. The scale of these techniques ranges from those with primarily domestic influence that have minor consequences outside a given domain (except for the small global reduction in the atmospheric greenhouse gas concentrations), to those with transboundary influences on the environment and on global economics, and thus on global societies.

In order to have a substantial impact on the global budgets of long-lived greenhouse gases such as CO₂, any removal technique would have to achieve a removal rate equivalent to at least a significant fraction of current global emissions; for CO₂ emissions, which now exceed 30 Gt CO₂/yr, this would mean removing at least 1 Gt CO₂/yr to have a noticeable influence, and much more than that to figure prominently in global climate policy. Many of the techniques considered in this assessment have a theoretical, though unproven, uptake capacity which is within this

range. However, for nearly all of the proposed techniques, accomplishing this would require massive infrastructures and energy input, which would take long timescales to develop and would incur costs that could be comparable to or even exceed those of mitigation measures. Furthermore, even at such scales of implementation, atmospheric CO₂ concentrations would still only decrease slowly (over decades).

The capacity for deployment at scale, along with the effectiveness of the proposed techniques, if deployed, would be constrained by several factors. These vary between the various techniques, but broadly include:

- the operational costs, both for installation and maintenance, which is one of the most important issues to resolve before serious consideration can be given to scaled-up implementation of any of the greenhouse gas removal techniques;
- the total biomass resources that would be available and their regeneration rate for biomass-based techniques, as well as the sustainability of intensive, large-scale agricultural practices;
- the strength of the “rebound effect”, in which any CO₂ removed from the atmosphere is counterbalanced by reduced uptake of CO₂, or by the release of CO₂ from other components of the global carbon cycle;
- the total capacity of various storage sites (e.g., depleted hydrocarbon fields and saline aquifers) and reservoirs (e.g., the deep ocean) under consideration; the total storage capacity on the global land surface (in biomass and soils) is at least an order of magnitude smaller than available fossil carbon reserves; the ocean has much greater storage capacity, theoretically in excess of all known fossil carbon resources, but methods to access this storage and the timescales of such storage have not yet been established, and it is unclear if it will ever be possible to establish appropriate long-term storage methods in the oceans.
- the degree of co-location of storage sites with major emissions sites (including bio-energy power plants in the case of BECCS), determining the need for development of significant CO₂ transportation infrastructures or relocation of CO₂-emitting facilities;
- the degree of permanence of storage, i.e., the potential for the future natural release or unintended leakage of the removed carbon; this becomes particularly relevant considering that, in order to prevent an enhanced future build-up of atmospheric carbon dioxide, the removal process would need to be continually maintained.

In addition to these limitations, there are numerous potential negative impacts of the techniques on the environment, ecosystems, and societies to take into consideration, including:

- competition and conflicts over land use and water supply being applied for various purposes;
- societal impacts of landscape and land use changes;
- degradation of ecosystems and the environment, e.g., due to chemical inputs for OIF or ocean alkalisation, modification of the marine biosphere due to OIF, or industrial agriculture and introduction of non-native species and monoculture;
- health impacts, e.g., associated with dust production from biochar;
- production and release of nitrous oxide (N₂O) and other climate-forcing gases (by OIF as well as due to agriculture practices for producing biofuel);
- major mining, processing, and distribution operations for any techniques such as artificial weathering, which would require substantial material resource inputs.

These various considerations, taken together, indicate that, based on current knowledge, greenhouse gas removal techniques cannot be relied upon to notably supplement mitigation measures in the next few decades. However, if significant investments were made in researching and developing some forms of greenhouse gas removal techniques, and if it were to emerge that they could be successfully scaled up, with well-understood and acceptable side effects, then greenhouse gas removal could eventually significantly supplement mitigation efforts and provide an additional degree of flexibility in international climate negotiations.

7.2.2 Albedo modification and related techniques

Albedo modification refers to deliberate, large-scale changes of the Earth's energy balance by increasing the reflection of sunlight away from the Earth, with the aim of reducing global mean temperatures. Suggestions for increasing the Earth's reflectivity include:

- enhancing the reflectivity of the Earth's surface;
- injecting particles into the atmosphere, either at high altitudes in the stratosphere to directly reflect sunlight or at low altitudes over the ocean to increase cloud reflectivity;
- placing reflective mirrors in space.

A few other related techniques have been proposed to alter the Earth's energy balance, especially by thinning or reducing the spatial coverage of cirrus clouds to decrease the amount of terrestrial radiation that is trapped in the atmosphere and radiated back towards the Earth's surface. Taken together, these are referred to here as albedo modification and related techniques.

Albedo modification and related techniques are distinct from mitigation and from most greenhouse gas removal techniques, in three key ways:

- their effects are potentially rapid and large — according to climate model calculations and observations of large volcanic eruptions, albedo modification might be capable of cooling the Earth's surface by 1°C or more, with the response being observable within a year or less;
- their operational costs are potentially low in comparison to the costs of mitigation, adaptation, or greenhouse gas removal at scales that have an impact on the global atmospheric CO₂ concentrations and thus on global temperatures;
- their evaluation is better characterised as a risk-risk trade-off.

In light of these distinctions, various potential roles for albedo modification and related techniques have been proposed:

- reducing climate risks as much as possible, potentially substituting for some degree of mitigation;
- use as a “stopgap” measure to allow time for reducing emissions;
- use in a potential “climate emergency”.

These potential roles are accompanied by various drawbacks, among them:

- albedo modification impacts the climate in a manner that is physically different from the impact of greenhouse gases, so that it would not directly reverse the effects of global warming; regional differences in the response could be expected, and precipitation would respond differently than temperature, so that albedo modification techniques may reduce some risks but in turn increase others;
- if any technique were being employed at a scale that had a significant cooling impact on global temperature, and then had to be stopped abruptly or over a short period of time, a rapid warming or “termination shock” would ensue, with concomitant risks for societies and ecosystems; the impacts could be made less severe by phasing out the implementation slowly, if possible;
- albedo modification does not address the direct effects of CO₂ on the environment, such as ocean acidification and impacts on terrestrial vegetation, so there is a risk that those issues might receive less attention or be neglected if terrestrial climate change — manifested in temperature, precipitation, and other parameters — is made less severe.

All of the techniques considered in this assessment harbour substantial uncertainties. In terms of effectiveness and technological feasibility, some of the main issues involved include:

- delivery mechanisms, which have received some attention for SAI, with initial studies suggesting that the most economically feasible method is likely to be atmospheric injection via high-flying aircraft or via tethered balloons in the tropics;

- Uncertainties about the scale and degree of implementation, e.g., for SAI or marine cloud brightening, the amount of aerosol particle mass that would need to be injected into the atmosphere to achieve a certain amount of cooling;
- Uncertainties about the maximum possible effect (e.g., in terms of radiative forcing in W/m^2), due to various environmental limitations and diminishing returns;
- Uncertainties about the relationship between the details of implementation (e.g., injection location and particle size) and the climate response;
- In terms of the impacts, these vary widely between the techniques, with the key impacts for a selection of the main techniques being:

SAI: reduction of polar stratospheric ozone, changes in the heating rates in the stratosphere, impacts on the dynamics of the stratosphere, impacts on tropospheric cirrus clouds, influence on vegetation growth, increased fraction of diffuse- to direct-radiation, among others.

Marine cloud brightening: changes in the hydrological cycle, potentially changes in the El Niño Southern Oscillation (ENSO), enhanced precipitation over low-latitude land regions, and corrosive destruction of infrastructures and detrimental effects on coastal plants due to increased atmospheric concentrations of sea salt.

Desert reflectivity enhancement: substantial perturbation of desert ecosystems, considerable regional climatic changes, e.g. reduced regional precipitation adjacent to deserts and reductions in monsoon intensity, along with reductions in the nutrient supply to the Amazon and oceanic regions downwind of the Sahara Desert.

Vegetation reflectivity enhancement: changes in land use may conflict with other goals of land use management such as biodiversity preservation and carbon sequestration; effects on market prices and local ecosystems, as well as on soil moisture and local meteorology.

Based on this assessment, while it might be possible to relatively quickly develop and implement the technological capability to modify the Earth's radiation budget on a global scale, it would very likely take many decades to be able to do so in an informed and responsible manner. This applies not only to understanding the environmental consequences, but also the societal context in which such an intervention would occur, including its broader ethical implications and the challenges for international regulation and governance that would need to be addressed; these considerations are summarised in the following sections.

7.3 Emerging societal issues

The range of techniques that have been proposed for removing greenhouse gases or for modifying the planetary albedo or cirrus clouds all raise complex questions in the social, ethical, legal, and political domains. However, despite a few decades of discussion, and intensified research and dialogue over the last decade (including several prior assessment reports), the EuTRACE assessment highlights that the vast majority of the societal, ethical, legal, and political concerns raised by climate engineering are still subject to substantial uncertainties and unknowns.

This section gives an overview of the main societal issues that are discussed in the assessment, starting with the *political and societal context* in which the discourse is unfolding, along with the *public awareness and perception* of this discourse, particularly *in the context of field experiments and prototype deployments*. Three further issues and their potential consequences are then described: “*moral hazard*”, *environmental responsibility*, and *conflict emergence*. The potential *economic impacts* of greenhouse gas removal and albedo modification techniques are then considered, along with the broader issues of the distribution of benefits and costs and how this relates to *questions of justice associated with possible climate engineering deployment* and to considerations of *compensation for harms*.

Political and societal context

Climate engineering techniques are each situated in a specific socio-political context, which may in turn be affected through the further development of that technique, e.g., through the use of resources during the deployment process, the direct impacts upon the environments in which the techniques might be implemented, and any unexpected consequences of the techniques. Furthermore, these changes would also be influenced by climate change, which would potentially intensify during the development and progressive deployment of any climate engineering techniques. To date, there has been no integrated analysis of the linkages between climate change, the different climate engineering techniques, and their combined effects on human security, conflict risks, and societal stability.

Public awareness and perception

According to the few studies conducted thus far, most public groups are broadly unaware of the various proposed climate engineering techniques and the debates around their possible consequences. Perceptions of climate engineering, including the degree of acceptance, are strongly dependent not only on the cultural background, but also on the context and framing in which information on climate engineering proposals is provided. Concepts that are often associated with climate engineering include “messing with nature”, “science-fiction”, “Star Wars”, and “environmental dystopia”. Key concerns expressed by members of the public include the potential for inducing international conflict, scepticism about predictability of impacts and about effective governance, and a “NIMBY” (Not In My Back Yard) attitude toward both deployment and field trials.

Public perception and stakeholder engagement in the context of field experiments and prototype deployments

Four example cases for field tests of various proposed techniques (two for BECCS, one for OIF, and one for SAI) were examined. However, given that thus far there have only been a very limited number of field trials of these and other techniques, it is not yet possible to derive clear lessons about the societal context

of field trials, and in turn the impacts of stakeholder engagement activities on the ways in which field trials are perceived. Nevertheless, the example field experiment cases are useful to demonstrate that several concrete questions are appropriate for future consideration, including:

- What is the role of risk assessment in designing climate engineering field experiments?
- What is the role of private sector interests in shaping public perceptions of climate engineering field experiments?
- What is the role of trust and public participation in shaping public perceptions of climate engineering field experiments?
- What is the role of governance in climate engineering field experiments?

A few key points that arise from the brief analysis in the assessment report are:

- Transparency and openness (about intent, design, scale, intellectual property, commercial or other vested interests, etc.) play apparently important but as yet indeterminate roles in shaping public perception;
- In all cases, those responsible for the projects considered early and ongoing public participation and engagement, as well as the application of some form of governance (including novel assessment frameworks or modifications of existing frameworks) to be of importance; however, anecdotally, it was found that neither of these guaranteed acceptance or the ability to successfully complete the projects.

The “moral hazard” argument

There is concern that discussing, researching, and developing climate engineering techniques may reduce the overall motivation to reduce greenhouse gas emissions. This concern applies to the range of techniques under both greenhouse gas removal and planetary albedo modification. The moral hazard response may occur via several different mechanisms, with a range of associated background assumptions. There are also sceptical viewpoints that suggest the

opposite mechanism may dominate in some contexts (i.e., that fear over the mere consideration of climate engineering techniques might drive an invigorated effort toward mitigation).

Environmental responsibility

While it is sometimes argued that the Earth system is already undergoing a large-scale experiment due to the anthropogenic emissions of greenhouse gases and aerosol particles, a key distinction is often drawn between unintentional (albeit not necessarily unknowing) versus intentional interventions in the climate system; associated with this concern is that the potential use of climate engineering techniques in general has been ascribed various negative character traits, including hubris, arrogance, and recklessness.

Conflict emergence

It has been argued that various forms of conflict may emerge throughout the lifecycle of climate engineering activities; these can broadly be distinguished as:

- competition over scarce resources;
- resistance against impacts and risks;
- conflicts over distribution of benefits, costs, and risks;
- complex multi-level security dilemmas and conflict constellations;
- power games over climate control.

Economic impacts

As with other societal concerns, economic analysis of climate engineering is in its infancy. The economics of removing greenhouse gases is commonly discussed within the context of the economics of mitigation, particularly considering the slow transformation of industrial structures that would be necessary for effective mitigation, so that greenhouse gas removal techniques such as BECCS are sometimes framed as possibly being useable to “buy time” for such mitigation technologies to be developed and for the transformation of industrial structures to occur. Accord-

ingly, economic assessments of greenhouse gas removal techniques need to consider various carbon costs, which reflect the social costs that arise from scarcity of storage sites or from the changed ambient carbon fluxes between the atmosphere and other carbon reservoirs.

In contrast to the economics of greenhouse gas removal, proposals for planetary albedo modification raise novel economic considerations. It has been argued that this could have the potential to immensely simplify climate change negotiations, transforming them from an extremely complex regulatory regime into a problem grounded in the familiar issue of international cost-sharing. However, this simplification would be accompanied by the numerous other challenges outlined in this section, along with the uncertainties and unknowns in the physical climate system discussed in the previous section, and the difficulties of developing regulation and governance mechanisms outlined in the following sections. It is thus clear that any implementation of albedo modification would entail various costs, such as price effects and social costs. Nevertheless, economic analyses of albedo modification have been primarily concerned with the possibility of cooling the planet at very low operational cost, often neglecting the other associated costs, so that present knowledge of such other costs is very limited. Further complicating the situation, potential side effects, which can take the form of external costs or external benefits, also need to be taken into account for a comprehensive analysis, and to be incorporated in the social costs associated with each technique.

Distribution of benefits and costs

The distribution of benefits, costs and risks — frequently posed as an issue of “winners and losers” — is not only an economic issue but also raises important normative questions, which vary considerably between different climate engineering techniques. It is not yet clear how, and to what degree, the various techniques would produce inequalities, or whether some would instead act to decrease the existing inequalities and historical injustice of climate change. It is also unclear how the possible redistribution of benefits, costs, and risks might influence inequalities between generations, as the future deployment of cli-

mate engineering techniques may allow risks and costs to be deferred to future generations; however, this issue is not unique to climate engineering, as it also applies to the use of fossil fuels and many other activities of modern society. Thus, while climate engineering techniques have the potential to reduce some of the worst impacts of climate change for both present and future generations, they might also lead to the externalisation of costs and risks over both space and time.

Questions of justice associated with possible climate engineering deployment

Problems concerning the distribution of benefits, costs, and risks can be addressed from various justice perspectives, such as that of intergenerational justice noted in the previous point. These perspectives are frequently based on assumptions about obligations towards others, their rights to certain goods, or their interests in decisions that could affect their wellbeing. Various subdomains of justice are particularly relevant for the normative evaluation of the possible deployment of climate engineering techniques:

- **Distributive justice**, reflecting upon the question of how benefits and costs should be distributed according to certain principles or criteria (such as maximisation, the priority view, egalitarianism or sufficientarianism);
- **Redistributive justice**, aiming to redress undeserved benefits or harms;
- **Intergenerational justice**, asking what current generations owe to future generations, and what the normative significance is of past generations' actions;
- **Compensatory justice**, based on the idea that wrongdoers or the beneficiaries of wrongful actions must compensate, in some form, those who were harmed;
- **Procedural justice**, concerned with the fairness and transparency of the processes by which decisions are made;
- **Global justice**, dealing with principles that should guide one state in its dealings with other states, as

well as with questions of the legitimacy (or lack thereof) of international institutions;

- **Environmental justice**, reflecting upon the possibilities and mechanisms to include non-human life and ecosystem sustainability in normative evaluations; and how to understand human responsibilities toward non-human nature.

Compensation

The issues of justice, and the associated potential for some to suffer while others might benefit from the deployment of climate engineering techniques, raise questions concerning compensation for possible harms. Three basic questions can be distinguished:

- Who should compensate? This question relates to the main principles of compensation for climate change impacts, with the most prominent approaches being the “polluter pays” principle (PPP), the “ability to pay” principle (ATP), and the “beneficiary pays” principle (BPP); these three approaches are not mutually exclusive and can often suggest similar courses of action and similar responsible parties.
- Whom should they compensate? The answer to this question is often less clear than might initially be expected. Different climate engineering techniques will affect different countries in many different ways, likely making them worse off in some ways and better off in other ways than they would be under global warming alone, thereby complicating judgments on which stakeholders should be compensated and in which ways, which leads to the third crucial question:
- What should be compensated? There are many aspects to this question, including: whether different normative approaches put limits on the kinds of harms that can be compensated; how to attribute monetary values to principally compensable harms; whether those who are compensated should all be equally compensated based on the degrees and types of harms caused; and how to attribute specific harmful impacts, e.g., prolonged drought or flooding, on a case-by-case basis to any form of climate engineering deployment.

The societal concerns outlined in this section form the basis for the development of regulation, policy, and governance frameworks for climate engineering research and possible deployment, as described in the following sections.

7.4 International regulation and governance

Three broad regulatory approaches for climate engineering are put forth in the EuTRACE assessment report:

- i) based on its potential role as a situational response to various conditions in the overarching context of climate change (context);
- ii) through risk management measures for individual climate engineering activities and technical processes at the operational level (activities);
- iii) through scientific assessment of potential environmental effects of different climate engineering techniques (effects).

To date, most discussion toward developing regulations for climate engineering has taken place within the competent treaty bodies of the London Convention/London Protocol (LC/LP), focused specifically on maritime climate engineering (“marine geoengineering activities” in the terms of the LC/LP), and of the Convention on Biological Diversity (CBD), focused particularly on the potential impacts of proposed climate engineering techniques on biological diversity. Other international treaties, in particular the UN Framework Convention on Climate Change (UNFCCC), would also be potentially applicable.

In the context of the three broad approaches noted above, these three treaty bodies would primarily address the issue of climate engineering as follows:

- the UNFCCC from the standpoint of **context**;
- the LC/LP from the standpoint of **activities**;
- the CBD from the standpoint of **effects**.

These three treaty bodies have very different characteristics. While the UNFCCC is focused on minimizing the harmful impacts of human activities on the climate system, the LC/LP is focused on protection of the marine environment, and the CBD on conservation of biodiversity. While the UNFCCC and CBD enjoy quasi-universal legal status (with the sole but significant exception of the USA, which has signed but not ratified the CBD), the LC/LP has only a limited international membership, although most member states of the EU are Parties to the treaty.

The LC/LP was the first treaty body to actively initiate significant steps towards the regulation of certain (maritime) greenhouse gas removal techniques, especially OIF. The LC/LP is a process-oriented instrument that seeks to articulate pathways toward decision making in situations involving potential pollution of the marine environment; it typically acts through developing assessment frameworks. As such, the efforts of the LC/LP have concentrated on the development of a risk management framework to regulate potential activities at the operational level, rather than attempting to address the larger contextual questions that climate engineering raises, which would be a role more befitting of the UNFCCC. This risk assessment approach of the LC/LP, following the precautionary principle, has the potential to be a role model for the future development of governance for climate engineering. The process followed by the LP — first adopting a non-binding COP decision and then proceeding to amend the treaty/protocol to create binding law — is also a potential model for other legal regimes in developing regulation for various forms of climate engineering.

In contrast to the LC/LP, the CBD is not designed to regulate specific activities, and in contrast to the UNFCCC, it is not dedicated to the specific context of climate change. The potential role of the CBD in the regulation of climate engineering is instead to identify normative categories and procedures by which the potential effects of climate engineering on biodiversity can be monitored, assessed, and evaluated. The CBD could also have the role of establishing limits, which may not be exceeded, for the reduction or loss of biological diversity. To date, the CBD COP has adopted two specific Decisions explicitly concerning climate engineering (using the term “geoengi-

neering”, without differentiating between albedo modification and greenhouse gas removal techniques).

Since each of the three approaches noted above (context, activities, and effects) would miss out on important aspects of regulation if applied as standalone approaches, in order to develop an effective regulatory structure for climate engineering, all three approaches would arguably have to be integrated. Such integration, although requiring extensive international effort, would at least be facilitated by the fact that all three relevant legal instruments are, to some extent, based on a common denominator (embodied, for example, in the precautionary principle). The development of a single, overarching, dedicated treaty that would subsume a wide range of techniques under the general term “climate engineering”, and that would attempt to address the full range of aspects involved, would be a prohibitively large undertaking, if at all realisable or desirable. A more promising option would likely be to bring together the three aforementioned regulatory approaches and associated treaty bodies at the operational level (i.e., through parallel action, common assessment frameworks, or Memoranda of Understanding).

Focusing on EU law: without a comprehensive international regulatory structure in place, EU law provides a “bottom-up” source of limitation on climate engineering for member states and the EU itself. Although present EU law cannot be interpreted as generally prohibiting or authorising climate engineering, it serves to structure the decision-making process and provide essential provisions for environmental protection. This applies through both primary and secondary EU law.

In EU primary law, this manifests for instance in the Treaty on the Functioning of the European Union (TFEU), which requires that environmental policy — including the evaluation of climate engineering techniques — “shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damages should as a priority be rectified at source and that the polluter should pay”. A further provision of the TFEU is that the Union is also required to take account of available scientific and technical data, including sci-

entific uncertainty, in preparing environmental policy, as well as of the potential benefits and costs of action or lack of action.

To date, no act of EU secondary law has sought to explicitly regulate climate engineering research and/or deployment. That said, examples of EU secondary law, both procedural and substantive, can be identified that could potentially be triggered, subject to more detailed assessment, in the context of climate engineering research or the possible deployment of climate engineering techniques. In particular, the standard of protection and care mandated by EU primary law has been further developed through EU secondary law and can contribute to international understanding and consensus-building on how international law on a given topic can be interpreted and implemented by other parties.

Finally, a key overall contribution of EU law is the high degree of importance it places on environmental protection and, most prominently, the central objective of improving the quality of the environment rather than merely maintaining it, which can help to provide more stringent scrutiny of potential climate engineering activities than the requirements of public international law. Ultimately, however, EU law will also not directly provide a clear mechanism for developing comprehensive regulation for climate engineering, suggesting that initiatives beyond formal legal approaches will be necessary to effectively govern climate engineering.

7.5 Research options

Over the past decades, there has been a substantial increase in the general interest in and research on the various proposed climate engineering techniques. For greenhouse gas removal techniques, this increase has generally been gradual over this period, while for albedo modification techniques, especially SAI, there was a very rapid increase in interest and research in the 2000s.

The increase in research has been accompanied by extensive discussion on whether or not — and in what forms — such research should be conducted, on how to effectively govern research, and on possible steps between field tests and large-scale deployment

of individual techniques. These arguments broadly apply to both greenhouse gas removal and albedo modification, although often in different ways and frequently differentiated between individual techniques.

The main arguments made in favour of conducting research are:

- information requirements;
- knowledge provision;
- deployment readiness;
- avoidance of premature implementation;
- elimination of specific proposals;
- national preparedness;
- scientific freedom.

The main arguments made against conducting research are:

- the “moral hazard” argument;
- allocation of resources for research;
- the “slippery slope” argument;
- concerns about large-scale field tests;
- backlash against research.

To the extent that research is continued, there are many open research questions on climate engineering that could be investigated more deeply, ranging from natural science and technological aspects to social sciences, humanities, and legal issues. The results of this assessment were used to identify important knowledge gaps and to draw up lists of key research questions, grouped into the following topical areas:

- natural sciences and engineering;
- public awareness and perception;

- ethical, political, and societal aspects;
- governance and regulation.

The list of research questions on climate engineering provided in the assessment is the first known compilation of this breadth, and is intended to give an overview of the range of issues that would benefit from further investigation for various purposes, e.g., as an improved basis for policy making.

7.6 Policy development for climate engineering

The complex socio-technical context within which discussions of climate engineering are emerging necessitates, as a basis for sound decision making, careful engagement with scientific, legal, political, economic, and ethical aspects of climate engineering, as well as with the overall context of climate change and climate change policy. Questions arise concerning technological feasibility, global fairness, international cooperation, distribution of costs and benefits, social acceptability, and possible effects on existing and potential strategies for mitigation and adaptation. Decision makers will thus face complex choices and trade-offs. While many general principles that can guide policy development are likely to apply to most or all climate engineering techniques, the differing stages of development and discourse about the various techniques need to be taken into account when assessing policy options and pathways. This is also reflected in the differences between the three example techniques considered in this assessment (BECCS, OIF, and SAI).

Should the EU decide to act as a global leader on climate engineering research, it could draw on established processes for ensuring comparatively high standards of environmental and social protection to develop farther-reaching propositions for the governance and regulation of both climate engineering research and deployment, with the goal of informing and guiding international discussions.

Discussions of climate engineering governance are not emerging in a legal void. Customary international law includes established principles such as the duty to inform and the duty to prevent transboundary harm.

National laws equally apply, for example the obligation to conduct environmental impact assessments, depending on the jurisdiction in question.

7.6.1 Development of research policy

In forming a position on climate engineering research, several factors might be considered:

- the urgency of such research;
- possible sequences in which the research might be conducted;
- the multiple applications for which climate engineering may create relevant knowledge.

Based on the experiences in the interdisciplinary EuTRACE project, the consortium broadly advocates a parallel research approach that simultaneously addresses questions of natural scientific and social scientific interest, without prioritising one to be carried out before the other, and emphasises that in doing so, it is valuable to place climate engineering research within the broader context of mitigation and adaptation.

Given the strong arguments that exist both for and against further research, there is a considerable debate about whether research into greenhouse gas removal and albedo modification should take place; great challenges remain for funding agencies and governing bodies, and also for research institutes and individual researchers, to weigh the arguments that speak in favour of and against research into climate engineering. In order to guide the scientific community and policy makers in this debate, several principles have been derived and applied in this assessment. These principles have been distilled from existing provisions in EU primary law, supplemented by international law and the development of climate engineering governance through the CBD and LC/LP, as well as principles from the academic literature

These principles are:

- the minimisation of harm;
- the precautionary principle;

- the principle of transparency;
- the principle of international cooperation;
- research as a public good.

Based on these principles, different strategies have been proposed that could be applied across all climate engineering approaches, including:

- early public engagement;
- independent assessment;
- operationalising transparency through adoption of research disclosure mechanisms and targeted public communication platforms;
- coordinating international legal efforts through joint adoption of a code-of-conduct for research that draws upon existing legal texts and principles;
- applying frameworks of responsible innovation and anticipatory governance to natural sciences and engineering research.

The realisation of some of these principles, demands, and instruments — especially in the governance of small-scale field tests of albedo modification techniques, but also similarly for perturbative experiments such as open-ocean OIF experiments — requires adequate governance mechanisms and institutions at national and international levels that currently do not exist.

7.6.2 Development of international governance

Taking into account the possible side effects and risks associated with different climate engineering techniques, the question arises: who can legitimately decide on climate engineering deployment or even research, and through what processes? Agreements involving the global commons that are acceptable to all parties may be impossible to reach, due to significantly divergent interests that are grounded in geopolitical, economic, and related issues. Furthermore, international decision-making structures often exclude or marginalise those who are especially vul-

nerable. Procedural norms provide guidance on how these difficulties and shortcomings can be overcome, and include:

- notification and consultation of those affected as well as the wider public and other nations;
- fostering public engagement early in the research phase;
- open preparation and execution of environmental as well as societal impact assessments prior to conducting activities that have the potential for significant environmental or other impacts;
- transparency and public disclosure of the rationales for policy decisions on climate engineering techniques;
- providing a mechanism for appeal and revision, to ensure fairness.

The comparatively rapid development of international governance for climate engineering over the past couple of years at the CBD and the LC/LP suggest a willingness amongst states to cooperate on the issue of climate engineering. In the medium term, this might signal the emergence of a regime complex consisting of regulatory provisions that include the CBD and the LC/LP, as well as potentially the UNFCCC (given the considerations noted above), supported by strategies designed to manage interplay between these institutions and by scientific assessments from the IPCC.

A possible way to prevent political and legal inter-institutional conflict could be seen in the conclusion of memoranda of understanding negotiated by the institutions' secretariats and then submitted to the respective COPs. Specifically for the CBD and the LC/LP this seems to be an achievable near-term goal, given the apparent similarities between the two conventions' views on climate engineering, as evidenced by their consistent approaches as well as mutual references contained in their statements on the objectives and the future of climate engineering regulation.

7.6.3 Development of technique-specific policy

In addition to general policy considerations, specific policy considerations for individual techniques may be considered desirable. Below are considerations for the three example techniques that have been considered in EuTRACE, on which policy development may draw, should the development of specific policies for individual techniques become a goal.

BECCS

EU policy attention to BECCS may be warranted for three reasons:

- the suggested importance of BECCS to achieving decarbonisation, e.g., its extensive use in scenarios prepared for the IPCC assessment reports;
- the experience that establishing deployment of technologies reliant on large resources and infrastructures requires many decades;
- the opposition that is becoming evident in some European countries against proposals for developing BECCS.

Should the EU envisage a substantial role for BECCS in its domestic emissions reduction strategy, steps toward this would include:

- research and technology development;
- infrastructure provision;
- market development;
- societal engagement.

OIF

The EU has very successfully taken the role of an "enforcement organ" of the International Maritime Organization (IMO) in the context of shipping.

A central policy option for the EU would be for the European Commission to urge all LP member states to ratify the amendment, and for all LC members to

become parties to the LP. Recent developments in the governance of OIF arguably place this technique at the most advanced stage of legal and norm development among climate engineering techniques. As such, it might provide insights into overall developments in climate engineering governance and, accordingly, guidance for developing governance for other techniques.

SAI

Thus far, the CBD is the only instrument that has directly addressed the issue of SAI, although only by general reference to the umbrella term “climate-related geoengineering”. It may therefore be valuable, at least in the near term, for the EU to maintain an exploratory stance on SAI.

One of the key challenges for SAI, and generally for albedo modification, is the governance of near-term outdoor experimentation. One option for the EU is to consider thresholds for the impacts of outdoor experiments on radiative forcing. However, such thresholds only aim to address known environmental concerns associated with field tests of SAI, but not the wider concerns that should be taken into account in developing effective governance.

7.6.4 Potential development of climate engineering policy in the EU

With regard to the potential development of climate engineering policy in the EU, two perspectives need to be distinguished:

- the positioning of the EU vis-à-vis climate engineering research;
- where the EU as a whole fits into the wider emerging regime complex on climate engineering.

With regard to climate engineering research, the EU, through its seventh framework research programme (FP7), has already funded two projects that focus explicitly on climate engineering. Should the EU decide to support further research, it would be consistent with the general principles outlined above to do so through programs that broadly investigate the environmental, political, legal, and societal implica-

tions of any climate engineering techniques that are being investigated, and that help to provide options for future actions. If a sufficiently large need for knowledge exists at a future time, then these programs could potentially be modelled on flagship projects akin to that currently conducted on the human brain, or based on “Joint Programming Initiatives” or “Joint Technology Initiatives” co-funded between the EC and national research budgets.

With regard to the emerging regime complex involving the LC/LP, CBD, and UNFCCC, the EU is arguably in a unique position: On the one hand, its member states are all parties to both the UNFCCC and the CBD. In addition, the EU itself, being a supranational organisation equipped with the competence to effectively enforce appropriate application of its laws vis-à-vis its member states, is a party to both conventions. Therefore, EU member states could, in principle, agree on a common position for proposal to both the UNFCCC and the CBD. So far, however, no specific EU perspective on climate engineering has been agreed upon. Taking into account its considerable political influence, the EU might one day contemplate leveraging and advancing a common position on climate engineering within the different regulatory settings, thereby — following internal negotiations — perhaps also contributing to the prevention of conflicts among its member states.

Politically, the implementation of a European climate engineering research policy would influence the structure and content of the EU’s climate change response portfolio as it stands today. For the past two decades, the EU has championed the internationally agreed target of limiting global warming to a 2°C increase in global mean surface temperature compared to pre-industrial levels. Given that in the “vast majority” of scenarios considered by the IPCC, staying within the 2°C target during the 21st century would necessitate some form of greenhouse gas removal, this commitment may have challenging implications for climate engineering policy in the EU. Seen from this perspective, research on greenhouse gas removal could become a significant component of developing and evaluating policy options for staying below the 2°C limit. Furthermore, given the currently slow progress on implementing climate change mitigation measures, combined with the limitations of

greenhouse gas removal techniques (in particular the technical uncertainties and the long timescales required to significantly influence global atmospheric CO₂ concentrations), a strict commitment to the 2°C limit could eventually lead to a very difficult decision over whether to deploy albedo modification techniques in order to stay within a given temperature threshold (e.g., the 2°C limit) or, while recognising the risks of such deployment, to allow the threshold to be crossed.

Should the EU decide to develop climate engineering policy, then the conscientious application of principles embodied in existing legal and regulatory structures, and the development of strategies based on these, may help ensure coherence and consistency with the basic principles upon which broader European research and environmental policy are built.

8. References

- Aaheim, A., Romstad, B., Wei, T., Kristjánsson, J. E., Muri, H., Niemeier, U. and Schmidt, H. (2015) “An economic evaluation of solar radiation management”, *Science of The Total Environment*, 532, pp. 61–69.
- Abelkop, A. D. K. and Carlson, J. C. (2012) “Reining in Phaethon’s chariot: principles for the governance of geoengineering”, *University of Iowa – Legal Studies Research Paper*, 21(27), pp. 101–145.
- Akbari, H., Menon, S. and Rosenfeld, A. (2009) “Global cooling: increasing world-wide urban albedos to offset CO₂”, *Climatic Change*, 94(3–4), pp. 275–286.
- Allen, M. R. (2003) “Liability for climate change”, *Nature*, 421(6926), pp. 891–892.
- Alterskjær, K. and Kristjánsson, J. E. (2013) “The sign of the radiative forcing from marine cloud brightening depends on both particle size and injection amount”, *Geophysical Research Letters*, 40(1), pp. 210–215.
- Alterskjær, K., Kristjánsson, J. E., Boucher, O., Muri, H., Niemeier, U., Schmidt, H., Schulz, M. and Timmreck, C. (2013) “Sea-salt injections into the low-latitude marine boundary layer: the transient response in three Earth system models”, *Journal of Geophysical Research: Atmospheres*, 118(21), pp. 12,195–12,206.
- Alterskjær, K., Kristjánsson, J. E. and Seland, Ø. (2012) “Sensitivity to deliberate sea salt seeding of marine clouds – observations and model simulations”, *Atmospheric Chemistry and Physics*, 12(5), pp. 2795–2807.
- Amelung, D. and Funke, J. (2013) “Dealing with the uncertainties of climate engineering: warnings from a psychological complex problem solving perspective”, *Technology in Society*, 35(1), pp. 32–40.
- Anderson-Teixeira, K. J., Davis, S. C., Masters, M. D. and Delucia, E. H. (2009) “Changes in soil organic carbon under biofuel crops”, *GCB Bioenergy*, 1(1), pp. 75–96.
- Anton, L., Antti-Ilari, P., Harri, K., Ari, L., Kari, E. J. L. and Hannele, K. (2012) “Stratospheric passenger flights are likely an inefficient geoengineering strategy”, *Environmental Research Letters*, 7(3), pp. 034021.
- Arrow, K. J. (2004) “Uncertainty and the welfare economics of medical care. 1963”, *Bulletin of the World Health Organization*, 82(2), pp. 141–149.
- Arthur, W. B. (1989) “Competing technologies, increasing returns, and lock-in by historical events”, *The Economic Journal*, 99(349), pp. 116–131.
- Athanasiou, T. and Baer, P. (2002) *Dead Heat: Global Justice and Global Warming* New York: Seven Stories Press.
- AWI (2009) *Risk Assessment for LOHAFEX*, Bremerhaven, Germany: Alfred Wegener Institute for Polar and Marine Research in the Helmholtz Association.

- Bailey, J. T. and Bailey, L. J. (2008) *A Mechanically Produced Thermocline Based Ocean Temperature Regulatory System*. [Online]. Available at: <http://www.google.com/patents/WO2008109187A2?cl=en>.
- Bala, G. and Caldeira, K. (2000) "Geoengineering Earth's radiation balance to mitigate CO₂-induced climate change", *Geophysical Research Letters*, 27(14), pp. 2141–2144.
- Bala, G., Caldeira, K., Nemani, R., Cao, L., Ban-Weiss, G. and Shin, H.-J. (2010) "Albedo enhancement of marine clouds to counteract global warming: impacts on the hydrological cycle", *Climate Dynamics*, 37(5–6), pp. 915–931.
- Bala, G., Duffy, P. B. and Taylor, K. E. (2008) "Impact of geoengineering schemes on the global hydrological cycle", *Proceedings of the National Academy of Sciences of the United States of America*, 105(22), pp. 7664–7669.
- Bala, G. and Nag, B. (2012) "Albedo enhancement over land to counteract global warming: impacts on hydrological cycle", *Climate Dynamics*, 39(6), pp. 1527–1542.
- Bala, G., Thompson, S., Duffy, P. B., Caldeira, K. and Delire, C. (2002) "Impact of geoengineering schemes on the terrestrial biosphere", *Geophysical Research Letters*, 29(22), pp. 18–1 – 18–4.
- Balint, P. J., Stewart, R. E., Desai, A. and Walters, L. C. (2011) *Wicked Environmental Problems: Managing Uncertainty and Conflict*. Washington: Island Press.
- Ban-Weiss, G. and Caldeira, K. (2010) "Geoengineering as an optimization problem", *Environmental Research Letters*, 5(3), pp. 1–9.
- Bao, L. and Trachtenberg, M. C. (2006) "Facilitated transport of CO₂ across a liquid membrane: comparing enzyme, amine, and alkaline", *Journal of Membrane Science*, 280(1), pp. 330–334.
- Barben, D., Fisher, E., Selin, C. and Guston, D. H. (2008) "Anticipatory Governance of Nanotechnology: Foresight, Engagement, and Integration", in Hackett, E. J., Amsterdamska, O., Lynch, M. & Wajcman, J. (eds.) *The Handbook of Science and Technology Studies*. Cambridge, MA: MIT Press, pp. 979–1000.
- Barnett, T. P., Hasselmann, K., Chelliah, M., Delworth, T., Hegerl, G., Jones, P., Rasmusson, E., Roeckner, E., Ropelewski, C., Santer, B. and Tett, S. (1999) "Detection and attribution of recent climate change: A status report", *Bulletin of the American Meteorological Society*, 80(12), pp. 2631–2659.
- Barrett, S. (2008a) "The incredible economics of geoengineering", *Environmental and Resource Economics*, 39(1), pp. 45–54.
- Barrett, S. (2008b) *A Portfolio System of Climate Treaties*. Cambridge, MA: The Harvard Project on International Climate Agreements.
- Barrett, S., Lenton, T. M., Millner, A., Tavoni, A., Carpenter, S., Anderies, J. M., Chapin III, F. S., Crépin, A.-S., Daily, G. and Ehrlich, P. (2014) "Climate engineering reconsidered", *Nature Climate Change*, 4(7), pp. 527–529.
- Bauen, A., Berndes, G., Junginger, M., Londo, M., Vuille, F., Ball, R., Bole, T., Chudziak, C., Faaij, A. and Mozaffarian, H. (2009) *Bioenergy – A Sustainable and Reliable Energy Source. A Review of Status and Prospects*, Paris: International Energy Agency Bioenergy.
- Baughman, E., Gnanadesikan, A., Degaetano, A. and Adcroft, A. (2012) "Investigation of the surface and circulation impacts of cloud-brightening geoengineering", *Journal of Climate*, 25(21), pp. 7527–7543.
- Beckett, K. P., Freer-Smith, P. H. and Taylor, G. (1998) "Urban woodlands: their role in reducing the effects of particulate pollution", *Environmental Pollution*, 99(3), pp. 347–360.
- Bellamy, R., Chilvers, J., Vaughan, N. E. and Lenton, T. M. (2012) "A review of climate geoengineering appraisals", *Wiley Interdisciplinary Reviews: Climate Change*, 3(6), pp. 597–615.
- Bellamy, R., Chilvers, J., Vaughan, N. E. and Lenton, T. M. (2013) "'Opening up' geoengineering appraisal: Multi-Criteria Mapping of options for tackling climate change", *Global Environmental Change*, 23(0), pp. 926–937.

- Bellamy, R. and Hulme, M. (2011) "Beyond the tipping point: understanding perceptions of abrupt climate change and their implications", *Weather, Climate and Society*, 3(1), pp. 48–60.
- Benedick, R. E. (2011) "Considerations on governance for climate remediation technologies: lessons from the 'ozone hole'", *Stanford Journal of Law, Science and Policy*, 4(1), pp. 6–9.
- Bengtsson, L. (2006) "Geo-Engineering to Confine Climate Change: Is it at all Feasible?", *Climatic Change*, 77(3–4), pp. 229–234.
- Berdahl, M., Robock, A., Ji, D., Moore, J. C., Jones, A., Kravitz, B. and Watanabe, S. (2014) "Arctic cryosphere response in the Geoengineering Model Intercomparison Project G3 and G4 scenarios", *Journal of Geophysical Research: Atmospheres*, 119(3), pp. 2013JD020627.
- Berndes, G., Hoogwijk, M. and van den Broek, R. (2003) "The contribution of biomass in the future global energy supply: a review of 17 studies", *Biomass and Bioenergy*, 25(1), pp. 1–28.
- Bhaduri, G. A. and Šiller, L. (2013) "Nickel nanoparticles catalyse reversible hydration of carbon dioxide for mineralization carbon capture and storage", *Catalysis Science and Technology*, 3(5), pp. 1234–1239.
- Bickel, J. E. (2013) "Climate engineering and climate tipping-point scenarios", *Environment Systems and Decisions*, 33(1), pp. 152–167.
- Bickel, J. E. and Agrawal, S. (2013) "Reexamining the economics of aerosol geoengineering", *Climatic Change*, 119(3–4), pp. 993–1006.
- Bickel, J. E. and Lane, L. (2009) *An Analysis of Climate Engineering as a Response to Climate Change*, Copenhagen: Copenhagen Consensus Centre. Available at: <http://www.aei.org/files/2009/08/07/AP-Climate-Engineering-Bickel-Lane-v3.0.pdf>. Available at: http://fixtheclimate.com/fileadmin/templates/page/scripts/downloadpdf.php?file=/uploads/tx_templavoila/AP_Climate_Engineering_Bickel_Lane_v5.0.pdf.
- Bindoff, N. L., Stott, P. A., AchutaRao, K. M., Allen, M. R., Gillett, N. P., Gutzler, D., Hansingo, K., Hegerl, G., Hu, Y., Jain, S., Mokhov, I. I., Overland, J., Perlwitz, J., Sebbari, R. and Zhang X., (2013) "Detection and Attribution of Climate Change: from Global to Regional", in Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P. M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, USA: Cambridge University Press, pp. 867–952.
- Bitz, C. M., Ridley, J. K., Marika Holland and Cattle, H. (2012) *Arctic Climate Change. Global Climate Models and 20th and 21st Century Arctic Climate Change*. Netherlands: Springer, p. 405–436.
- Blackstock, J. J., Battisti, D., Caldeira, K., Eardley, D. E., Katz, J. I., Keith, D. W., Aristides, A. N. P., Schrag, D. P., Socolow, R. H. and Koonin, S. E. (2009) *Climate Engineering Responses to Climate Emergencies*. Novim: archived online at <http://arxiv.org/pdf/0907.5140>.
- Blackstock, J. J. and Long, J. C. S. (2010) "The politics of geoengineering", *Science*, 327(5965), pp. 527–527.
- Blain, S., Queguiner, B., Armand, L., Belviso, S., Bombled, B., Bopp, L., Bowie, A., Brunet, C., Brussaard, C., Carlotti, F., Christaki, U., Corbiere, A., Durand, I., Ebersbach, F., Fuda, J. L., Garcia, N., Gerringa, L., Griffiths, B., Guigue, C., Guillerm, C., Jacquet, S., Jeandel, C., Laan, P., Lefevre, D., Lo Monaco, C., Malits, A., Mosseri, J., Obernosterer, I., Park, Y. H., Picherl, M., Pondaven, P., Remenyi, T., Sandroni, V., Sarthou, G., Savoye, N., Scouarnec, L., Souhaut, M., Thuiller, D., Timmermans, K., Trull, T., Uitz, J., van Beek, P., Veldhuis, M., Vincent, D., Viollier, E., Vong, L. and Wagener, T. (2007) "Effect of natural iron fertilization on carbon sequestration in the Southern Ocean", *Nature*, 446(7139), pp. 1070–1074.
- Bodansky, D. (1996) "May we engineer the climate?", *Climatic Change*, 33(3), pp. 309–321.
- Bodansky, D. (2011) *Governing Climate Engineering: Scenarios for Analysis*, Cambridge, MA: Harvard Project on Climate Agreements.

- Bodansky, D. (2013) “The who, what, and wherefore of geoengineering governance.”, *Climatic Change*, 121(3), pp. 539–551.
- Bodle, R. (2010) “Geoengineering and international law: The search for common legal ground”, *Tulsa Law Review* 46(10), pp. 305–322.
- Bodle, R., with Homann, G., Schiele, S., and Tedsen, E. (2012) *The Regulatory Framework for Climate-Related Geoengineering Relevant to the Convention on Biological Diversity*. Part II of: *Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters*. Secretariat of the Convention on Biological Diversity. Montreal, Technical Series No. 66.
- Bodle, R. (2013) “Climate Law and Geoengineering”, in Hollo, E. J., Kulovesi, K. & Mehling, M. (eds.), *Climate Change and the Law, Ius Gentium: Comparative Perspectives on Law and Justice* 21 Springer Netherlands, pp. 447–470.
- Bodle, R., Oberthür, S., Donat, L., Homann, G., Sina, S. and Tedsen, E. (2013) *Options and Proposals for the International Governance of Geoengineering*, Berlin: Ecologic Institute.
- Bonan, G. B. (2008) “Forests and climate change: forcings, feedbacks, and the climate benefits of forests”, *Science*, 320, pp. 1444–1449.
- Borgmann, A. (2012) “The Setting of the Scene. Technological Fixes and the Design of the Good Life”, in Preston, C. J. (ed.) *Engineering the Climate: The Ethics of Solar Radiation Management*. Plymouth: Lexington Books, pp. 189–199.
- Bostrom, A., O'Connor, R., Bohm, G., Hanss, D., Bodi, O., Ekstrom, F., Halder, P., Jeschke, S., Mack, B., Qu, M., Rosentrater, L., Sandve, A. and Saelensminde, I. (2012) “Causal thinking and support for climate change policies: international survey findings.”, *Global Environmental Change-Human and Policy Dimensions*, 22(1), pp. 210–222.
- Boucher, O. and Folberth, G. A. (2010) “New directions: atmospheric methane removal as a way to mitigate climate change?”, *Atmospheric Environment*, 44, pp. 3343–3345.
- Boucher, O., Forster, P. M., Gruber, N., Ha-Duong, M., Lawrence, M. G., Lenton, T. M., Maas, A. and Vaughan, N. E. (2014) “Rethinking climate engineering categorization in the context of climate change mitigation and adaptation”, *Wiley Interdisciplinary Reviews: Climate Change*, 5(1), pp. 23–35.
- Boucher, O., Halloran, P. R., Burke, E. J., Doutriaux-Boucher, M., Jones, C. D., Lowe, J. A., Ringer, M. A., Robertson, E. and Wu, P. (2012) “Reversibility in an Earth System model in response to CO₂ concentration changes”, *Environmental Research Letters*, 7(2), pp. 1–9.
- Bower, K., Choularton, T., Latham, J., Sahraei, J. and Salter, S. (2006) “Computational assessment of a proposed technique for global warming mitigation via albedo-enhancement of marine stratocumulus clouds”, *Atmospheric Research*, 82(1–2), pp. 328–336.
- Boyd, P. W., Jickells, T., Law, C. S., Blain, S., Boyle, E. A., Buesseler, K. O., Coale, K. H., Cullen, J. J., de Baar, H. J. W., Follows, M., Harvey, M., Lancelot, C., Levasseur, M., Owens, N. P. J., Pollard, R., Rivkin, R. B., Sarmiento, J., Schoemann, V., Smetacek, V., Takeda, S., Tsuda, A., Turner, S. and Watson, A. J. (2007) “Mesoscale iron enrichment experiments 1993–2005: synthesis and future directions”, *Science*, 315(5812), pp. 612–617.
- Bracmort, K. and Lattanzio, R. K. (2013) *Geoengineering: Governance and Technology Policy*, Washington, DC: Congressional Research Service, Library of Congress. Available at: <https://www.fas.org/sgp/crs/misc/R41371.pdf>.
- Brandani, S. (2012) “Carbon dioxide capture from air: a simple analysis”, *Energy and Environment*, 23(2), pp. 319–328.
- Brzoska, M., Link, P. M. and Neuneck, G. (2012) “Geoengineering - Möglichkeiten und Risiken”, *Sicherheit + Frieden*, 2012(4).

- Buck, H. J. (2012) “Climate Remediation to Address Social Development Challenges. Going Beyond Cost-Benefit and Risk Approaches to Assessing Solar Radiation Management”, in Preston, C. J. (ed.) *Engineering the Climate: The Ethics of Solar Radiation Management*. Plymouth: Lexington Books, pp. 133–148.
- Budyko, M. I. (1974) *Climate and Life*. New York: Academic Press.
- Buesseler, K. O., Doney, S. C., Karl, D. M., Boyd, P. W., Caldeira, K., Chai, F., Coale, K. H., de Baar, H. J. W., Falkowski, P. G., Johnson, K. S., Lampitt, R. S., Michaels, A. F., Naqvi, S. W. A., Smetacek, V., Takeda, S. and Watson, A. J. (2008) “Environment – Ocean iron fertilization – Moving forward in a sea of uncertainty”, *Science*, 319(5860), pp. 162–162.
- Bunzl, M. (2009) “Researching geoengineering: should not or could not?”, *Environmental Research Letters*, 4(4), pp. 045104.
- Bunzl, M. (2011) “Geoengineering harms and compensation”, *Stanford Journal of Law, Science and Policy*, 4, pp. 71–76.
- Burns, W. C. G. (2011) “Climate geoengineering: solar radiation management and its implications for intergenerational equity”, *Stanford Journal of Law, Science and Policy* 1, pp. 39–55.
- Caldeira, K. (2009) “Geoengineering to shade Earth”, *State of the World 2009: Into a Warming World*, pp. 96–98.
- Caldeira, K. (2012) “The great climate experiment - How far can we push the planet?”, *Scientific American*, 307(3) pp. 78– 83.
- Caldeira, K. and Keith, D. (2010) “The need for climate engineering research”, *Issues in Science and Technology*, 27(1), pp. 57–62.
- Caldeira, K. and Wood, L. (2008) “Global and Arctic climate engineering: numerical model studies”, *Philosophical Transactions of the Royal Society A*, 366(1882), pp. 4039–4056.
- Caney, S. (2010) “Climate change and the duties of the advantaged”, *Critical Review of International Social and Political Philosophy*, 13(1), pp. 203–228.
- Carbon Engineering, Ltd. Calgary, AB, Canada, T2L 2K8. Available at: <http://carbonengineering.com/> (Accessed: 28 May 2015).
- Carlin, A. (2007) “Implementation and utilization of geoengineering for global climate change control”, *Sustainable Development Law and Policy*, 7(2), pp. 56–58.
- Carr, W. A., Preston, C. J., Yung, L., Szerszynski, B., Keith, D. W. and Mercer, A. M. (2013) “Public engagement on solar radiation management and why it needs to happen now”, *Climatic Change*, 121 (Geoengineering Research and its Limitations), pp. 1–11.
- CEO (2011) *EU Research Funding: For Who's Benefit?* Brussels, Belgium: Corporate Europe Observatory. Available at: <http://corporateeurope.org/lobbycracy/2011/12/eu-research-funding-whose-benefit>.
- Chapin III, F. S., Zavaleta, E. S., Eviner, V. T., Naylor, R. L., Vitousek, P. M., Reynolds, H. L., Hooper, D. U., Lavelle, S., Sala, O. E., Hobbie, S. E., Mack, M. C. and Díaz, S. (2000) “Consequences of changing biodiversity”, *Nature*, 405, pp. 234–242.
- Chisholm, S. W., Falkowski, P. G. and Cullen, J. J. (2001) “Oceans: dis-crediting ocean fertilization”, *Science*, 294(5541), pp. 309–310.
- Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R. B., Piao, S. and Thornton, P. (2014) “Carbon and Other Biogeochemical Cycles”, in Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P. M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, pp. 465–570.

- Cicerone, R. J. (2006) “Geoengineering: encouraging research and overseeing implementation”, *Climatic Change*, 77(3–4), pp. 221–226.
- Cirisan, A., Spichtinger, P., Luo, B. P., Weisenstein, D. K., Wernli, H., Lohmann, U. and Peter, T. (2013) “Microphysical and radiative changes in cirrus clouds by geoengineering the stratosphere”, *Journal of Geophysical Research: Atmospheres*, 118(10), pp. 4533–4548.
- Collingridge, D. (1980) *The Social Control of Technology*. London: Frances Pinter.
- Conca, K. and Dabelko, G. (2010) *Green Planet Blues: Four Decades of Global Environmental Politics*. 4 edn. Boulder, CO: Westview Press.
- Convention on Biological Diversity (2009) *Decision IX/16 on Biodiversity and Climate Change*. Montreal: Secretariat of the Convention on Biological Diversity.
- Convention on Biological Diversity, Convention on Biological Diversity (2010) *Decision X/33 on Biodiversity and Climate Change*.
- Convention on Biological Diversity, Convention on Biological Diversity (2012) *Decision XI/20 on Climate-related Geoengineering*.
- Corner, A. and Pidgeon, N. (2010) “Geoengineering the climate: the social and ethical implications”, *Environment*, 52(1), pp. 24–37.
- Corner, A., Pidgeon, N. and Parkhill, K. (2012) “Perceptions of geoengineering: public attitudes, stakeholder perspectives, and the challenge of ‘upstream’ engagement”, *Wiley Interdisciplinary Reviews: Climate Change*, 3(5), pp. 451–466.
- Craik, N., Blackstock, J. J. and Hubert, A.-M. (2013) “Regulating geoengineering research through domestic environmental protection frameworks: reflections on the recent canadian ocean fertilization case”, *Carbon and Climate Law Review* pp. 117–124.
- Craik, N. and Moore, N. (2014) *Disclosure-Based Governance for Climate Engineering Research*, Waterloo, Canada and Potsdam, Germany: the Centre for International Governance Innovation and the Institute for Advanced Sustainability Studies. Available at: <https://www.cigionline.org/sites/default/files/no.50.pdf>.
- Cressey, D. (2012) “Cancelled project spurs debate over geoengineering patents”, *Nature*, (no. 7399), pp. 429.
- Crutzen, P. J. (2006) “Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma?”, *Climatic Change*, 77(3–4), pp. 211–219.
- Cziczo, D. J., Froyd, K. D., Hoose, C., Jensen, E. J., Diao, M., Zondlo, M. A., Smith, J. B., Twohy, C. H. and Murphy, D. M. (2013) “Clarifying the dominant sources and mechanisms of cirrus cloud formation”, *Science*, 340(6138), pp. 1320–1324.
- Daniels, N. and Sabin, J. E. (1997) “Limits to healthcare: fair procedures, democratic deliberation, and the legitimacy problem for insurers”, *Philosophy and Public Affairs*, 26, pp. 303–350.
- Davidson, P., Burgoyne, C., Hunt, H. and Causier, M. (2012) “Lifting options for stratospheric aerosol geoengineering: advantages of tethered balloon systems”, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1974), pp. 4263–4300.
- Davies, G. T. (2009) “Law and Policy Issues of Unilateral Geoengineering: Moving to a Managed World”. Available at: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1334625.
- Davies, G.T. (2010) “Geoengineering: a critique”, *Climate Law*, 1(3), pp. 429–441.
- Davies, G.T. (2011) “Framing the social, political, and environmental risks and benefits of geoengineering: balancing the hard-to-imagine against the hard-to-measure”, *Tulsa Law Review*, 43, pp. 261–282.
- Davis, S. C., Anderson-Teixeira, K. J. and DeLucia, E. H. (2009) “Life-cycle analysis and the ecology of biofuels”, *Trends in Plant Science*, 14(3), pp. 140–146.

- Denman, K. L. (2008) "Climate change, ocean processes and ocean iron fertilization", *Marine Ecology Progress Series*, 364, pp. 219–225.
- Dilling, L. and Hauser, R. (2013) "Governing geoengineering research: why, when and how?", *Climatic Change*, 121(3), pp. 553–565.
- Dixon, T., Leamon, G., Zakkour, P. and Warren, L. (2013) "CCS projects as Kyoto Protocol CDM activities", *Energy Procedia*, 37, pp. 7596–7604.
- Dornburg, V. and Marland, G. (2008) "Temporary storage of carbon in the biosphere does have value for climate change mitigation: a response to the paper by Miko Kirschbaum", *Mitigation and Adaptation Strategies for Global Change*, 13(3), pp. 211–217.
- Dornburg, V., van Vuuren, D., van de Ven, G., Langeveld, H., Meeusen, M., Banse, M., van Oorschot, M., Ros, J., van den Born, G. J. and Aiking, H. (2010) "Bioenergy revisited: key factors in global potentials of bioenergy", *Energy and Environmental Science*, 3(3), pp. 258–267.
- Doughty, C., Field, C. and McMillan, A. (2010) "Can crop albedo be increased through the modification of leaf trichomes, and could this cool regional climate?", *Climatic Change*, 104(2), pp. 379–387.
- Driscoll, S., Bozzo, A., Gray, L. J., Robock, A. and Stenchikov, G. (2012) "Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions", *Journal of Geophysical Research: Atmospheres*, 117(D17), pp. D17105.
- Dröge, S. (2012) "Geoengineering Looming: Climate Control the American or Chinese Way", in Perthes, V. & Lippert, B. (eds.) *Expect the Unexpected: Ten Situations to Keep an Eye On*. Berlin: German Institute for International and Security Affairs.
- Dupouey, J. L., Dambrine, E., Laffite, J. D. and Moares, C. (2002) "Irreversible impact of past land use change on forest soils and biodiversity", *Ecology*, 83(11), pp. 2978–2984.
- Dykema, J. A., Keith, D. W., Anderson, J. G. and Weisenstein, D. (2014) "Stratospheric controlled perturbation experiment: a small-scale experiment to improve understanding of the risks of solar geoengineering", *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2031).
- EASAC (2013) *Carbon Capture and Storage in Europe*. Brussels: European Academies Science Advisory Council.
- Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Field, C., Barros, V., Stocker, T. F., Dahe, Q., Minx, J., Mach, K., Plattner, G.-k., Schlömer, S., Hansen, G. and Mastrandrea, M. (2011) *IPCC Expert Meeting on Geoengineering: Meeting Report*, 20–22 June. Lima, Peru (9789291691364). Available at: https://www.ipcc-wg2.gov/meetings/EMs/EM_GeoE_Meeting_Report_final.pdf.
- Eliseev, A. (2012) "Climate change mitigation via sulfate injection to the stratosphere: impact on the global carbon cycle and terrestrial biosphere", *Atmospheric and Oceanic Optics*, 25(6), pp. 405–413.
- Emmerling, J. and Tavoni, M. (2013) *Geoengineering and Abatement: A 'Flat' Relationship under Uncertainty*, Italy: Fondazione Eni Enrico Mattei.
- English, J. M., Toon, O. B. and Mills, M. J. (2012) "Microphysical simulations of sulfur burdens from stratospheric sulfur geoengineering", *Atmospheric Chemistry and Physics*, 12(10), pp. 4775–4793.
- ETC Group (2010) *Geoengineering: Gambling with GAIA*, Ottawa: The ETC Group.
- European Union (1992/43/EEC) *Directive of the European Parliament and of the Council of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora*. OJ No. L 206 of 22.7.1992.
- European Union (2000/60/EC) *Directive of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy*, OJ No. L 327 of 22.12.2000.
- European Union (2002/49/EC) *Directive of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise*, OJ No. L 189 of 18.7.2002.

- European Union (2004/35/CE) *Directive of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage*, OJ No. L 143 of 30.4.2004.
- European Union (2008/50/EC) *Directive of the European Parliament and the Council of 21 May 2008 on ambient air quality and cleaner air for Europe*, OJ No. L 152 of 11.6.2008.
- European Union (2009/28/EC) *Directive of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*.
- European Union (2009/31/EC) *Directive of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006*, OJ No. L 140 of 5.6.2009.
- European Union (2009/147/EC) *Directive of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds*. OJ No. L of 26.1.2010.
- European Union (2011/92/EU) *Directive of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment*, OJ No. L 26 of 28.1.2012.
- Feichter, J. and Leisner, T. (2009) “Climate engineering: a critical review of approaches to modify the global energy balance”, *European Physical Journal-Special Topics*, 176, pp. 81–92.
- Ferraro, A. J., Highwood, E. J. and Charlton-Perez, A. J. (2011) “Stratospheric heating by potential geoengineering aerosols”, *Geophysical Research Letters*, 38.
- Ferraro, A. J., Highwood, E. J. and Charlton-Perez, A. J. (2014) “Weakened tropical circulation and reduced precipitation in response to geoengineering”, *Environmental Research Letters*, 9(1), pp. 014001.
- Finley, R. J. (2014) “An overview of the Illinois Basin—Decatur project”, *Greenhouse Gases: Science and Technology*, 4(5), pp. 571–579.
- Finley, R. J., Frailey, S. M., Leetaru, H. E., Senel, O., Couëslan, M. L. and Scott, M. (2013) “Early operational experience at a one-million tonne CCS demonstration project, Decatur, Illinois, USA”, *Energy Procedia*, 37, pp. 6149–6155.
- Fischedick, M., Pietzner, K., Supersberger, N., Esken, A., Kuckshinrichs, W., Zapp, P. and Idrissova, F. (2009) “Stakeholder acceptance of carbon capture and storage in Germany”, *Energy Procedia*, 1(1), pp. 4783–4787.
- Fleming, J. R. (2010) *Fixing the Sky: The Checkered History of Weather and Climate Control*. New York: Columbia University Press.
- Foley, R. W., Guston, D. and Sarewitz, D. (2015 forthcoming) “Towards the Anticipatory Governance of Geo-engineering”, in Blackstock, J.J. & Low, S. (eds.) *Geoengineering Our Climate? Ethics, Politics and Governance. A Working Paper Series on the Ethics, Politics and Governance of Climate Engineering*. London: Routledge.
- Franks, P. J., Adams, M. A., Amthor, J. S., Barbour, M. M., Berry, J. A., Ellsworth, D. S., Farquhar, G. D., Ghannoum, O., Lloyd, J., McDowell, N., Norby, R. J., Tissue, D. T. and von Caemmerer, S. (2013) “Sensitivity of plants to changing atmospheric CO₂ concentration: from the geological past to the next century”, *New Phytologist*, 197(4), pp. 1077–1094.
- Freeman, C., Fenner, N. and Shirsat, A. H. (2012) “Peatland geoengineering: an alternative approach to terrestrial carbon sequestration”, *Philosophical Transactions of The Royal Society A*, 370(1974), pp. 4404–4421.
- Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., Jackson, R. B., Jones, C. D., Kraxner, F. and Nakicenovic, N. (2014) “Betting on negative emissions”, *Nature Climate Change*, 4(10), pp. 850–853.

- Fyfe, J. C., Cole, J. N. S., Arora, V. K. and Scinocca, J. F. (2013) “Biogeochemical carbon coupling influences global precipitation in geoengineering experiments”, *Geophysical Research Letters*, 40(3), pp. 651–655.
- Galaz, V. (2012) “Geo-engineering, governance, and social-ecological systems: critical issues and joint research needs”, *Ecology and Society*, 17(1).
- GAO (2011) *Climate engineering: Technical status, future directions, and potential responses*, Washington, DC.
- Gardiner, S. M. (2010) “Is “Arming the Future” with Geoengineering Really the Lesser Evil? Some Doubts about the Ethics of Intentionally Manipulating the Climate System”, in Gardiner, S.M., Caney, S., Jamieson, D. & Shue, H. (eds.) *Climate Ethics: Essential Readings*. Oxford: Oxford University Press, pp. 284–314.
- Gardiner, S. M. (2011) *A Perfect Moral Storm: The Ethical Challenge of Climate Change*. Oxford: Oxford University Press.
- Gardiner, S. M. (2013) “The desperation argument for geoengineering”, *Political Science and Politics*, 46(01), pp. 28–33.
- Gaskill, A. (2004) “Desert Area Coverage: Global Albedo Enhancement Project”. Available at: <http://www.global-warming-geo-engineering.org/1/contents.html>.
- Genesio, L., Miglietta, F., Lugato, E., Baronti, S., Pieri, M. and Vaccari, F. P. (2011) “Surface albedo following biochar application in durum wheat”, *Environmental Research Letters*, 7(1), pp. 014025.
- Ginzky, H., Herrmann, F., Kartschall, K., Leujak, W., Lipsius, K., Mäder, C., Schwermer, S. and Straube, G. (2011) *Geoengineering: Effective climate protection or megalomania?*, Dessau: Umweltbundesamt.
- Glienke, S., Irvine, P. J. and Lawrence, M. G. (2015) “The impact of geoengineering on vegetation in experiment G1 of the Geoengineering Model Intercomparison Project (GeoMIP)”, *submitted to Journal of Geophysical Research*.
- Gnanadesikan, A., Sarmiento, J. L. and Slater, R. D. (2003) “Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production”, *Global Biogeochemical Cycles*, 17(2).
- Goeppert, A., Czaun, M., Prakash, G. S. and Olah, G. A. (2012) “Air as the renewable carbon source of the future: An overview of CO₂ capture from the atmosphere”, *Energy and Environmental Science*.
- Goes, M., Tuana, N. and Keller, K. (2011) “The economics (or lack thereof) of aerosol geoengineering”, *Climatic Change*, 109(3–4), pp. 1–26.
- Gollakota, S. and McDonald, S. (2014) “Commercial-scale CCS project in Decatur, Illinois – construction status and operational plans for demonstration”, *Energy Procedia*, 63, pp. 5986–5993.
- Gordon, B. (2010) *Engineering the Climate: Research Needs and Strategies for International Coordination*, Washington DC.: U.S. House of Representatives Science and Technology Committee.
- Gramstad, K. and Tjøtta, S. (2010) “Climate Engineering: Cost Benefit and Beyond”. Available at: http://www.uib.no/filearchive/wp-05.10_2.pdf.
- Groombridge, B. and Jenkins, M. D. (2002) *World Atlas of Biodiversity: Earth's Living Resources in the 21st Century*. Berkeley, CA: University of California Press.
- Gu, L. H., Baldocchi, D., Verma, S. B., Black, T. A., Vesala, T., Falge, E. M. and Dowty, P. R. (2002) “Advantages of diffuse radiation for terrestrial ecosystem productivity”, *Journal of Geophysical Research: Atmospheres*, 107 (5–6), pp. 2-1–2-21.
- Gu, L. H., Baldocchi, D. D., Wofsy, S. C., Munger, J. W., Michalsky, J. J., Urbanski, S. P. and Boden, T. A. (2003) “Response of a deciduous forest to the Mount Pinatubo eruption: enhanced photosynthesis”, *Science*, 299(5615), pp. 2035–2038.

- Güssow, K., Proelß, A., Oschlies, A., Rehdanz, K. and Rickels, W. (2010) “Ocean iron fertilization: why further research is needed”, *Marine Policy*, 34(5), pp. 911–918.
- Gustavsson, L., Pingoud, K. and Sathre, R. (2006) “Carbon dioxide balance of wood substitution: comparing concrete- and wood-framed buildings”, *Mitigation and Adaptation Strategies for Global Change*, 11(3), pp. 667–691.
- Guston, D. H. (2014) “Understanding ‘anticipatory governance’”, *Social Studies of Science*, 44(2), pp. 218–242.
- Hale, B. (2009) “What’s so moral about the moral hazard?”, *Public Affairs Quarterly*, pp. 1–25.
- Hale, B. (2012) “The World that Would Have Been: Moral Hazard Arguments against Geoengineering”, in Preston, C.J. (ed.) *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press, pp. 113–131.
- Hamilton, C. (2013) *Earthmasters: Playing God with the Climate*. Crows Nest: Allen & Unwin.
- Hammond, J. and Shackley, S. (2010) *Towards a Public Communication and Engagement Strategy for Carbon Dioxide Capture and Storage Projects in Scotland: A Review of Research Findings, CCS Project Experiences, Tools, Resources and Best Practices*: Scottish Carbon Dioxide Capture, Transport and Storage Development Study, Working Paper SCCS 2010 08.
- Hammond, J., Shackley, S., Sohi, S. and Brownsort, P. (2011) “Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK”, *Energy Policy*, 39, pp. 2646–2655.
- Hamwey, R. (2007) “Active amplification of the terrestrial albedo to mitigate climate change: an exploratory study”, *Mitigation and Adaptation Strategies for Global Change*, 12(4), pp. 419–439.
- Harris, N. R. P. (1997) “Trends in stratospheric and free tropospheric ozone”, *Journal of Geophysical Research: Atmospheres*, 102(D1), pp. 1571–1590.
- Hartmann, J. and Kempe, S. (2008) “What is the maximum potential for CO₂ sequestration by ‘stimulated’ weathering on the global scale?”, *Naturwissenschaften*, 95(12), pp. 1159–1164.
- Hartmann, J., West, A. J., Renforth, P., Köhler, P., De La Rocha, C. L., Wolf-Gladrow, D. A., Dürr, H. H. and Scheffran, J. (2013) “Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients and mitigate ocean acidification”, *Philosophical Transactions of the Royal Society*, 51(2), pp. 1–37.
- Harvey, L. (2008) “Mitigating the atmospheric CO₂ increase and ocean acidification by adding limestone powder to upwelling regions”, *Journal of Geophysical Research*, 113(C4), pp. C04028.
- Haywood, J. M., Jones, A., Bellouin, N. and Stephenson, D. (2013) “Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall”, *Nature Climate Change*, 3(7), pp. 660–665.
- Heckendorn, P., Weisenstein, D., Fueglistaler, S., Luo, B. P., Rozanov, E., Schraner, M., Thomason, L. W. and Peter, T. (2009) “The impact of geoengineering aerosols on stratospheric temperature and ozone”, *Environmental Research Letters*, 4(4), pp. 045108.
- Hegerl, G. C. and Solomon, S. (2009) “Risks of climate engineering”, *Science*, 325(5943), pp. 1178530.
- Held, I. M. and Soden, B. J. (2006) “Robust responses of the hydrological cycle to global warming”, *Journal of Climate*, 19(21), pp. 5686–5699.
- Heyder, U., Schaphoff, S., Gerten, D. and Lucht, W. (2011) “Risk of severe climate change impact on the terrestrial biosphere”, *Environmental Research Letters* 6(3), pp. 034036.
- Heyward, C. (2013) “Situating and abandoning geoengineering: a typology of five responses to dangerous climate change”, *Political Science and Politics*, 46(1), pp. 23–27.
- Honegger, M., Michaelowa, A. and Butzengeiger-Geyer, S. (2012) *Climate Engineering: Avoiding Pandora’s Box through Research and Governance*: Lysaker, Norway: Fridtjof Nansens Institut.

- Honegger, M., Sugathapala, K. and Michaelowa, A. (2013) "Tackling climate change: where can the generic framework be located?", *Carbon and Climate Law Review*, 2, pp. 125–135.
- Horton, J., Parker, A. and Keith, D. (2015) "Liability for solar geoengineering: historical precedents, contemporary innovations, and governance possibilities", *N.Y.U. Environmental Law Journal*, 22, pp. 225–273.
- House, K. Z., Baclig, A. C., Ranjan, M., van Nierop, E. A., Wilcox, J. and Herzog, H. J. (2011) "Economic and energetic analysis of capturing CO₂ from ambient air", *Proceedings of the National Academy of Sciences of the United States of America*, 108(51), pp. 20428–33.
- House, K. Z., House, C. H., Schrag, D. P. and Aziz, M. J. (2007) "Electrochemical acceleration of chemical weathering as an energetically feasible approach to mitigating anthropogenic climate change", *Environmental Science and Technology*, 41(24), pp. 8464–8470.
- House, K. Z., Schrag, D. P., Harvey, C. F. and Lackner, K. S. (2006) "Permanent carbon dioxide storage in deep-sea sediments", *Proceedings of the National Academy of Sciences of the United States of America*, 103(33), pp. 12291–12295.
- Howard Jr., E. G., Edward, G. and O'Brien, T. C. (1999) *Water-buoyant particulate materials containing micronutrients for phytoplankton*. [Online]. Available at: <http://www.google.com/patents/US5965117>.
- Hu, Y. H. and Huo, Y. (2011) "Fast and exothermic reaction of CO₂ and Li₃N into C–N-containing solid materials", *The Journal of Physical Chemistry A*, 115(42), pp. 11678–11681.
- Hubert, A.-M. (2011) "The new paradox in marine scientific research: regulating the potential environmental impacts of conducting ocean science", *Ocean Development and International Law*, 42(4), pp. 329–355.
- Hubert, A.-M. and Reichwein, D. (2015) *An Exploration of a Code of Conduct for Responsible Scientific Research Involving Geoengineering*, Potsdam and Oxford: IASS and InSIS.
- Huijts, N., Midden, C. J. and Meijnders, A. L. (2007) "Social acceptance of carbon dioxide storage", *Energy Policy*, 35(5), pp. 2780–2789.
- Hulme, M. (2014) *Can Science Fix Climate Change? A Case Against Climate Engineering*. Cambridge: Polity Press.
- IEA (2011) *Combining Bioenergy with CCS. Reporting and Accounting for Negative Emissions under UNFCCC and the Kyoto Protocol*, Paris, France: International Energy Agency.
- IEA (2011) *Technology Roadmap - Biofuels for Transport*, Paris, France: International Energy Agency.
- IEA (2012) *Technology Roadmap: Bioenergy for Heat and Power*: International Energy Agency. Available at: http://www.iea.org/publications/freepublications/publication/2012_Bioenergy_Roadmap_2nd_Edition_WEB.pdf.
- IEAGHG (2009) *Biomass CCS Study*, Cheltenham, UK: International Energy Agency Greenhouse Gas R&D Programme (IEAGHG).
- IEAGHG (2011) *Potential for Biomass and Carbon Dioxide Capture and Storage*, Cheltenham, UK: International Energy Agency Greenhouse Gas R&D Programme (IEAGHG).
- IPCC (2005) *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.
- IPCC (2007a) *Climate Change 2007: Synthesis Report. Contributions of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.
- IIPCC (2007b) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

- IPCC (2013a) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.
- IPCC (2013b) “Summary for Policymakers”, in Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, USA: Cambridge University Press, pp. 3–29.
- IPCC (2014a) *Climate Change 2014: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.
- IPCC (2014b) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.
- IPCC (2014c) “Summary for Policymakers.”, in Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y.O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R. & White, L. L. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, USA: Cambridge University Press, pp. 1–32.
- Irvine, P. J., Boucher, O., Kravitz, B., Alterskjær, K., Cole, J. N., Ji, D., Jones, A., Lunt, D. J., Moore, J. C. and Muri, H. (2014a) “Key factors governing uncertainty in the response to sunshade geoengineering from a comparison of the GeoMIP ensemble and a perturbed parameter ensemble”, *Journal of Geophysical Research: Atmospheres*, 119(13), pp. 7946–7962.
- Irvine, P. J., Lunt, D. J., Stone, E. J. and Ridgwell, A. J. (2009) “The fate of the Greenland Ice Sheet in a geoengineered, high CO₂ world”, *Environmental Research Letters*, 4(4).
- Irvine, P. J., Ridgwell, A. and Lunt, D. J. (2010) “Assessing the regional disparities in geoengineering impacts”, *Geophysical Research Letters*, 37(18), pp. 1–6.
- Irvine, P. J., Ridgwell, A. J. and Lunt, D. J. (2011) “Climatic effects of surface albedo geoengineering”, *Journal of Geophysical Research: Atmospheres*, 116(D24), pp. D24112.
- Irvine, P. J., Schäfer, S. and Lawrence, M. G. (2014b) “Solar radiation management could be a game changer”, *Nature Climate Change*, 4(10), pp. 842–842.
- Irvine, P. J., Sriver, R. L. and Keller, K. (2012) “Tension between reducing sea-level rise and global warming through solar-radiation management”, *Nature Climate Change*, 2(2), pp. 97–100.
- Itaoka, K., Saito, A., M. Paukovic, M., de Best-Waldhober, A.-M. Dowd, T. Jeanneret, P. Ashworth and James, M. (2012) *Understanding How Individuals Perceive Carbon Dioxide: Implications for Acceptance of Carbon Dioxide Capture and Storage*. CSIRO Report EP 118160, Australia: Global CCS Institute. Available at: <ftp://ftp.ecn.nl/pub/www/library/report/2012/e12056.pdf>.
- Jamieson, D. (1996) “Ethics and intentional climate change”, *Climatic Change*, 33(3), pp. 323–336.
- Jamieson, D. (2013) “Some whats, whys and worries of geoengineering”, *Climatic Change*, 121(3), pp. 1–11.
- Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D. W., Minkinen, K. and Byrne, K. A. (2007) “How strongly can forest management influence soil carbon sequestration?”, *Geoderma*, 137(3–4), pp. 253–268.
- Jaramillo, P., Griffin, W. M. and McCoy, S. T. (2009) “Life cycle inventory of CO₂ in an enhanced oil recovery system”, *Environmental Science and Technology*, 43(21), pp. 8027–8032.
- Jarvis, A. and Leedal, D. (2012) “The Geoengineering Model Intercomparison Project (GeoMIP): a control perspective”, *Atmospheric Science Letters*, 13(3), pp. 157–163.

- Jenkins, A. K. L. and Forster, P. M. (2013) “The inclusion of water with the injected aerosol reduces the simulated effectiveness of marine cloud brightening”, *Atmospheric Science Letters*, 14(3), pp. 164–169.
- Jenkins, A. K. L., Forster, P. M. and Jackson, L. S. (2013) “The effects of timing and rate of marine cloud brightening aerosol injection on albedo changes during the diurnal cycle of marine stratocumulus clouds”, *Atmospheric Chemistry and Physics*, 13(3), pp. 1659–1673.
- Jin, X. and Gruber, N. (2003) “Offsetting the radiative benefit of ocean iron fertilization by enhancing N₂O emissions”, *Geophysical Research Letters*, 30(24).
- Jones, A., Haywood, J. and Boucher, O. (2009) “Climate impacts of geoengineering marine stratocumulus clouds”, *Journal of Geophysical Research: Atmospheres*, 114, pp. 9.
- Jones, A., Haywood, J. and Boucher, O. (2011) “A comparison of the climate impacts of geoengineering by stratospheric SO₂ injection and by brightening of marine stratocumulus cloud”, *Atmospheric Science Letters*, 12(2), pp. 176–183.
- Jones, A., Haywood, J., Boucher, O., Kravitz, B. and Robock, A. (2010) “Geoengineering by stratospheric SO₂ injection: results from the Met Office HadGEM(2) climate model and comparison with the Goddard Institute for Space Studies ModelE”, *Atmospheric Chemistry and Physics*, 10(13), pp. 5999–6006.
- Jones, A. and Haywood, J. M. (2012) “Sea-spray geoengineering in the HadGEM2-ES earth-system model: radiative impact and climate response”, *Atmospheric Chemistry and Physics*, 12(22), pp. 10887–10898.
- Jones, A., Haywood, J. M., Alterskjær, K., Boucher, O., Cole, J. N. S., Curry, C. L., Irvine, P. J., Ji, D., Kravitz, B., Kristjánsson, J. E., Moore, J. C., Niemeier, U., Robock, A., Schmidt, H., Singh, B., Tilmes, S., Watanabe, S. and Yoon, J.-H. (2013) “The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP)”, *Journal of Geophysical Research: Atmospheres*, 118(17), pp. 9743–9752.
- Jones, C. D., Cox, P. and Huntingford, C. (2003) “Uncertainty in climate-carbon cycle projections associated with the sensitivity of soil respiration to temperature”, *Tellus B*, 55(2), pp. 642–648.
- Joronen, S., Oksane, M. and Vuorisalo, T. (2011) “Towards weather ethics: from chance to choice with weather modification”, *Ethics, Policy and Environment* 14(1), pp. 55–67.
- Kahan, D. M., Silva, C. L., Jenkins-Smith, H., Braman, D. and Tarantola, T. (2012) “Geoengineering and the science communication environment: a cross-cultural experiment”, *SSRN Electronic Journal*, 92(41).
- Kalidindi, S., Bala, G., Modak, A. and Caldeira, K. (2014) “Modeling of solar radiation management: a comparison of simulations using reduced solar constant and stratospheric sulphate aerosols”, *Climate Dynamics*, pp. 1–17.
- Karinen, R. and Guston, D. H. (2010) “Toward anticipatory governance: the experience with nanotechnology”, *Governing Future Technologies: Springer*, pp. 217–232.
- Keenan, T. F., Hollinger, D. Y., Bohrer, G., Dragoni, D., Munger, J. W., Schmid, H. P. and Richardson, A. D. (2013) “Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise”, *Nature*, 499(7458), pp. 324–327.
- Keith, D. W. (2000) “Geoengineering the climate: history and prospect”, *Annual Review of Energy and the Environment*, 25, pp. 245–284.
- Keith, D. W. (2010) “Photophoretic levitation of engineered aerosols for geoengineering”, *Proceedings of the National Academy of Sciences of the United States of America*, 107(38), pp. 16428–16431.
- Keith, D. W., Duren, R. and MacMartin, D. G. (2014) “Field experiments on solar geoengineering: report of a workshop exploring a representative research portfolio”, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2031).

- Keith, D. W., Parson, E. and Morgan, M. G. (2010) "Research on global sun block needed now", *Nature*, 463(7280), pp. 426–427.
- Keller, D. P., Feng, E. Y. and Oschlies, A. (2014) "Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario", *Nature Communications*, 5, pp. 3304.
- Kember, M. R., Buchard, A. and Williams, C. K. (2011) "Catalysts for CO₂/epoxide copolymerisation", *Chemical Communications*, 47(1), pp. 141–163.
- Keohane, R. O. and Victor, D. G. (2011) "The regime complex for climate change.", *Perspectives on Politics*, 9(1), pp. 7–23.
- Kheshgi, H. S. (1995) "Sequestering atmospheric carbon dioxide by increasing ocean alkalinity", *Energy-The International Journal*, 20(9), pp. 915–922.
- Kiehl, J. T. (2006) "Geoengineering climate change: treating the symptom over the cause?", *Climatic Change*, 77(3–4), pp. 227–228.
- Kiehl, J. T. and Trenberth, K. E. (1997) "Earth's annual global mean energy budget", *Bulletin of the American Meteorological Society*, 78(2), pp. 197–208.
- Klein, R. J. T., Midgley, G. F. and Preston, B. L. (2014) "Adaptation Opportunities, Constraints, and Limits", in IPCC (ed.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, USA: Cambridge University Press, pp. 899–943.
- Klepper, G. (2012) "What are the costs and benefits of climate engineering? And can we assess them?", *S+F Sicherheit und Frieden*, Special Issue: Geoengineering: An Issue for Peace and Security?(4).
- Klepper, G. and Rickels, W. (2012) "The Real Economics of Climate Engineering", *Economics Research International*, 2012, pp. 1–20.
- Klepper, G. and Rickels, W. (2014) "Climate engineering: economic considerations and research challenges", *Review of Environmental Economics and Policy*, 8(2), pp. 270–289.
- Köhler, P., Abrams, J. F., Völker, C., Hauck, J. and Wolf-Gladrow, D. A. (2013) "Geoengineering impact of open ocean dissolution of olivine on atmospheric CO₂, surface ocean pH and marine biology", *Environmental Research Letters*, 8(1), pp. 14009–14009.
- Köhler, P., Hartmann, J. and Wolf-Gladrow, D. A. (2010) "Geoengineering potential of artificially enhanced silicate weathering of Olivine", *Proceedings of the National Academy of Sciences of the United States of America*, 107(47), pp. 20228–33.
- Koren, I., Kaufman, Y. J., Washington, R., Todd, M. C., Rudich, Y., Martins, J. V. and Rosenfeld, D. (2006) "The Bodélé depression: A single spot in the Sahara that provides most of the mineral dust to the Amazon forest", *Environmental Research Letters*, 1(1).
- Korhonen, H., Carslaw, K. S. and Romakkaniemi, S. (2010) "Enhancement of marine cloud albedo via controlled sea spray injections: a global model study of the influence of emission rates, microphysics and transport", *Atmospheric Chemistry and Physics*, 10(9), pp. 4133–4143.
- Kravitz, B., Caldeira, K., Boucher, O., Robock, A., Rasch, P. J., Alterskjær, K., Bou Karam, D., Cole, J. N., Curry, C. L., Haywood, J. M., Irvine, P. J., Ji, D., Jones, A., Kristjánsson, J. E., Lunt, D. J., Moore, J. C., Niemeier, U., Schmidt, H., Schulz, M., Singh, B., Tilmes, S., Watanabe, S., Yang, S. and Yoon, J.-H. (2013a) "Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP)", *Journal of Geophysical Research: Atmospheres*, 118(15), pp. 8320–8332.
- Kravitz, B., Forster, P. M., Jones, A., Robock, A., Alterskjær, K., Boucher, O., Jenkins, A. K. L., Korhonen, H., Kristjánsson, J. E., Muri, H., Niemeier, U., Partanen, A.-I., Rasch, P. J., Wang, H. and Watanabe, S. (2013b) "Sea spray geoengineering experiments in the Geoengineering Model Intercomparison Project (GeoMIP): experimental design and preliminary results", *Journal of Geophysical Research: Atmospheres*, 118(19), pp. 11175–11186.

- Kravitz, B., MacMartin, D. G., Robock, A., Rasch, P. J., Ricke, K. L., Cole, J. N. S., Curry, C. L., Irvine, P. J., Ji, D., Keith, D. W., Kristjánsson, J. E., Moore, J. C., Muri, H., Singh, B., Tilmes, S., Watanabe, S., Yang, S. and Yoon, J.-H. (2014) “A multi-model assessment of regional climate disparities caused by solar geoengineering”, *Environmental Research Letters*, 9, 074013.
- Kravitz, B., Robock, A., Boucher, O., Schmidt, H., Taylor, K. E., Stenchikov, G. and Schulz, M. (2011) “The Geoengineering Model Intercomparison Project (GeoMIP)”, *Atmospheric Science Letters*, 12(2), pp. 162–167.
- Kravitz, B., Robock, A. and Irvine, P. (2013c) “Robust Results From Climate Model Simulations of Geoengineering”, *Eos, Transactions American Geophysical Union*, 94(33), pp. 292–292.
- Kravitz, B., Robock, A., Oman, L., Stenchikov, G. and Marquardt, A. B. (2009) “Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols”, *Journal of Geophysical Research: Atmospheres*, 114, pp. 7.
- Kravitz, B., Robock, A., Shindell, D. T. and Miller, M. A. (2012) “Sensitivity of stratospheric geoengineering with black carbon to aerosol size and altitude of injection”, *Journal of Geophysical Research-Atmospheres*, 117(D9), pp. D09203.
- Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G. and Klein, D. (2013) “Is atmospheric carbon dioxide removal a game changer for climate change mitigation?“, *Climatic Change*, 118(1), pp. 45–57.
- Kroecker, K. J., Kordas, R. L., Crim, R. N. and Singh, G. G. (2010) “Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms”, *Ecology Letters*, 13(11), pp. 1419–1434.
- Kuebbeler, M., Lohmann, U. and Feichter, J. (2012) “Effects of stratospheric sulfate aerosol geo-engineering on cirrus clouds”, *Geophysical Research Letters*, 39(23), pp. L23803.
- Lackner, K. S. (2009) “Capture of carbon dioxide from ambient air”, *European Physical Journal-Special Topics*, 176, pp. 93–106.
- Lackner, K. S., Brennan, S., Matter, J. M., Park, A.-H., Wright, A. and Van Der Zwaan, B. (2012) “The urgency of the development of CO₂ capture from ambient air: supporting information”. *Proceedings of the National Academy of Sciences of the United States of America*, 109(33), pp. 13156–13162.
- Lackner, K. S., Wendt, C. H., Butt, D. P., Joyce Jr, E. L. and Sharp, D. H. (1995) “Carbon dioxide disposal in carbonate minerals”, *Energy*, 20(11), pp. 1153–1170.
- Lafforgue, G., Magné, B. and Moreaux, M. (2008) “Energy substitutions, climate change and carbon sinks”, *Ecological Economics*, 67(4), pp. 589–597.
- Latham, J. (1990) “Control of global warming”, *Nature*, 347(6291), pp. 339–340.
- Latham, J., Rasch, P., Chen, C. C., Kettles, L., Gadian, A., Gettelman, A., Morrison, H., Bower, K. and Choulaton, T. (2008) “Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds”, *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, 366(1882), pp. 3969–3987.
- Lawrence, M. G. (2002) “Side effects of oceanic iron fertilization”, *Science*, 297(September), pp. 2002–2002.
- Lawrence, M. G. (2006) “The geoengineering dilemma: to speak or not to speak”, *Climatic Change*, 77(3–4), pp. 245–248.
- Lee, J. W. (2008) *Method for reducing carbon dioxide in atmosphere using deep-ocean water and method for preventing global warming using the same*. Patent no. KR20100034135. [Online]. Available at: <http://europepmc.org/patents/PAT/KR20100034135>.
- Lee, J. W., Yang, P., Dessler, A. E., Gao, B. C. and Platnik, S. (2009) “Distribution and radiative forcing of tropical thin cirrus clouds”, *Journal of Atmospheric Science*, 66(12), pp. 3721–3731.

- Lehmann, J., Gaunt, J. and Rondon, M. (2006) "Bio-char sequestration in terrestrial ecosystems – A review", *Mitigation and Adaptation Strategies for Global Change*, 11(2), pp. 395–419.
- Lenton, T. M. and Vaughan, N. E. (2009) "The radiative forcing potential of different climate geoengineering options", *Atmospheric Chemistry and Physics*, 9(15), pp. 5539–5561.
- Lenton, T. M. and Vaughan, N. E. (eds.) (2013) *Geoengineering Responses to Climate Change – Biochar, Tool for Climate Change Mitigation and Soil Management*. New York, Heidelberg, Dordrecht, London: Springer.
- Levine, J. S., Matter, J. M., Goldberg, D., Cook, A. and Lackner, K. S. (2007) "Gravitational trapping of carbon dioxide in deep sea sediments: permeability, buoyancy, and geomechanical analysis", *Geophysical Research Letters*, 34(24).
- Lin, A. C. (2009) "Geoengineering governance", *Issues in Legal Scholarship*, 8(1).
- Lin, A.C. (2012) "Does Geoengineering Present a Moral Hazard", *UC Davis Legal Studies Research Paper*, (312).
- Lin, A.C. (2013) "Does Geoengineering Present a Moral Hazard?", *Ecology Law Quarterly*, Forthcoming, 40, pp. 673–712.
- Link, P. M., Brzoska, M., Maas, A., Neuneck, G. and Scheffran, J. (2013) "Possible implications of climate engineering for peace and security", *Bulletin of the American Meteorological Society*, 94(2), pp. ES13–ES16.
- Liss, P., Chuck, A., Bakker, D. and Turner, S. (2005) "Ocean fertilization with iron: effects on climate and air quality", *Tellus B*, 57(3), pp. 269–271.
- Liu, S. C., Fu, C., Shiu, C. J., Chen, J. P. and Wu, F. (2009) "Temperature dependence of global precipitation extremes", *Geophysical Research Letters*, 36(17).
- Lloyd, I. D. and Oppenheimer, M. (2011) "On the Design of an International Governance Framework for Geoengineering", *Global Environmental Politics*, (609), pp. 1–25.
- Lobell, D. B., Hammer, G. L., McLean, G., Messina, C., Roberts, M. J. and Schlenker, W. (2013) "The critical role of extreme heat for maize production in the United States", *Nature Climate Change*, 3(5), pp. 497–501.
- Lobell, D. B., Schlenker, W. and Costa-Roberts, J. (2011) "Climate trends and global crop production since 1980", *Science*, 333(6042), pp. 616–620.
- London Convention and Protocol (2006) *Resolution LP.1(1) of 2 November 2006, Amendment to Include CO₂ Sequestration in Sub-seabed Geological Formations in Annex 1 to the London Protocol*.
- London Convention and Protocol (2008) *Resolution LC-LP.1 of 31 October 2008 on the Regulation of Ocean Fertilization, LC 30/16, Annex 6*.
- London Convention and Protocol (2009) *Resolution LP.3(4) of 30 October 2009 on the Amendment to Article 6 of the London Protocol*.
- London Convention and Protocol (2010) *Resolution LC-LP.2 of 14 October 2010 on the Assessment Framework for Scientific Research Involving Ocean Fertilization*.
- Lovelock, J. E. and Rapley, C. G. (2007) "Ocean pipes could help the Earth to cure itself", *Nature*, 449.
- Lovett, A. A., Sünnerberg, G. M., Richter, G. M., Dailey, A. G., Riche, A. B. and Karp, A. (2009) "Land use implications of increased biomass production identified by GIS-based suitability and yield mapping for miscanthus in England", *BioEnergy Research*, 2(1–2), pp. 17–28.
- Luckow, P., Wise, M. A., Dooley, J. J. and Kim, S. H. (2010) "Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO₂ concentration limit scenarios", *International Journal of Greenhouse Gas Control*, 4(5), pp. 865–877.
- Luderer, G., Pietzcker, R. C., Krieglner, E., Haller, M. and Bauer, N. (2012) "Asia's role in mitigating climate change: A technology and sector specific analysis with ReMIND-R", *Energy Economics*, 34, pp. S378–S390.

- Lunt, D. J., Ridgwell, A., Valdes, P. J. and Seale, A. (2008) “Sunshade World: A fully coupled GCM evaluation of the climatic impacts of geoengineering”, *Geophysical Research Letters*, 35(12), pp. L12710.
- Maas, A. and Scheffran, J. (2012) “Climate conflicts 2.0? Climate engineering as a challenge for international peace and security”, *Security and Peace*, 30(4), pp. 193–200.
- MacCracken, M., Barrett, S., Barry, R., Crutzen, P., Hamburg, S., Lampitt, R., Liverman, D., Lovejoy, T., McBean, G., Parson, E., Seidel, S., Shepherd, J., Somerville, R. and Wigley, T. M. L. (2010) “The Asilomar Conference Recommendations on Principles for Research into Climate Engineering Techniques”, *Asilomar International Conference on Climate Intervention* Pacific Grove, CA, March 22–26, 2010: Climate Change Institute.
- MacCracken, M. C., Shin, H. J., Caldeira, K. and Ban-Weiss, G. (2012) “Climate response to imposed solar radiation reductions in high latitudes”, *Earth System Dynamics Discussions*, 3(2), pp. 715–757.
- MacMartin, D. G., Caldeira, K. and Keith, D. W. (2014) “Solar geoengineering to limit the rate of temperature change”, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2031), pp. 20140134.
- MacMartin, D. G., Keith, D. W., Kravitz, B. and Caldeira, K. (2012) “Management of trade-offs in geoengineering through optimal choice of non-uniform radiative forcing”, *Nature Climate Change*, 3, pp. 365–368.
- MacMynowski, D. G., Keith, D. W., Caldeira, K. and Shin, H.-J. (2011) “Can we test geoengineering?”, *Energy and Environmental Science*, 4(12), pp. 5044–5052.
- Macnaghten, P. and Owen, R. (2011) “Environmental science: good governance for geoengineering”, *Nature*, 479(7373), pp. 293.
- Macnaghten, P. and Szerszynski, B. (2013) “Living the global social experiment: an analysis of public discourse on solar radiation management and its implications for governance”, *Global Environmental Change-Human and Policy Dimensions*, 23(2), pp. 465–474.
- March, J. G. and Olsen, J. P. (1998) “The institutional dynamics of international political orders”, *International Organization*, 52(04), pp. 943–969.
- Markus, T. and Ginzky, H. (2011) “Regulating climate engineering: paradigmatic aspects of the regulation of ocean fertilization”, *Carbon and Climate Law Review (CCLR)*, (4), pp. 477–490.
- Markusson, N., Ginn, F., Singh Ghaleigh, N. and Scott, V. (2014) “‘In case of emergency press here’: framing geoengineering as a response to dangerous climate change”, *Wiley Interdisciplinary Reviews: Climate Change*, 5(2), pp. 281–290.
- Marshall, M. (2013) “Get cirrus in the fight against climate change”, *New Scientist Environment*, (no. 2901), pp. 14.
- Martin, J. H., Gordon, R. M. and Fitzwater, S. E. (1990) “Iron in Antarctic waters”, *Nature*, 345, pp. 156–158.
- Martin, P., Rutgers van der Loeff, M., Cassar, N., Vandromme, P., d’Ovidio, F., Stemann, L., Rengarajan, R., Soares, M., González, H. E. and Ebersbach, F. (2013) “Iron fertilization enhanced net community production but not downward particle flux during the Southern Ocean iron fertilization experiment LOHAFEX”, *Global Biogeochemical Cycles*, 27(3), pp. 871–881.
- Maruyama, S., Taira, K. and Ishikawa, M. (2000) *Method and equipment for pumping up deep water as well as ocean greening method using them* Patent no. JP2001-336479.
- Mathews, J. A. and Tan, H. (2009) “Biofuels and indirect land use change effects: the debate continues”, *Biofuels, Bioproducts and Biorefining*, 3(3), pp. 305–317.
- Matter, J. M. and Kelemen, P. B. (2009) “Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation”, *Nature Geoscience*, 2(12), pp. 837–841.

- Matthews, H. D. and Caldeira, K. (2007) “Transient climate–carbon simulations of planetary geoengineering”, *Proceedings of the National Academy of Sciences of the United States of America*, 104(24), pp. 9949–9954.
- Matthews, H. D. and Turner, S. E. (2009) “Of mongooses and mitigation: ecological analogues to geoengineering”, *Environmental Research Letters*, 4(4), pp. 045105.
- McClellan, J., Keith, D. W. and Apt, J. (2012) “Cost analysis of stratospheric albedo modification delivery systems”, *Environmental Research Letters*, 7(3), pp. 034019.
- McGlashan, N., Workman, M., Caldecott, B. and Shah, N. (2012) *Negative Emissions Technologies*: Grantham Institute. Available at: <https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Briefing%20Papers/Briefing%20Paper%208.pdf>.
- McGrail, B. P., Schaef, H. T., Ho, A. M., Chien, Y. J., Dooley, J. J. and Davidson, C. L. (2006) “Potential for carbon dioxide sequestration in flood basalts”, *Journal of Geophysical Research: Solid Earth*, 111(12).
- McLaren, D. (2012) “Governance and equity in the development and deployment of negative emissions technologies”, *Paper presented at Lund Conference on Earth System Governance, Lund April 18–20, 2012*.
- McNutt, M. K., Abdalati, W., Caldeira, K., Doney, S. C., Falkowski, P. G., Fetter, S., Fleming, J. R., Hamburg, S. P., Morgan, M. G., Penner, J. E., Pierrehumbert, R. T., Rasch, P. J., Russell, L. M., Snow, J. T., Titley, D. W. and Wilcox, J. (2015a) *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*, Washington, DC: National Research Council of the National Academies.
- McNutt, M. K., Abdalati, W., Caldeira, K., Doney, S. C., Falkowski, P. G., Fetter, S., Fleming, J. R., Hamburg, S. P., Morgan, M. G., Penner, J. E., Pierrehumbert, R. T., Rasch, P. J., Russell, L. M., Snow, J. T., Titley, D. W. and Wilcox, J. (2015b) *Climate Intervention: Reflecting Sunlight to Cool Earth*, Washington, DC: National Research Council of the National Academies.
- Meehl, G. A. and Tebaldi, C. (2004) “More intense, more frequent, and longer lasting heat waves in the 21st century”, *Science*, 305(5686), pp. 994–997.
- Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J. F., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Riahi, K., Thomson, A., Velders, G. J. M. and van Vuuren, D. P. P. (2011) “The RCP greenhouse gas concentrations and their extensions from 1765 to 2300”, *Climatic Change*, 109(1–2), pp. 213–241.
- Mercado, L. M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M. and Cox, P. M. (2009) “Impact of changes in diffuse radiation on the global land carbon sink”, *Nature*, 458(7241), pp. 1014–1017.
- Mercer, A. M., Keith, D. W. and Sharp, J. D. (2011) “Public understanding of solar radiation management”, *Environmental Research Letters*, 6(4), pp. 044006.
- Metz, B., Davidson, O., de Coninck, H., Loos, M. and Meyer, L. A. (2005) *IPCC Special Report on Carbon Dioxide Capture and Storage: Prepared by Working Group III of the Intergovernmental Panel on Climate Change: (Intergovernmental Panel on Climate Change)*. Cambridge, UK and New York, USA: Cambridge University Press.
- Meyer, L. H. (2008) *Intergenerational Justice*. *Stanford Encyclopedia of Philosophy*.
- Meyer, S., Bright, R. M., Fischer, D., Schulz, H. and Glaser, B. (2012) “Albedo impact on the suitability of biochar systems to mitigate global warming”, *Environmental Science and Technology*, 46(22), pp. 12726–12734.
- Millard-Ball, A. (2012) “The Tuvalu syndrome: can geoengineering solve climate’s collective action problem?”, *Climatic Change*, 110(3–4), pp. 1047–1066.
- Mitchell, D. L. and Finnegan, W. (2009) “Modification of cirrus clouds to reduce global warming”, *Environmental Research Letters*, 4(4), pp. 045102.

- Mitchell, D. L., Mishra, S. and Lawson, R. P. (2011) "Cirrus Clouds and Climate Engineering: New Findings on Ice Nucleation and Theoretical Basis", in Carayannis, E.G. (ed.) *Planet Earth 2011 – Global Warming Challenges and Opportunities for Policy and Practice*: InTech, pp. 257-288.
- Moellendorf, D. (2002) *Cosmopolitan Justice*. Oxford and Boulder, Col: Westview Press.
- Mooney, P., Wetter, K. J. and Bronson, D. (2012) "Darken the sky and whiten the earth – The dangers of geoengineering", *Development Dialogue*, 3, pp. 210–237.
- Moore, J. C., Jevrejeva, S. and Grinsted, A. (2010) "Efficacy of geoengineering to limit 21st century sea-level rise", *Proceedings of the National Academy of Sciences of the United States of America*, 107(36), pp. 15699–15703.
- Moreno-Cruz, J. and Keith, D. (2013) "Climate policy under uncertainty: a case for solar geoengineering", *Climatic Change*, 121(3), pp. 1–14.
- Moreno-Cruz, J., Ricke, K. and Keith, D. (2011) "A simple model to account for regional inequalities in the effectiveness of solar radiation management", *Climatic Change*, 110(3-4), pp. 1–20.
- Moreno-Cruz, J. B. and Smulders, S. (2010) "Revisiting the Economics of Climate Change: The Role of Geoengineering", *The Selected Works of Juan B. Moreno-Cruz*. Available at: <http://works.bepress.com/morenocruz/4>.
- Moreshet, S., Cohen, Y. and Fuchs, M. (1979) "Effect of increasing foliage reflectance on yield, growth, and physiological behavior of a aryland cotton crop", *Crop Science*, 19(6), pp. 863–868.
- Morgan, M. G., Nordhaus, R. R. and Gottlieb, P. (2013) "Needed: research guidelines for solar radiation management", *Issues in Science and Technology*, Spring 2013(3), pp. 37–44.
- Morgan, M. G. and Ricke, K. (2010) *Cooling the Earth through SRM: The need for research and an approach to its governance. An opinion piece for International Risk Governance Council*, Available at: http://irgc.org/wp-content/uploads/2012/04/SRM_Opinion_Piece_web.pdf.
- Morrow, D. R. "Ethical Principles for Trials of Climate Intervention Technologies", *Asilomar International Conference on Climate Intervention Technologies*, Asilomar, CA, March 23, 2010.
- Morrow, D. R., Kopp, R. E. and Oppenheimer, M. (2009) "Toward ethical norms and institutions for climate engineering research", *Environmental Research Letters*, 4(4), pp. 045106.
- Moss, R. H., Babiker, M., Brinkman, S., Calvo, E., Carter, T. R., Edmonds, J. A., Elgizouli, I., Emori, S., Erda, L., Hibbard, K. A., Jones, R., Kainuma, M., Kelleher, J., Lamarque, J. F., Manning, M., Matthews, B., Meehl, J., Meyer, L., Mitchell, J., Nakicenovic, N., O'Neill, B. C., Pichs, R., Riahi, K., Rose, S. K., Runci, P., Stouffer, R. J., Van Vuuren, D. P., Weyant, J. P., Wilbanks, T. J., Van Ypersele, J. P. and Zurek, M. (2008) *Towards new Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies*, Geneva: IPCC. Available at: <https://www.ipcc.ch/pdf/supporting-material/expert-meeting-ts-scenarios.pdf>.
- Mueller, K., Cao, L., Caldeira, K. and Jain, A. (2004) "Differing methods of accounting ocean carbon sequestration efficiency", *Journal of Geophysical Research: Oceans* 109(C12).
- Muri, H., Kristjánsson, J. E., Storelvmo, T. and Pfeffer, M. A. (2014) "The climatic effects of modifying cirrus clouds in a climate engineering framework", *Journal of Geophysical Research: Atmospheres*, 119(7), pp. 2013JD021063.
- Muri, H., Niemeier, U. and Kristjánsson, J. E. (2015) "Tropical rainforest response to marine sky brightening climate engineering", *Geophysical Research Letters*, 42(8), pp. 2951–2960.
- Naik, V., Wuebbles, D. J., DeLucia, E. H. and Foley, J. A. (2003) "Influence of geoengineered climate on the terrestrial biosphere", *Environmental Management*, 32(3), pp. 373–381.
- Niemeier, U., Schmidt, H., Alterskjær, K. and Kristjánsson, J. E. (2013) "Solar irradiance reduction via climate engineering: impact of different techniques on the energy balance and the hydrological cycle", *Journal of Geophysical Research-Atmospheres*, 118(21), pp. 11,905–11,917.

- Niemeier, U., Schmidt, H. and Timmreck, C. (2011) “The dependency of geoengineered sulfate aerosol on the emission strategy”, *Atmospheric Science Letters*, 12(2), pp. 189–194.
- Niemeier, U. and Timmreck, C. (2015) “What is the limit of stratospheric sulfur climate engineering?”, *Atmospheric Chemistry and Physics Discussions*, 15(7), pp. 10939–10969.
- NOAA (2012) *Ethics and Issues Surrounding Geo-engineering to Mitigate Climate Change*.: NOAA
Available at: <http://www.climatewatch.noaa.gov/video/2012/ethics-and-issues-surrounding-geo-engineering-to-mitigate-climate-change>.
- Nordhaus, W. D. (2008) *A Question of Balance: Weighing the Options on Global Warming Policies*.
United States: Yale University Press
- Nordhaus, W. D. and Boyer, J. (2000) *Warming the World: Economic Models of Global Warming*.
Cambridge MA: MIT Press.
- Oldham, P., Szerszynski, B., Stilgoe, J., Brown, C., Eacott, B. and Yuille, A. (2014) “Mapping the landscape of climate engineering”, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2031), pp. 20140065.
- Oleson, K. W., Bonan, G. B. and Feddema, J. (2010) “Effects of white roofs on urban temperature in a global climate model”, *Geophysical Research Letters*, 37, pp. L03701.
- Olgun, N., Duggen, S., Langmann, B., Hort, M., Waythomas, C. F., Hoffmann, L. and Croot, P. (2013) “Geochemical evidence of oceanic iron fertilization by the Kasatochi volcanic eruption in 2008 and the potential impacts on Pacific sockeye salmon.”, *Marine Ecology Progress Series*, 488, pp. 81–88.
- Oliveira, P. J. C., Davin, E. L., Levis, S. and Seneviratne, S. I. (2011) “Vegetation-mediated impacts of trends in global radiation on land hydrology: A global sensitivity study”, *Global Change Biology*, 17(11), pp. 3453–3467.
- Olson, R. L. (2011) *Geoengineering for Decision Makers*, Washington and DC.: Woodrow Wilson Center Report. Available at: http://www.wilsoncenter.org/event/report-release-geoengineering-for-decision-makers#field_files.
- Oltra, C., Sala, R., Sola, R., Di Masso, M. and Rowe, G., & Frewer, L. J. (2010) “Lay perceptions of carbon capture and storage technology”, *International Journal of Greenhouse Gas Control*, 4(4), pp. 698–706.
- Ornstein, L., Aleinov, I. and Rind, D. (2009) “Irrigated afforestation of the Sahara and Australian Outback to end global warming”, *Climatic Change*, 97(3–4), pp. 409–437.
- Orr, J. C. (2004) *Modelling of ocean storage of CO₂: The GOSAC study*. Cheltenham, UK: International Energy Agency Greenhouse Gas R&D Programme (IEAGHG).
- Oschlies, A., Koeve, W., Rickels, W. and Rehdanz, K. (2010a) “Side effects and accounting aspects of hypothetical large-scale Southern Ocean iron fertilization”, *Biogeosciences*, 7(12), pp. 4017–4035.
- Oschlies, A., Pahlow, M., Yool, A. and Matear, R. (2010b) “Climate engineering by artificial ocean upwelling: channelling the sorcerer’s apprentice”, *Geophysical Research Letters*, 37(4).
- Ott, K. (2012) “Might Solar Radiation Management Constitute a Dilemma?”, in Preston, C.J. (ed.) *Engineering the climate: The Ethics of Solar Radiation Management*. Plymouth: Lexington Books, pp. 33–42.
- Page, E. (2006) *Climate Change, Justice and Future Generations*. Cheltenham: Edward Elgar.
- Page, E. (2008) “Distributing the burdens of climate change”, *Environmental Politics*, 17, pp. 556–575.
- Page, E. (2012) “Give it up for climate change: a defence of the beneficiary pays principle”, *International Theory*, 4(2), pp. 300–30.

- Palmgren, C. R., Morgan, M. G., Bruine de Bruin, W. and Keith, D. W. (2004) “Initial public perceptions of deep geological and oceanic disposal of carbon dioxide”, *Environmental Science and Technology*, 38(24), pp. 6441–6450.
- Paludan-Müller, G., Saxe, H., Pedersen, L. B. and Randrup, T. B. (2002) “Differences in salt sensitivity of four deciduous tree species to soil or airborne salt”, *Physiologia Plantarum*, 114(2), pp. 223–230.
- Parker, A. (2014) “Governing solar geoengineering research as it leaves the laboratory”, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2031), pp. 20140173.
- Parkhill, K. and Pidgeon, N. 2011 Public Engagement on Geoengineering Research: Preliminary Report on the SPICE Deliberative Workshops. *Working Paper. Cardiff: School of Psychology*. Cardiff, UK.
- Parson, E. A. and Keith, D. W. (2013) “End the deadlock on governance of geoengineering research”, *Science*, 339(6125), pp. 1278–1279.
- Partanen, A.-I., Kokkola, H., Romakkaniemi, S., Kerminen, V.-M., Lehtinen, K. E. J., Bergman, T., Arola, A. and Korhonen, H. (2012) “Direct and indirect effects of sea spray geoengineering and the role of injected particle size”, *Journal of Geophysical Research: Atmospheres*, 117(D2), pp. D02203.
- Peng, S.-S., Piao, S., Zeng, Z., Ciais, P., Zhou, L., Li, L. Z. X., Myneni, R. B., Yin, Y. and Zeng, H. (2014) “Afforestation in China cools local land surface temperature”, *Proceedings of the National Academy of Sciences of the United States of America* 111(8), pp. 2915–2919.
- Pidgeon, N., Corner, A., Parkhill, K., Spence, A., Butler, C. and Poortinga, W. (2012) “Exploring early responses to geoengineering”, *Philosophical Transactions of the Royal Society A*, 370(1974), pp. 4176–4196.
- Pidgeon, N., Parkhill, K., Corner, A. and Vaughan, N. (2013) “Deliberating stratospheric aerosols for climate geoengineering and the SPICE project”, *Nature Climate Change*, 3(5), pp. 451–457.
- Pierce, J. R., Weisenstein, D. K., Heckendorn, P., Peter, T. and Keith, D. W. (2010) “Efficient formation of stratospheric aerosol for climate engineering by emission of condensable vapor from aircraft”, *Geophysical Research Letters*, 37.
- Pires, J., Alvim-Ferraz, M., Martins, F. and Simoes, M. (2012) “Carbon dioxide capture from flue gases using microalgae: engineering aspects and biorefinery concept”, *Renewable and Sustainable Energy Reviews*, 16(5), pp. 3043–3053.
- Plevin, R. J., O’Hare, M., Jones, A. D., Torn, M. S. and Gibbs, H. K. (2010) “Greenhouse gas emissions from biofuels’ indirect land use change are uncertain but may be much greater than previously estimated”, *Environmental Science and Technology-Columbus*, 44(21), pp. 8015.
- Pogge, T. (2002) *World Poverty and Human Rights: Cosmopolitan Responsibilities and Reforms*. London: Polity Press.
- Pollard, R T, et al. (2009) “Southern Ocean deep-water carbon export enhanced by natural iron fertilization”, *Nature*, 457, pp. 577–581.
- Pongratz, J., Lobell, D. B., Cao, L. and Caldeira, K. (2012) “Crop yields in a geoengineered climate”, *Nature Climate Change*, 2(2), pp. 101–105.
- Pope, F. D., Braesicke, P., Grainger, R. G., Kalberer, M., Watson, I. M., Davidson, P. J. and Cox, R. A. (2012) “Stratospheric aerosol particles and solar-radiation management”, *Nature Climate Change*, 2(10), pp. 713–719.

- Post, E., Mads C. Forchhammer, M. Sydonia Bret-Harte, Terry V. Callaghan, Torben R. Christensen, Bo Elberling, Anthony D. Fox, Olivier Gilg, David S. Hik, Toke T. Høye, Rolf A. Ims, Erik Jeppesen, David R. Klein, Jesper Madsen, A. David McGuire, Søren Rysgaard, Daniel E. Schindler, Ian Stirling, Mikkel P. Tamstorf, Nicholas J.C. Tyler, Rene van der Wal, Jeffrey Welker, Philip A. Wookey, Niels Martin Schmidt and Austrup, P. (2009) “Ecological dynamics across the Arctic associated with recent climate change”, *Science*, 325(5946), pp. 1355–1358.
- Poumadère, M., Bertoldo, R. and Samadi, J. (2011) “Public perceptions and governance of controversial technologies to tackle climate change: nuclear power, carbon capture and storage, wind, and geoengineering”, *Wiley Interdisciplinary Reviews: Climate Change*, 2(5), pp. 712–727.
- Powell, T. W. R. and Lenton, T. M. (2012) “Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends”, *Energy and Environmental Science* 5(8), pp. 8116–8133.
- Preston, C. J. (2012) “Solar Radiation Management and Vulnerable Populations: The Moral Deficit and its Prospects”, in Preston, C. J. (ed.) *Engineering the Climate: The Ethics of Solar Radiation Management*. Lanham, MD: Lexington Press, pp. 77–94.
- Preston, C. J. (2013) “Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and carbon dioxide removal”, *Wiley Interdisciplinary Reviews: Climate Change*, 4(1), pp. 23–37.
- Pringle, K. J., Carslaw, K. S., Fan, T., Mann, G. W., Hill, A., Stier, P., Zhang, K. and Tost, H. (2012) “A multi-model assessment of the impact of sea spray geoengineering on cloud droplet number”, *Atmospheric Chemistry and Physics*, 12(23), pp. 11647–11663.
- Proelss, A. (2009) *Legal Opinion on the Legality of the LOHAFEX Marine Research Experiment under International Law*, Kiel: Walther-Schücking-Institut for International Law.
- Proelss, A. (2010) “International environmental law and the challenge of climate change”, *German Yearbook of International Law*, 53, pp. 65–88.
- Proelss, A. (2012) “Geoengineering and international law”, *S+F Sicherheit und Frieden*, 30(4), pp. 205–211.
- Proelss, A. (2013) “The ‘Erika III’ Package: Progress or Breach of International Law?”, in Koch, H.-J., König, D., Sanden, J. & Verheyen, R. (eds.) *Climate Change and Environmental Hazards Related to Shipping: An International Legal Framework*. Leiden: Martinus Nijhoff Publishers.
- Rahaman, M. S. A., Cheng, L.-H., Xu, X.-H., Zhang, L. and Chen, H.-L. (2011) “A review of carbon dioxide capture and utilization by membrane integrated microalgal cultivation processes”, *Renewable and Sustainable Energy Reviews*, 15(8), pp. 4002–4012.
- Ralston, S. J. (2009) “Engineering an artful and ethical solution to the problem of global warming”, *Review of Policy Research*, 26(6), pp. 821–837.
- Rasch, P. J. (2010) *Geoengineering II: The Scientific Basis and Engineering Challenges*. Washington, DC: Committee on Science, Space, and Technology. Subcommittee on Energy.
- Rasch, P. J., Latham, J. and Chen, C.-C. (2009) “Geoengineering by cloud seeding: influence on sea ice and climate system”, *Environmental Research Letters*, 4(4), pp. 045112.
- Rasch, P. J., Tilmes, S., Turco, R. P., Robock, A., Oman, L., Chen, C. C., Stenchikov, G. L. and Garcia, R. R. (2008) “An overview of geoengineering of climate using stratospheric sulphate aerosols”, *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, 366(1882), pp. 4007–4037.
- Rayfuse, R., Lawrence, M. G. and Gjerde, K. M. (2008) “Ocean fertilisation and climate change: the need to regulate emerging high sea uses”, *International Journal of Marine and Coastal Law*, 23, pp. 297–326.

- Rayner, S., Heyward, C., Kruger, T., Pidgeon, N., Redgwell, C. and Savulescu, J. (2013) “The Oxford Principles”, *Climatic Change*, 121(3), pp. 499–512.
- Rayner, S., Redgwell, C., Savulescu, J., Pidgeon, N. and Kruger, T. (2009) *Memorandum on draft principles for the conduct of geoengineering research*. London, UK: House of Commons Science and Technology Committee enquiry into The Regulation of Geoengineering.
- Reichwein, D. (2012) Basic Instruments to Tackle Risks and Uncertainties in International Environmental Law. In: Amelung, D. & al., e. (eds.) Beyond calculation. *Climate Engineering risks from a social sciences perspective*. Heidelberg: Forum Marsilius Kolleg.
- Reichwein, D., Hubert, A.-M., Irvine, P. J., Benduhn, F. and Lawrence, M. G. (2015 in review) “State responsibility for environmental harm from climate engineering”, *Carbon and Climate Law Review*.
- Reynolds, J. (2011) “The regulation of climate engineering”, *Law, Innovation and Technology*, 3(1), pp. 113–136.
- Reynolds and Fleurke (2013) “Climate engineering research: a precautionary response to climate change?”, *Carbon and Climate Law Review* (2/2013), pp. 101–107.
- Ricke, K., Allen, M. R., Ingram, W., Keith, D. and Granger, M. M. “Global and Regional Climate Responses Solar Radiation Management: Results from a climateprediction. net Geoengineering Experiment”. *EGU General Assembly 2010*, Vienna, Austria, 2–7 May, 11719–11719.
- Ricke, K., Morgan, M. G. and Allen, M. R. (2010) “Regional climate response to solar-radiation management”, *Nature Geoscience*, 3(8), pp. 537–541.
- Rickels, W., Klepper, G., Dovern, J., Betz, G., Brachatzek, N., Cacean, S., Güssow, K., Heintzenberg, J., Hiller, S., Hoose, C., Leisner, T., Oschlies, A., Platt, U., Proelß, A., Renn, O., Schäfer, S. and Zürn, M. (2011) *Large-Scale Intentional Interventions into the Climate System? Assessing the Climate Engineering Debate. Scoping Report Conducted on Behalf of the German Federal Ministry of Education and Research*, Kiel: Kiel Earth Institute. Available at: <http://www.kiel-earth-institute.de/projekte/forschung/resolveUId/d809088ae83ba7e3873f9e71f59f243d>.
- Rickels, W. and Lontzek, T. (2012) “Optimal Global Carbon Management with Ocean Sequestration”, *Oxford Economic Papers*, in press.
- Rickels, W., Rehdanz, K. and Oschlies, A. (2010) “Methods for greenhouse gas offset accounting: A case study of ocean iron fertilization”, *Ecological Economics*, 69(12), pp. 2495–2509.
- Ridgwell, A., Freeman, C. and Lampitt, R. (2012) “Geoengineering: taking control of our planet’s climate?”, *Philosophical Transactions of the Royal Society A: Physical, Mathematical and Engineering Sciences*, 370(1974), pp. 4163–5.
- Ridgwell, A., Singarayer, J. S., Hetherington, A. M. and Valdes, P. J. (2009) “Tackling regional climate change by leaf albedo bio-geoengineering”, *Current Biology*, 19(2), pp. 146–150.
- Robock, A. (2000) “Volcanic eruptions and climate”, *Reviews of Geophysics*, 38(2), pp. 191–219.
- Robock, A. (2008) “20 reasons why geoengineering may be a bad idea”, *Bulletin of the Atomic Scientists*, 64(2), pp. 14–18.
- Robock, A. (2011) “Geoengineering research”, *Issues in Science and Technology*, 27(2), pp. 5–9.
- Robock, A. (2012) “Is geoengineering research ethical?”, *S+F Sicherheit und Frieden*, 30(4), pp. 226–229.
- Robock, A., Bunzl, M., Kravitz, B. and Stenchikov, G. L. (2010) “A test for geoengineering?”, *Science*, 327(5965), pp. 530–531.
- Robock, A., Marquardt, A., Kravitz, B. and Stenchikov, G. (2009) “Benefits, risks, and costs of stratospheric geoengineering”, *Geophysical Research Letters*, 36, pp. 9.

- Robock, A., Oman, L. and Stenchikov, G. L. (2008) “Regional climate responses to geoengineering with tropical and Arctic SO₂ injections”, *Journal of Geophysical Research-Atmospheres*, 113(D16), pp. D16101.
- Roderick, M. L., Farquhar, G. D., Berry, S. L. and Noble, I. R. (2001) “On the direct effect of clouds and atmospheric particles on the productivity and structure of vegetation”, *Oecologia*, 129(1), pp. 21–30.
- Rowe, G. and Frewer, L. J. (2005) “A typology of public engagement mechanisms. “, *Science Technology and Human Values*, 30(2), pp. 251–290.
- RWE (2012) *Tilbury Biomass Power Station*. Available at: <http://www.rwe.com/web/cms/en/1763234/rwe-npower/about-us/our-businesses/power-generation/tilbury/tilbury-biomass-power-station/>.
- Sala, O. E., Chapin III, F. S., Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L. F., Jackson, R. B., Kinzig, A., Leemans, R., Lodge, D. M., Mooney, H. A., Oesterheld, M., Poff, N. L., Sykes, M. T., Walker, B. H. and Wall, D. H. (2000) “Global biodiversity scenarios for the year 2100”, *Science*, 287(5459), pp. 1770–1774.
- Salter, S., Sortino, G. and Latham, J. (2008) “Sea-going hardware for the cloud albedo method of reversing global warming”, *Philosophical Transactions of the Royal Society A-Mathematical Physical and Engineering Sciences*, 366(1882), pp. 3989–4006.
- Sarmiento, J., Slater, R. D., Dunne, J., Gnanadesikan, A. and Hiscock, M. R. (2010) “Efficiency of small scale carbon mitigation by patch iron fertilization”, *Biogeoscience*, 7, pp. 3593–3624.
- Sassen, K., O’C Starr, D., Mace, G. G., Poellot, M. R., Melfi, S. H., Eberhard, W. L., Spinhirne, J. D., Eloranta, E., Hagen, D. E. and Hallett, J. (1995) “The 5–6 December 1991 FIRE IFO II jet stream cirrus case study: possible influences of volcanic aerosols”, *Journal of the Atmospheric Sciences*, 52(1), pp. 97–123.
- Sathaye, K. J., Hesse, M. A., Cassidy, M. and Stockli, D. F. (2014) “Constraints on the magnitude and rate of CO₂ dissolution at Bravo Dome natural gas field”, *Proceedings of the National Academy of Sciences*, 111(43), pp. 15332–15337.
- Sathre, R., Chester, M., Cain, J. and Masanet, E. (2011) “A framework for environmental assessment of CO₂ capture and storage systems. 7th Biennial International Workshop: Advances in Energy Studies”, *Energy*, 37(1), pp. 540–548.
- Savile, C. K. and Lalonde, J. J. (2011) “Biotechnology for the acceleration of carbon dioxide capture and sequestration”, *Current Opinion in Biotechnology*, 22(6), pp. 818–823.
- Schaeffer, M., Hare, W., Rahmstorf, S. and Vermeer, M. (2012) “Long-term sea-level rise implied by 1.5C and 2C warming levels”, *Nature Climate Change*, 2(12), pp. 867–870.
- Schäfer, S., Irvine, P. J., Hubert, A.-M., Reichwein, D., Low, S., Stelzer, H., Maas, A. and Lawrence, M. G. (2013a) “Field tests of solar climate engineering”, *Nature Climate Change*, 3(9), pp. 766–766.
- Schäfer, S. and Low, S. (2014) “Asilomar moments: formative framings in recombinant DNA and solar climate engineering research”, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2031), pp. 20140064.
- Schäfer, S., Maas, A. and Irvine, P. J. (2013b) “Bridging the gaps in interdisciplinary research on solar radiation management”, *GAIA-Ecological Perspectives for Science and Society*, 22(4), pp. 242–247.
- Schäfer, S., Maas, A., Stelzer, H. and Lawrence, M. G. (2014) “Earth’s future in the Anthropocene: technological interventions between piecemeal and utopian social engineering”, *Earth’s Future*, 2(4), pp. 239–243.
- Schallock, J. (2015) *Effektivitätsstudie zur Injektion von Sulfataerosol in die Stratosphäre*. Diploma, Johannes Gutenberg-Universität Mainz, Mainz.
- Scheffran, J. and Cannaday, T. (2013) “Resistance Against Climate Change Policies: The Conflict Potential of Non-fossil Energy Paths and CE.”, in Balazs, B., Burnley, C., Comardicea, I., Maas, A. & Roffey, R. (eds.) *Global Environmental Change: New Drivers for Resistance, Crime and Terrorism?* Baden-Baden: Nomos.

- Schelling, T. C. (1996) “The Economic Diplomacy of Geoengineering”, *Climatic Change*, 33(3), pp. 303–307.
- Schmidt, H., Alterskjær, K., Bou Karam, D., Boucher, O., Jones, A., Kristjánsson, J. E., Niemeier, U., Schulz, M., Aaheim, A., Benduhn, F., Lawrence, M. and Timmreck, C. (2012a) “Solar irradiance reduction to counteract radiative forcing from a quadrupling of CO₂: climate responses simulated by four earth system models”, *Earth System Dynamics*, 3(1), pp. 63–78.
- Schmidt, H., Niemeier, U., Timmreck, C., Aaheim, A., Romstad, B., Wei, T., Kristjánsson, J. E., Alterskjær, K., Muri, H. Ø., Lawrence, M. G., Benduhn, F., Schulz, M., Bou Karam, D. and Boucher, O. (2012b) *The FP7 Project IMPLICC: Implications and Risks of Engineering Solar Radiation to Limit Climate Change. Final Publishable Summary Report*. Available at: http://implicc.zmaw.de/fileadmin/user_upload/implicc/other_documents/implicc_final_report_20121130_publishable_summary.pdf.
- Scott, D. (2012) “Geoengineering and environmental ethics”, *Nature Education Knowledge*, 3(10), pp. 10.
- Scott K. N. (2013) “Regulating ocean fertilization under international law: the risks”, *Carbon and Climate Law Review* pp. 108–116.
- Scott, V., Gilfillan, S., Markusson, N., Chalmers, H. and Haszeldine, R. S. (2013) “Last chance for carbon capture and storage”, *Nature Climate Change*, 3(2), pp. 105–111.
- Scott, V., Haszeldine, R. S., Tett, S. F. B. and Oschlies, A. (2015) “Fossil fuels in a trillion tonne world”, *Nature Climate Change*, 5(5), pp. 419–423.
- Seidel, D. J., Feingold, G., Jacobson, A. R. and Loeb, N. (2014) “Detection limits of albedo changes induced by climate engineering”, *Nature Climate Change*, 4(2), pp. 93–98.
- Shackley, S. and Sohi, S. (2011) *An assessment of the benefits and issues associated with the application of biochar to soil*: United Kingdom Department for Environment, Food and Rural Affairs, and Department of Energy and Climate Change. Available at: <http://www.biochar.org.uk/project.php?id=17>.
- Shao, Y., Mirza, M. S. and Wu, X. (2006) “CO₂ sequestration using calcium-silicate concrete”, *Canadian Journal of Civil Engineering*, 33(6), pp. 77–784.
- Shepherd, J. G. (2009) Hearing on Geoengineering. *US House of Representatives Committee on Science and Technology*.
- Shepherd, J. G., Cox, P., Haigh, J., Keith, D. W., Launder, B., Mace, G., MacKerron, G., Pyle, J., Rayner, S., Redgwell, C. and Watson, A. (2009) *Geoengineering the Climate: Science, Governance and Uncertainty*. London: The Royal Society.
- Singarayer, J. S., Ridgwell, A. and Irvine, P. (2009) “Assessing the benefits of crop albedo bio-geoengineering”, *Environmental Research Letters*, 4(4), pp. 8.
- Smetacek, V., Klaas, C., Strass, V. H., Assmy, P., Montresor, M., Cisewski, B., Savoye, N., Webb, A., d’Ovidio, F., Arrieta, J. M., Bathmann, U., Bellerby, R., Berg, G. M., Croot, P., Gonzalez, S., Henjes, J., Herndl, G. J., Hoffmann, L. J., Leach, H., Losch, M., Mills, M. M., Neill, C., Peeken, I., Rottgers, R., Sachs, O., Sauter, E., Schmidt, M. M., Schwarz, J., Terbruggen, A. and Wolf-Gladrow, D. (2012) “Deep carbon export from a Southern Ocean iron-fertilized diatom bloom”, *Nature*, 487(7407), pp. 313–319.
- Smith, P. T. (2012) “Domination and the Ethics of Solar Radiation Management”, in Preston, C. J. (ed.) *Engineering the Climate: The Ethics of Solar Radiation Management*. Plymouth: Lexington Books, pp. 43–61.
- Socolow, R., Desmond, M., Alnes, R., Balckstock, J., Bolland, O., Kaarsberg, T., Lewis, N., Mazzotti, M., Pfeffer, A., Siirola, J., Smit, B. and Wilcox, J. (2011) *Direct Air Capture of CO₂ with Chemicals: A Technology Assessment for the APS Panel on Public Affairs: American Physical Society*. Available at: <http://www.aps.org/policy/reports/assessments/upload/dac2011.pdf>.

- Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. and Miller, H. L. (2007) “Climate Change 2007: The Physical Science Basis”, in S. Solomon, D.Q., M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller (ed.) *Climate Change 2007: The Physical Science Basis. Contribution of working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge: Cambridge University Press, pp. 996 pp.
- SRMGI (2012) *Solar Radiation Management: the Governance of Research*, Available at: http://www.srmgi.org/files/2012/01/DES2391_SRMGI-report_web_11112.pdf.
- Stapleton, A. E. (1992) “Ultraviolet radiation and plants: burning questions”, *Plant Cell*, 4(11), pp. 1353–1358.
- Stenchikov, G., Hamilton, K., Stouffer, R. J., Robock, A., Ramaswamy, V., Santer, B. and Graf, H. F. (2006) “Arctic Oscillation response to volcanic eruptions in the IPCC AR4 climate models”, *Journal of Geophysical Research: Atmospheres*, 111(D7).
- Stevens, B. and Boucher, O. (2012) “Climate science: the aerosol effect”, *Nature*, 490(7418), pp. 40–41.
- Stewart, C. E., Zheng, J., Botte, J. and Cotrufo, M. F. (2013) “Co-generated fast pyrolysis biochar mitigates green-house gas emissions and increases carbon sequestration in temperate soils”, *GCB Bioenergy*, 5(2), pp. 153–164.
- Stilgoe, J., Owen, R. and Macnaghten, P. (2013) “Developing a framework for responsible innovation”, *Research Policy*, 42(9), pp. 1568–1580.
- Stirling, A. (2008) “‘Opening up’ and ‘closing down’: power, participation, and pluralism in the social appraisal of technology”, *Science, Technology, and Human Values*, 33(2), pp. 262–294.
- Stone, D. A., Allen, M. R., Stott, P. A., Pall, P., Min, S. K., Nozawa, T. and Yukimoto, S. (2009) “The detection and attribution of human influence on climate”, *Annual Review of Environment and Resources*, 34, pp. 1–16.
- Storelvmo, T. and Herger, N. (2014) “Cirrus cloud susceptibility to the injection of ice nuclei in the upper troposphere”, *Journal of Geophysical Research: Atmospheres*, 119(5), pp. 2375–2389.
- Storelvmo, T., Kristjansson, J. E., Muri, H., Pfeffer, M., Barahona, D. and Nenes, A. (2013) “Cirrus cloud seeding has potential to cool climate”, *Geophysical Research Letters*, 40(1), pp. 178–182.
- Stott, P. A., Stone, D. A. and Allen, M. R. (2004) “Human contribution to the European heatwave of 2003”, *Nature*, 432(7017), pp. 610–614.
- Stott, P. A., Gillett, N. P., Hegerl, G. C., Karoly, D. J., Stone, D. A., Zhang, X. and Zwiers, F. (2010) “Detection and attribution of climate change: a regional perspective”, *Wiley Interdisciplinary Reviews: Climate Change*, 1(2), pp. 192–211.
- Strand, S. E. and Benford, G. (2009) “Ocean sequestration of crop residue carbon: recycling fossil fuel carbon back to deep sediments”, *Environmental Science and Technology*, 43(4), pp. 1000–1007.
- Streibel, M., Finley, R. J., Martens, S., Greenberg, S., Möller, F. and Liebscher, A. (2014) “From pilot to demo scale—Comparing Ketzin results with the Illinois Basin-Decatur project”, *Energy Procedia*, 63, pp. 6323–6334.
- Strong, A. L., Chisholm, S. W., Miller, C. and Cullen, J. J. (2009a) “Ocean fertilization: time to move on”, *Nature*, 67, pp. 347–348.
- Strong, A. L., Cullen, J. J. and Chisholm, S. W. (2009b) “Ocean fertilization: science, policy, and commerce”, *Oceanography*, 22(Special issue 3), pp. 236–261.
- Stuart, G., Stevens, R., Partanen, A.-I., Jenkins, A., Korhonen, H., Forster, P., Spracklen, D. and Pierce, J. (2013) “Reduced efficacy of marine cloud brightening geoengineering due to in-plume aerosol coagulation: parameterization and global implications”, *Atmospheric Chemistry and Physics Discussions*, 13(7), pp. 18679–18711.

- Suzuki, T. (2005) *Method for evaluating the amount of immobilized CO₂ in artificial upwelling sea area*, Patent no. JP2003000315219. [Online].
- Svoboda, T. and Irvine, P. J. (2014) “Ethical and Technical Challenges in Compensating for Harm Due to Solar Radiation Management Geoengineering”, *Ethics, Policy and Environment*, 17(2), pp. 157–174.
- Svoboda, T., Keller, K., Goes, M. and Tuana, N. (2011) “Sulfate aerosol geoengineering: the question of justice”, *Public Affairs Quarterly*, 25(3), pp. 157–179.
- Swann, A. L. S., Fung, I. Y. and Chiang, J. C. H. (2010) “Mid-latitude afforestation shifts general circulation and tropical precipitation”, *Proceedings of the National Academy of Sciences*, 109(3), pp. 712–716.
- Swap, R., Garstang, M., Greco, S., Talbot, R. and Kållberg, P. (1992) “Saharan dust in the Amazon Basin”, *Tellus B*, 44(2), pp. 133–149.
- Swart, R. and Marinova, N. (2010) “Policy options in a worst case climate change world”, *Mitigation and Adaptation Strategies for Global Change*, 15(6), pp. 531–549.
- Tagesson, T., Mastepanov, M., Tamstorf, M. P., Eklundh, L., Schubert, P., Ekberg, A., Sigsgaard, C., Christensen, T. R. and Ström, L. (2012) “High-resolution satellite data reveal an increase in peak growing season gross primary production in a high-Arctic wet tundra ecosystem 1992–2008”, *International Journal of Applied Earth Observation and Geoinformation*, 18, pp. 407–416.
- Tedsen, E. and Homann, G. (2013) “Implementing the Precautionary Principle for Climate Engineering”, *Carbon and Climate Law Review* pp. 90–100.
- Teller, E., Hyde, R. and Ishikawa, M. (2003) *Active Stabilization of Climate: Inexpensive, Low-Risk, Near-Term Options for Preventing Global Warming and Ice Ages via Technologically Varied Solar Radiative Forcing*, Livermore, CA: Lawrence Livermore National Laboratory.
- Terwel, B. W. and Daamen, D. D. L. (2012) “Initial public reactions to carbon capture and storage (CCS): differentiating general and local views”, *Climate Policy*, 12(3), pp. 288–300.
- The Member States of the European Union (2012a) *Consolidated Version of the Treaty on European Union. Maastricht: EUR-Lex*.
- The Member States of the European Union (2012b) *Consolidated Version of the Treaty on the Functioning of the European Union. Maastricht: EUR-Lex*.
- Thornton, P. E., Doney, S. C., Lindsay, K., Moore, J. K., Mahowald, N., Randerson, J. T., Fung, I., Lamarque, J.-F., Feddesma, J. J. and Lee, Y.-H. (2009) “Carbon-nitrogen interactions regulate climate-carbon cycle feedbacks: results from an atmosphere-ocean general circulation model”, *Biogeosciences*, 6(10), pp. 2099–2120.
- Tilmes, S., Fasullo, J., Lamarque, J.-F., Marsh, D. R., Mills, M., Alterskjær, K., Muri, H., Kristjánsson, J. E., Boucher, O., Schulz, M., Cole, J. N. S., Curry, C. L., Jones, A., Haywood, J., Irvine, P. J., Ji, D., Moore, J. C., Karam, D. B., Kravitz, B., Rasch, P. J., Singh, B., Yoon, J.-H., Niemeier, U., Schmidt, H., Robock, A., Yang, S. and Watanabe, S. (2013) “The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP)”, *Journal of Geophysical Research: Atmospheres*, 118(19), pp. 11036–11058.
- Tilmes, S., Garcia, R. R., Kinnison, D. E., Gettelman, A. and Rasch, P. J. (2009) “Impact of geoengineered aerosols on the troposphere and stratosphere”, *Journal of Geophysical Research: Atmospheres*, 114, pp. 22.
- Tilmes, S., Kinnison, D. E., Garcia, R. R., Salawitch, R., Canty, T., Lee-Taylor, J., Madronich, S. and Chance, K. (2012) “Impact of very short-lived halogens on stratospheric ozone abundance and UV radiation in a geo-engineered atmosphere”, *Atmospheric Chemistry and Physics*, 12(22), pp. 10945–10955.
- Tilmes, S., Muller, R. and Salawitch, R. (2008) “The sensitivity of polar ozone depletion to proposed geoengineering schemes”, *Science*, 320(5880), pp. 1201–1204.

- Timmreck, C., Graf, H. F., Lorenz, S. J., Niemeier, U., Zanchettin, D., Matei, D., Jungclaus, J. H. and Crowley, T. J. (2010) "Aerosol size confines climate response to volcanic super-eruptions", *Geophysical Research Letters*, 37(24).
- Trick, C., Billb, B. D., Cochlan, W. P., Wells, M. L., Trainer, V. L. and Pickell, L. D. (2010) "Iron enrichment stimulates toxic diatom production in high-nitrate, low-chlorophyll areas", *Proceedings of the National Academy of Sciences*, 107(13), pp. 5887–92.
- Tsvetsinskaya, E. A., Schaaf, C. B., Gao, F., Strahler, A. H., Dickinson, R. E., Zeng, X. and Lucht, W. (2002) "Relating MODIS-derived surface albedo to soils and rock types over Northern Africa and the Arabian peninsula", *Geophysical Research Letters*, 29(9), pp. 67–1–67–4.
- Tuana, N. (2013) "The Ethical Dimensions of Geoengineering: Solar Radiation Management through Sulphate Particle Injection", *Working Paper, Geoengineering Our Climate Working Paper and Opinion Article Series*, www.geoengineeringourclimate.com.
- Tuana, N., Sriver, R. L., Svoboda, T., Olson, R., Irvine, P. J., Haqq-Misra, J. and Keller, K. (2012) "Towards integrated ethical and scientific analysis of geoengineering: a research agenda", *Ethics, Policy and Environment*, 15(2), pp. 136–157.
- Uddin, M. N. and Marshall, D. R. (1988) "Variation in epicuticular wax content in wheat", *Euphytica*, 38(1), pp. 3–9.
- UK House of Commons Science and Technology Committee (2010) *The Regulation of Geoengineering*, London: UK House of Commons. Available at: <http://www.publications.parliament.uk/pa/cm200910/cmselect/cmsctech/221/221.pdf>.
- Unruh, G. C. and Carrillo-Hermosilla, J. (2006) "Globalizing carbon lock-in", *Energy Policy*, 34(10), pp. 1185–1197.
- Upham, P. and Roberts, T. (2011a) "Public perceptions of CCS in context: Results of NearCO₂ focus groups in UK, Belgium, the Netherlands, Germany, Spain and Poland", *Energy Procedia*, 4, pp. 6338–6344.
- Upham, P. and Roberts, T. (2011b) "Public perceptions of CCS: emergent themes in pan-European focus groups and implications for communications.", *International Journal of Greenhouse Gas Control*, 5(5), pp. 1359–1367.
- Van Vuuren, D. P., Edmonds, J. A., Kainuma, M., Riahi, K. and Weyant, J. (2011a) "A special issue on the RCPs", *Climatic Change*, 109(1), pp. 1–4.
- Van Vuuren, D. P., Stehfest, E., den Elzen, M. G. J., Kram, T., van Vliet, J., Deetman, S., Isaac, M., Goldewijk, K. K., Hof, A., Beltran, A. M., Oostenrijk, R. and van Ruijven, B. (2011b) "RCP2. 6: exploring the possibility to keep global mean temperature increase below 2 C", *Climatic Change*, 109(1–2), pp. 95–116.
- Vaughan, N. E. and Lenton, T. M. (2011) "A review of climate geoengineering proposals", *Climatic Change*, 109(3–4), pp. 745–790.
- Verlaan, P. (2009) "Geo-engineering, the law of the sea, and climate change", *Carbon and Climate Law Review*, (04/2009), pp. 446–458.
- Vichi, M., Navarra, A. and Fogli, P. G. (2013) "Adjustment of the natural ocean carbon cycle to negative emission rates", *Climatic Change*, 118(1), pp. 105–118.
- Victor, D. G. (2008) "On the regulation of geoengineering", *Oxford Review of Economic Policy*, 24(2), pp. 322–336.
- Victor, D. G., Morgan, M. G., Apt, J., Steinbruner, J. and Rieke, K. L. (2013) "The truth about geoengineering: science fiction and science fact", *Foreign Affairs*, 92(2).
- Virgoe, J. (2009) "International governance of a possible geoengineering intervention to combat climate change", *Climatic Change*, 95(1–2), pp. 103–119.

- Volk, T. and Hoffert, M. I. (1985) "Ocean carbon pumps, analysis of relative strengths and efficiencies in ocean-driven atmospheric CO₂ changes", *Geophysical Monographs*, 32, pp. 99–110.
- Volodin, E. M., Kostykin, S. V. and Ryaboshapko, A. G. (2011) "Climate response to aerosol injection at different stratospheric locations", *Atmospheric Science Letters*, 12, pp. 381–385.
- Wallace, D. W. R., Law, C. S., Boyd, P. W., Collos, Y., Croot, P., Denman, K., Lam, P. J., Riebesell, U., Takeda, S. and Williamson, P. (2010) *Ocean Fertilization: A Scientific Summary for Policy Makers*, Paris: IOC/UNESCO.
- Wang, H., Rasch, P. J. and Feingold, G. (2011) "Manipulating marine stratocumulus cloud amount and albedo: a process-modelling study of aerosol-cloud-precipitation interactions in response to injection of cloud condensation nuclei", *Atmospheric Chemistry and Physics*, 11(9), pp. 4237–4249.
- Watson, M. (2013) "Why we'd be mad to rule out climate engineering", *The Guardian*, 8 October 2013.
- Weiland, P. (2010) "Biogas production: current status and perspectives", *Applied Microbiology and Biotechnology*, 85, pp. 849–860.
- Weisser, D. (2007) "A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies", *Energy*, 32(9), pp. 1543–1559.
- Wigley, T. M. L. (2006) "A combined mitigation/geoengineering approach to climate stabilization", *Science*, 314(5798), pp. 452–454.
- Williamson, P., Wallace, D. W., Law, C. S., Boyd, P. W., Collos, Y., Croot, P., Denman, K., Riebesell, U., Takeda, S. and Vivian, C. (2012) "Ocean fertilization for geoengineering: a review of effectiveness, environmental impacts and emerging governance", *Process Safety and Environmental Protection*, 90(6), pp. 475–488.
- Winter, G. (2011) "CE and international law: last resort or the end of humanity?", *Review of European Community and International Environmental Law*, 20, pp. 277–289.
- Wise, M. E., Baustian, K. J., Koop, T., Freedman, M. A., Jensen, E. J. and Tolbert, M. A. (2012) "Depositional ice nucleation onto crystalline hydrated NaCl particles: a new mechanism for ice formation in the troposphere", *Atmospheric Chemistry and Physics*, 12(2), pp. 1121–1134.
- Wolfrum, R. and Matz, N. (2003) *Conflicts in International Environmental Law*. Berlin: Springer.
- Wong, P.-H., Douglas, T. and Savulescu, J. (2014) *Compensation for Geoengineering Harms and No-Fault Climate Change Compensation*: Institute for Science, Innovation and Society and Oxford Uehiro Centre for Practical Ethics.
- Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J. and Joseph, S. (2010) "Sustainable biochar to mitigate global climate change", *Nature Communications*, 1(5), pp. 56–56.
- Worrall, F., Bell, M. and Bhogal, A. (2010) "Assessing the probability of carbon and greenhouse gas benefit from the management of peat soils", *Science of the Total Environment*, 408(13), pp. 2657–2666.
- Wüstenhagen, R., Wolsink, M. and Bürer, M. J. (2007) "Social acceptance of renewable energy innovation: an introduction to the concept.", *Energy policy*, 35(5), pp. 2683–2691.
- Wylie, D., Jackson, D. L., Menzel, W. P. and Bates, J. J. (2005) "Trends in global cloud cover in two decades of HIRS observations", *Journal of Climate*, 18(15), pp. 3021–3031.
- Xia, L., Robock, A., Cole, J., Curry, C. L., Ji, D., Jones, A., Kravitz, B., Moore, J. C., Muri, H., Niemeier, U., Singh, B., Tilmes, S., Watanabe, S. and Yoon, J.-H. (2014) "Solar radiation management impacts on agriculture in China: a case study in the Geoengineering Model Intercomparison Project (GeoMIP)", *Journal of Geophysical Research: Atmospheres*, 119(14), pp. 8695–8711.
- Yool, A., Shepherd, J. G., Bryden, H. L. and Oschlies, A. (2009) "Low efficiency of nutrient translocation for enhancing oceanic uptake of carbon dioxide", *Journal of Geophysical Research-Oceans*, 114.

- Young, R. E., Houben, H. and Toon, O. B. (1994) “Radiatively forced dispersion of the Mt. Pinatubo volcanic cloud and induced temperature perturbations in the stratosphere during the first few months following the eruption”, *Geophysical Research Letters*, 21(5), pp. 36–372.
- Zedalis, R. J. (2010) “Climate change and the National Academy of Sciences’ idea of geoengineering: one American academy’s perspective on first considering the text of existing international agreements”, *European Energy and Environmental Law Review (EELR)*, 19(1), pp. 18–32.
- Zhang, Y., Qu, Y., Wang, J., Liang, S. and Liu, Y. (2012) “Estimating leaf area index from MODIS and surface meteorological data using a dynamic Bayesian network”, *Remote Sensing of Environment*, 127, pp. 30–43.
- Zhou, S. and Flynn, P. (2005) “Geoengineering downwelling ocean currents: a cost assessment”, *Climatic Change*, 71, pp. 203–220.
- Zürn, M. and Schäfer, S. (2013) “The paradox of climate engineering”, *Global Policy*, 3(4), pp. 266–277.

Final report of the FP7 CSA project EuTRACE

European Transdisciplinary Assessment of
Climate Engineering

Potsdam, July 2015

Institute for Advanced Sustainability Studies Potsdam (IASS) e. V.

Contact:

Stefan Schäfer: stefan.schaefer@iass-potsdam.de

Mark Lawrence: mark.lawrence@iass-potsdam.de

Address:

Berliner Strasse 130

14467 Potsdam

Germany

Phone +49 331-28822-340

www.iass-potsdam.de

e-mail

media@iass-potsdam.de

Management Board

Prof. Dr. Dr. h. c. mult. Klaus Töpfer

Prof. Dr. Mark Lawrence

Print

Druckerei Steffen

Doi: 10.2312/iass.2015.018

