CLIMATE ENGINEERING

Risks, Challenges, Opportunities?

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Current State and Future Perspectives

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Climate Engineering Research: Current State and Future Perspectives

Session 1: Scientific Feasibility of Climate Engineering Ideas

Chairs: Prof. Dr. Thomas Leisner (Karlsruhe Institute of Technology) and Prof. Dr. Klaus Lackner (The Earth Institute Columbia University)

Session 2: Exploring Climate Engineering Uncertainties

Chairs: Prof. Dr. Gregor Betz (Karlsruhe Institute of Technology) and Prof. Dr. Ulrike Lohmann (ETH Zürich)

Session 3: Governing Climate Engineering Research, Potential Development and Deployment

Chairs: Prof. Dr. Alexander Proelß (Trier University) and Prof. Edward A. Parson, Ph.D. (Emmett Institute on Climate Change and the Environment)

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Chairs: Prof. Dr. Katrin Rehdanz (Kiel Institute for the World Economy),
Dr. Jack Stilgoe (Univeristy College London)

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„Geoengineering“, or „climate engineering“, i.e. the deliberate and large scale manipulation of the earth system to counteract global warming, has recently received considerable interest. Especially solar radiation management (SRM), which aims to control the amount of solar energy input into the climate system, promises to be a fast and comparatively cheap remedy for anthropogenic global warming. The most discussed and most feasible method of SRM up to date is stratospheric sulfur injection (SSI), the introduction of sulfuric acid aerosol into the stratosphere. Here we focus on an often overlooked side effect of SSI, which is its effect on the optical appearance of the sky to the human observer and its consequences to human well-being and psychological condition. We present spatially resolved images of a geoengineered sky in a direct visual representation and as optical spectra and discuss the appearance of a colored 60° halo around the sun, if an efficient geoengineering aerosol with narrow size distribution is used for SSI (c.f. our figure 3). This halo was not seen in spatially averaged spectra and represents a striking characteristic of the geoengineered sky.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Potential consequences of element release from Enhanced Weathering

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The application of rock flour on suitable land ("Enhanced Weathering") is one proposed strategy to reduce the increase of atmospheric CO_2 concentrations. Investigations of this method focused on the impact on the carbonate system, as well as on engineering aspects of a large-scale application, but potential side effects were never discussed quantitatively.

We analysed about 120,000 geochemically characterised volcanic rock samples from the literature. Applying basic statistics, theoretical release rates of nutrients and potential contaminants by Enhanced Weathering were evaluated for typical rock types.

Highest heavy metal concentrations are found in (ultra-) basic rocks, the class with the highest CO_2 drawdown potential. More acidic rocks contain less or no critical amounts, but sequester less CO_2. The applied rock material can contain significant amounts of essential or beneficial nutrients (potassium, phosphorus, micronutrients). Their release can partly cover the demand of major crops like wheat, rice or corn, thereby increasing crop yield on degraded soils. However, the concentrations of considered elements are variable within a specific rock type, depending on the geological setting.

Findings show that the rock selection determines the capability to release critical amounts of potentially harmful elements, or to supply significant amounts of nutrients, which could partly substitute industrial mineral fertiliser usage. Through careful selection of regionally available rocks, benefits could be maximised and drawbacks reduced. The deployment of Enhanced Weathering to sequester CO_2 and ameliorate soils necessitates an ecosystem management, considering the release and fate of weathered elements in plants, soils and water. Other CDR strategies, like afforestation, biofuel production, and biochar application could benefit from Enhanced Weathering side effects and should be considered as a set of tools that could be jointly applied.

2 | EXPLORING CLIMATE ENGINEERING UNCERTAINTIES

Response of Indian Subcontinent to the Geoengineering of Climate: The effect of SRM on Cloud Area Fraction and Rainfall

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The objective of this paper is to study the effects of Solar Radiation Management (SRM) on the climate over the Indian Subcontinent, particularly how it changes the cloud area fraction and total precipitation over the region. Cloud area fraction and precipitation are highly model sensitive parameters which depend greatly on other parameters like surface air temperature and evaporation. These parameters play a major role in governing small and large scale weather activities in any area and a small change in them can trigger repercussions on a much larger scale. As such it becomes extremely important to analyze closely the effects of SRM on our climate before implementing it in reality. The data for five important and interdependent variables: cloud area fraction, total precipitation, precipitable water, evaporation and surface air temperature was studied exhaustively for nine models namely BNU-ESM, CCSM4, CanESM, CAM5.1, GISS-E2-R, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM and MPI-ESM-LR, for a period of 50 years and the graphical results for the changes in these parameters was plotted using NCAR Command Language (NCL). The results obtained from these plots were indicative of the fact that cloud area fraction and precipitation, particularly over the Indian Subcontinent, are indeed highly model sensitive parameters; where a small change in the solar radiation caused changes as high as 30% in these parameters. With the given uncertainty in the simulated parameters, it becomes crucial to have more robust modeling before implementing any decision, particularly for a country like India where the economy is largely driven by monsoon dependent agriculture and even a small change in the climate can affect severely the livelihood of millions of people. Therefore any decision, big or small, must be pondered upon carefully, to analyze the risks and the benefits being derived from it, before implementing it on a local, regional or global scale.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Governance measures to minimize trade-offs between mitigation and CE technologies: afflicted with serious drawbacks and not warranted anyway?

Christian Baatz // Kiel University

Although the so-called Moral-Hazard-Argument, claiming that deployment or even the mere prospect of Climate Engineering (CE) will undermine mitigation efforts, is mentioned in many publications, it has not been investigated in any detail for quite a while. This recently changed with several investigations, including empirical studies, economic model studies, as well as a small number of publications addressing the issue from an ethical perspective. Given that the term "moral hazard" is misleading, I elsewhere proposed to refer to trade-offs between mitigation and CE instead. At present, two issues are worth investigating in particular: how likely is a trade-off and why is a trade-off problematic at all? Moreover, it is important to discriminate between different CE technologies; presumably, setting up artificial trees will have different effects in terms of a trade-off than sulphate aerosols injections. Regarding large-scale SRM technologies, I have argued in a previous paper that, so far, arguments in favour of the trade-off hypothesis are much more convincing than those against it. Also, I provided a robust normative argument for why a trade-off would indeed be problematic. If both arguments are convincing, a trade-off between mitigation and SRM is a serious danger. This paper will pursue two objectives. First, I will discuss different proposals to avoid or ease a trade-off. I will argue that governance measures either insufficiently tackle the relevant trade-off mechanisms or have far-reaching consequences that are rejected by many commentators. I will further discuss the implications of this (highly unsatisfying) conclusion. Second, I will identify different properties of CE technologies that will likely trigger potential trade-off mechanism that have been identified in the literature. My preliminary conclusion will be that the more of these properties a technology features the greater the likelihood that it will cause a trade-off.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Climate engineering as a robust and adaptive closed-loop system

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It is clear that current concentrations of atmospheric CO_2 exceed any measured historical levels in modern times, and is largely attributed to anthropogenic forcing since the industrial revolution. In response to this, efforts have been made to develop techniques both to reduce atmospheric carbon dioxide and to mitigate the radiative forcing it generates. Carbon Dioxide Removal (CDR) methods require very long timescales to deliver a significant reduction in carbon dioxide concentration, however Solar Radiation Management (SRM) can be considered a relatively fast-acting method, although it does not directly affect the carbon cycle. Therefore, considering that CDR is a slow process which could reduce the cumulative impact of emissions, it can be considered to be deployed in conjunction with faster-acting SRM. Then only modest SRM interventions may be necessary in the longer term through this dual effort.
This paper evaluates such methods by using a closed-loop control scheme with both SRM and CDR as control variables to investigate new hybrid control strategies, taking into account the long-term response of the climate system through a transfer function model. Methods for climate engineering based on both CDR and SRM are evaluated with actuator models developed for each; for example considering the dynamics of aerosol washout for SRM. Such actuator dynamics are key since they impose hard limits on the responsiveness of the control scheme and will lead to practical saturation limits for CDR and SRM controls. The system is investigated as a closed-loop control problem with uncertainties in the dynamics of the climate system which will be tackled by means of robust and adaptive strategies. In particular, the impact of the wide separation of timescales for SRM and CDR action on the dynamics of the closed-loop system will be considered. Finally, recommendations will be made as to strategies for deploying a long-term mix of both CDR and SRM interventions.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Low climate potentials but large side-effects of terrestrial CO_2 removal – insights from quantitative model assessments

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Terrestrial carbon dioxide removal (tCDR) through dedicated biomass plantations is considered as one climate engineering (CE) option if implemented at large-scale. The Royal Society judged afforestation projects to be of lower risk and more affordable than other CE options. However, tCDR is only moderately effective and its implementation requires both long time horizons and extensive cultivation areas.

The dynamic global vegetation model LPJmL simulates such large-scale, effectively managed biomass plantations and enables us to assess their associated tradeoffs from an earth system-analytic perspective. Therefore, we analyzed 12 scenarios including a range from far-fetched (e.g. conversion of all cropland) to more conservative (e.g. 10% of the agricultural area) assumptions about the transformed areas. Furthermore, the implementation of tCDR takes place immediately at full scale after the 2°C target is crossed around 2050 in an RCP8.5 storyline. The resulting tCDR potentials in year 2100 include changes in all land carbon pools and 50% of the accumulated annual biomass harvests to include leakage effects.

The climate potentials of tCDR are not sufficient to bring global mean temperatures down to the 2° target in 2100 under otherwise RCP8.5 emissions. Even on maximum spatial scales diminish carbon emissions of the massive land use and land cover changes the tCDR effectiveness. Smaller tCDR plantations do not build up enough biomass over this period and high leakage rates substantially lower the potential to achieve global warming reductions of more than 1°C.
Finally, we demonstrate that the (non-economic) costs for the Earth system also include negative impacts on the water cycle and on ecosystems, which are already under pressure due to land use and climate change. Overall, tCDR may lead to a further transgression of land- and water-based planetary boundaries while not being able to set back the crossing of the boundary for climate change.

2 | EXPLORING CLIMATE ENGINEERING UNCERTAINTIES

Detecting climate engineering effects: challenges from non-stationarity

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We study the potential of detecting and attributing, as early as possible, the effects of climate engineering (CE) measures in a warming world.

Conventional detection methods rely on the stationary paradigm that the null hypothesis is given by a constant climate. For the detection of CE the appropriate null hypothesis is non-stationary, represented by the continued warming from greenhouse gases.

As CE measures have not been employed so far, our analysis takes place in the simulated world of climate models. We use the suite of RCP4.5 simulations of CMIP5 to represent the null hypothesis of continued warming, including corresponding uncertainty. As possible observations we use two sets of CE scenarios from the GeoMIP project, based on solar radiation management initiated in 2020. For both, the net radiative increase from greenhouse gases is counterbalanced by a corresponding increase in stratospheric sulfur injections. In one scenario (G3), it is done smoothly by stabilizing the overall net radiation to 2020 levels. The other scenario (G4) is given by a rather short-term, shock-like climate forcing that mimicks a succession of Pinatubo events, for which early detection is relevant. The latter, however, aggravates the challenges posed by non-stationarity, as we will demonstrate.

We show that G4 effects become detectable and attributable after only a few years and, unsurprisingly, earlier than G3 efects. The use of spatio-temporal fingerprints helps to increase the signal over the noise.

5 | PERCEPTIONS OF AND PERSPECTIVES ON CLIMATE ENGINEERING RESEARCH AND DEPLOYMENT

Solar Radiation Management and Intergenerational Equity

William Burns // American University

Due to the feckless response of the global community in the context of climate policy making, climate geoengineering has emerged as an increasingly viable option among commentators and some policymakers. One of the most widely discussed of these options is solar radiation management, or efforts to increase atmospheric albedo through techniques such as sulfur particle injection or cloud brightening. Unfortunately, while such techniques have the potential to avert "climate emergencies," or to serve as a stopgap measure to buy time for effective emissions mitigation responses, they also pose serious risks. Many commentators have focused on intragenerational risks, such as changes in precipitation patterns, or increases in sulfur dioxide loads in the troposphere. However, SRM approaches may also poses grave threats to future generations should their use ultimately cease without concomitant reductions in greenhouse emissions, termed the so-called "rebound effect." This presentation focuses on the implications of the international legal principle of intergenerational equity in terms of potential deployment of SRM technologies. It advances the argument that the potential threat to intergenerational interests that SRM technologies pose may violate international law under most circumstances, and that this must be taken into consideration by policy makers who might contemplate the use of such technologies to address climate change. The presentation will also respond to the argument by some proponents of SRM approaches that deployment of such technologies might, under certain circumstances, actually constitute fulfillment of our responsibilities to future generations.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Vertical Mussel Reef Farming: Exploring climate change solutions with economic and ecologic significance

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Arman Sarkisyan // Sea Harmony
Violeta Koleva //

We are currently involved with an EU-funded project for Research and Restoration of the Essential Filters of the Sea (REEFS). It is a pilot project focused on the scientific research of environmental impact of the artificial reefs in the Black sea countries. REEFS is a joint cross-border initiative of five partners from – Bulgaria, Ukraine, Romania, Georgia and Turkey.

Essentially, this project applies our technology for vertical mussel farming, with the aim to evaluate the extent of its bio-effectivity at different locations within the Black Sea basin. According to their specifics our vertical mussel reefs, if applied at large scale, are able to recover marine biocenoses damaged by eutrophication. Following are some of the long-terms goals we expect the vertical mussel reefs to help tackle: the sustainable and natural recovery of eutrophied marine ecosystems and habitats, reducing deforestation consequential to the growing food necessity, may protect the coastline, combat climate change.

Here are some of the effects we have observed that are directly linked and consequential of the installation of our vertical mussel reefs:

- The damaged bottom communities gain access to the more favorable above-bottom layers of the sea.
- The marine food chain is restored at its key link – the mussels, which assimilate the primary phytoplankton production, and intensify its relationship with the organisms higher in the food chain.

From our point of view, the solutions to the large scale problems we are and will be facing should be designed with consideration of both environmental and economic consequences. We are interested in solutions that can on the one hand boost economic growth and on the other - to restore the ecological balance and biodiversity in eutrophic marine regions In our experience the key to answering this question is in restoring one of the most widely spread natural bio-filtrates of the marine ecosystems in the moderate latitudes – the mytilus species.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Can artificial ocean alkalinization protect tropical coral ecosystem from ocean acidification?

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Artificial Ocean Alkalinization (AOA) as a method to mitigate local ocean acidification and protect tropical coral ecosystems during a 21st century high CO_2 emission scenario is investigated with an Earth system model. In our implementation of AOA in the Great Barrier Reef, Caribbean Sea and South China Sea regions, alkalinization has the potential to counteract expected 21st century local acidification in regard to both oceanic surface aragonite saturation Ω and surface pCO_2. Regional AOA, however, results in locally elevated aragonite oversaturation, unprecedented carbon chemistry states and altered regional sensitivities towards further AOA input. A notable consequence of stopping regional AOA is a rapid shift back to the acidified conditions of the target regions. We conclude that artificial ocean alkalinization may be a method that could help to keep regional coral ecosystems within saturation states and pCO_2 values close to present-day values even in a CO_2 high-emission scenario and thereby might "buy some time" against the ocean acidification threat, even though the warming threat could not be counteracted by regional AOA.

2 | EXPLORING CLIMATE ENGINEERING UNCERTAINTIES

Atmospheric CO_2 stabilization by means of ocean alkalinization within the 21st century

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Artificial ocean alkalinization (AOA) is one of the ocean-based carbon dioxide removal (CDR) methods that aims at enhancing the natural and slow process of weathering by which CO_2 is taken out of the atmosphere. Alkalinity is the charge balance of ions in seawater and it determines the CO_2 oceanic uptake and storage as well as seawater pH. This technology would not only tackle climate change, but also ocean acidification. We use the Max Planck Institute Earth System Model based on the Coupled Model Intercomparison Project Phase 5 version with low-resolution to investigate the mitigation potential and side-effects of AOA. Model scenarios of alkalinity enhancement are designed to keep the atmospheric CO_2 levels similar to values of the stabilization scenario Representative Concentration Pathway (RCP) 4.5, whilst fossil fuel emissions follow the pathway of the high CO_2 scenario RCP8.5. In total, approx. 105 Petamol would be needed until the year 2100 for such a scenario. Compared to the unmitigated scenario (RCP8.5) this AOA scenario leads to a reduction in the annual global mean of air surface temperature of around 1.5.K, following more closely the RCP4.5. The slightly higher temperature (0.5.K) of AOA compared to RCP4.5 is mainly due to the radiative forcing effect of other GHGs (e.g. N2O, CH4 and Halogenated GHGs). AOA strongly mitigates ocean acidification leading to higher pH and saturation state of carbonate minerals values than those associated with the RCP4.5. This climate engineering scenario leads to changes in different properties of the climate system that are noticeable within centennial timescale. Between others, changes in temperature, precipitation, ocean circulation, sea ice extent as well as in the carbon cycle are here addressed. After our analysis, it is clear that this technology leads to a state of the climate that approaches the one of the RCP4.5 scenario. However, mitigating atmospheric CO_2 alone does not lead to an identical climate state.

4 | A COMPARATIVE VIEW ON CLIMATE ENGINEERING OPTIONS AND ASSESSMENT METRICS

Assessing the impact of different climate engineering measures on ocean acidification with an Earth system model

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Julia Pongratz // Max Planck Institute for Meteorology
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Current climate engineering (CE) research is mainly focused on addressing the increase in temperature, sea level rise and changes in precipitation, whilst the marine carbon cycle receives less attention. However, the response of the ocean carbon cycle to CE, and in particular in regards to ocean acidification, is a crucial aspect that should be considered. Our claim is based on the fact that the ocean carbon sink has already buffered around 25% of the CO_2 emissions and ocean acidification has been found to pose risks for marine organisms and accelerate climate change. Thus, we tackle the response of the marine carbon cycle to different CE measures. We study scenarios that explore the mitigation potential and side-effects of different CE technologies. Our tool is the Max Planck Institute Earth System Model based on the Coupled Model Intercomparison Project Phase 5 version with low-resolution. The high CO_2 Representative Concentration Pathway (RCP) 8.5 is the common unmitigated scenario for the three considered CE methods: i) afforestation scenario in which land use changes are prescribed according to RCP4.5 ii) ocean alkalinization scenario designed to keep atmospheric CO_2 concentrations similar to values of the scenario RCP4.5 iii) solar radiation management through stratospheric sulphur injection with a reduction in radiative forcing to RCP4.5 levels. Direct and indirect effects of carbon dioxide removal methods on the marine carbon cycle, strongly differ from those associated with solar radiation management technologies because they depend upon the joint responses and synergies between different elements of the Earth system. That is why effects on oceanic carbon cycle are not intuitively understood. We study changes in the strength of the marine carbon sink, seawater pH and saturation state of carbonate minerals. Collateral changes in ocean biogeochemistry and marine biota will be also discussed.

2 | EXPLORING CLIMATE ENGINEERING UNCERTAINTIES

Arctic stratospheric sulphur injections and its radiative forcing

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Ben Kravitz // PNNL

Observations and climate projections show a high sensitivity of the Arctic climate to the increase in greenhouse gas emissions, known as the polar amplification. This study evaluates the options of counteracting the rising polar temperatures by stratospheric sulphur injections in the Northern Hemisphere high latitudes.10 Mt of sulphur dioxide are emitted in a point emission source setup centred at the 100 hPa pressure level over Svalbard island (80°N,15°E). We perform simulations with the general circulation models ECHAM5, ECHAM6, and GISS ModelE.

We study pulsed emission simulations that differ among themselves by the injection starting date (March-September), injection length (1, 30, or 90 day emission period), and the vertical resolution of the model (for ECHAM6).

We find injections in April to be the most efficient in terms of the shortwave radiative forcing at the top-of-the atmosphere over the Arctic region. The distribution of sulphate aerosol spreads out beyond the injection region, with a significant share reaching the Southern Hemisphere.

Climate-effective terrestrial carbon dioxide removal could induce biogeochemical state shifts

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One of the discussed climate engineering methods is the extraction of carbon dioxide (CO_2) from the atmosphere, by increasing the terrestrial carbon sink (tCDR). Large-scale biomass plantations could theoretically act as a measure to reduce atmospheric CO_2 concentrations (sequestration plus substitution effect) in case mitigation efforts fail to substantially reduce greenhouse gas emissions within this century.
To provide a quantitative assessment of the biospheric impacts of such biomass plantations (if cultivated over an area as large as current cropland), we assess its consequences for major biogeochemical and hydrological state variables of the Earth system (net primary production, soil respiration , harvest flux, soil and vegetation carbon stocks, evapotranspiration, runoff). The changes are compared against both the current state under agricultural land-use and a state of potential natural vegetation. Respective simulations for these three ‚worlds' were conducted with LPJmL, an intermediately complex dynamic global vegetation model. The confidence in the model results is underpinned by an evaluation of the modeled biomass harvest against available observations from literature.
Simulation results indicate a remarkable increase in net primary production in the bioenergy world compared to potential natural vegetation; nevertheless, owing to the regular harvests on such plantations, vegetation carbon stocks are significantly lower. The water cycle is impacted by decreasing river discharge and increasing transpiration. We also developed a metric (covering the joint effect of the different process changes) to assess the degree and likelihood of state shifts in Earth system functioning. We find that commitment to tCDR via biomass plantations potentially alters major determinants of ecosystem functioning even more than current agricultural practices do. Hence, the biogeochemical state of the global biosphere could be shifted considerably in a world with tCDR.

4 | A COMPARATIVE VIEW ON CLIMATE ENGINEERING OPTIONS AND ASSESSMENT METRICS

Cost-effective integrated mitigation and solar radiation management scenarios under uncertainty

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Most likely society will decide about the application of climate engineering options not in mere isolation, but in the context of mitigation and adaptation options. Here we present a metric for an integrated assessment of mitigation options in conjunction with solar radiation management (SRM). As costs of SRM are rather low, the crucial non-trivial part of the assessment is to represent SRM risks in the integrated assessment.
In earlier work we extended a cost effectiveness analysis of the 2° target to include a key risk category of SRM: changes in precipitation patterns. We defined regional targets for precipitation changes that are consistent with the 2° target. We found that for a spatial resolution of the Giorgi regions, about 1/3 of mitigation costs could be saved by including SRM in the portfolio of climate policy options. Here we elaborate on the effects of the uncertainty whether SRM is allowed to enter the portfolio in the future. Furthermore we outline how to generalize our approach to include uncertainty about climate response. For this, major obstacles of including uncertainty in cost effectiveness analysis are discussed and solutions are offered.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Strategic Conflicts on the Horizon: R&D Incentives for Environmental Technologies

Daniel Heyen // Heidelberg University

Climate Engineering technologies (CE) are being discussed as potentially beneficial measures against global warming. Future deployment however is infeasible without research and development (R&D) today. The required R&D expenditures are substantial and, in the absence of a global regulating entity, fall on self-interested countries. Thus, the prospects of successful innovation critically depend on innovation incentives. This paper focuses on a specific mechanism for strategic distortions in this R&D game. In this mechanism, the outlook of future conflicts surrounding CE deployment directly impacts on the willingness to undertake R&D. Apart from free-riding, the strategic conflict we can expect for carbon dioxide removal (CDR) techniques characterized by high deployment costs, a different deployment conflict with distortive effects on innovation may occur: The low deployment costs and heterogeneous preferences surrounding solar radiation management (SRM) might give rise to so-called 'free-driving'. In this recently considered possibility (Weitzman 2012), the country with the highest preference for SRM deployment, the free-driver, may dominate the deployment outcome to the detriment of others. The present paper develops a simple two stage model for analyzing how technology deployment conflicts, free-riding and free-driving, shape R&D incentives of two asymmetric countries. The framework gives rise to rich findings, underpinning the narrative that future deployment conflicts pull forward to the R&D stage. While the outlook of free-riding unambiguously weakens innovation incentives, the findings for free-driving are more complex, including the possibility of super-optimal R&D and incentives for counter-R&D.

Regional Disparities in Solar Radiation Management Impacts: Limitations to Simple Assessments and the Role of Diverging Preferences

Daniel Heyen // Heidelberg University
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Peter Irvine // IASS Potsdam

Solar radiation management (SRM) has been proposed as a potential method to reduce risks from global warming. A widely held concern about SRM, however, is that its climate effects will be unevenly distributed in space. Recent research has used climate model projections to quantitatively assess how regional disparities affect the overall efficiency of global SRM and what the resulting potential for cooperation and conflict with regard to SRM may be. First results indicate that regional disparities, although present, may not be severe. We challenge this finding by reconsidering some of the simplifying assumptions made in existing assessment studies. Our main focus is the prevalent assumption in SRM research that, for all regions, any deviation from a past climate state inflicts damages. While climate change will have negative implications for most people and ecosystems around the world, it is plausible that some actors will have different preferences as regards how much climate change ought to be compensated by SRM. Using an illustrative two-region model, we show that even limited variation in actors' preferences about a target climate state can significantly change assessments of regional disparities from SRM. We also discuss other common simplifications, for example, the design of damage indicators, spatial aggregation, and the neglect of uncertainties, which could have equally strong implications. We therefore suggest that current research results do not allow us to draw conclusions about the socio-political implications of regionally diverging effects of SRM. Research should pay more attention to the difficulty of assessing impacts based on climate model projections and to the general limitations of simple assessment frameworks.

Impact of SRM on preferences for mitigation by application of cultural cognition

Matthias Honegger // Perspectives

Whether or not research or deployment of SRM is worthy of serious consideration is a question that contains elements of natural science research, ethical questions and social science research questions. In particular one major concern – namely that considering SRM would lead to neglecting mitigation – poses a question, which is to be addressed by social science research: Does consideration of SRM reduce individuals' preferences to undertake mitigation? I propose addressing this via application of cultural cognition theory – which has been successfully applied to preferences for mitigation. Previous studies have indicated somewhat greater support for mitigation after exposing subjects to information on SRM. I suspect that this effect does not occur uniformly, but rather depends on subject's cultural views and the cultural meaning of information on climate engineering technologies. I propose an experimental design to test the conditions under which preferences for mitigation are reduced or grow, when subjects are exposed to information about SRM.

By improving the understanding of preferences for mitigation versus SRM, communication of scientific findings on SRM can be improved, thus enhancing society's ability to take adequate decisions on SRM and to achieve a second best outcome with a conscious choice to include or exclude application of SRM.

5 | PERCEPTIONS OF AND PERSPECTIVES ON CLIMATE ENGINEERING RESEARCH AND DEPLOYMENT

Omission bias in judgment of SRM research

Matthias Honegger // Perspectives

Whether or not research or deployment of SRM is worthy of serious consideration is a question that contains elements of natural science research, ethical questions and social science research questions. While natural science will allow to answer questions on expected regional impacts from SRM, there will remain a strong element of value judgments. Such value judgments contain ethical considerations such as on weighing of uneven distributions of benefits and damages. These value judgments will – besides through ethics – also be shaped via cognitive processes which steer human judgment of uncertain and risky technologies.

Consensus could emerge that SRM is not a strategy worth pursuing in view of potentially serious regional impacts. Many scholars forcefully argue that the risks outweigh the potential benefits and that it might even be counterproductive to fund scientific research into it – research that would be necessary to better estimate the risks, because even such research could increase the likelihood of SRM ultimately being deployed. Given that one choice – pursuing research – represents an action, while the other choice – not to address SRM research – represents inaction, I postulate that omission bias, a feature of decision-making long recognized in behavioural economics, is at play. I propose an analytical approach to explore, whether omission bias creates a tendency to reject SRM despite the possibility that it is consistent with individual and social objectives.

By improving the understanding of how social factors, rather than objective scientific "facts," contribute to people's beliefs about SRM's desirability I believe one can contribute to society's ability to take adequate decisions on SRM, aiming for a second best outcome – given that we appear to be in an imperfect world with insufficient efforts to reduce greenhouse gas emissions.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Findings from Workshop on Designing Procedural Mechanisms for the Governance of SRM Field Experiments

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Neil Craik // University of Waterloo
Jason Blackstock // University College London

In February 2015, climate engineering governance experts, experienced research funding and environmental regulatory practitioners, and potential field experimentalists took part in a two-day workshop titled Designing Procedural Mechanisms for the Governance of Solar Radiation Management Field Experiments. Drawing on previous work that identified a portfolio of potential SRM field experiments (Keith, Duren, and MacMartin, 2014), and focusing on micro- and meso-scale experiments, participants explored a range of design criteria for Environmental Assessments (EAs) and research registries that could satisfy governance objectives. The goal was to provide a concrete and evaluated set of mechanism options for consideration by decision-makers that may be faced with SRM field experiment proposals. Attendees worked through a number of hypothetical field experiment proposals, with a view to generating a more detailed understanding of the institutional and technical requirements for each mechanism. Particular attention was paid to variations and trade-offs in mechanism design. Consideration was also given to how these project-oriented mechanisms would relate to programmatic and policy level assessments of SRM research and technology. The workshop considered both national level and transboundary governance contexts, with a focus on U.S., Canadian and European settings.

In this presentation, workshop organizers will present and discuss key findings from the meeting.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Minilateral Governance of Solar Geoengineering

Joshua Horton // Harvard Kennedy School

Minilateralism, or institutionalized cooperation among a limited subset of states, is a model of governance that blends the thick institutions typical of global multilateral fora with exclusivity reflecting the distribution of power. With one notable exception (Ricke, Moreno-Cruz, and Caldeira, 2013), scant attention has been paid to the concept of minilateralism within the geoengineering literature. This is despite the fact that many in the geoengineering research community intuit that a "consortium," "coalition," or other selective interstate arrangement is the most likely form of real-world geoengineering governance. Some analysts have suggested that SRM might constitute an excludable but nonrivalrous "club good," yet this possibility has not been explored in depth. The purpose of this research is to explore the concept of minilateralism in the context of possible governance of solar geoengineering. A typology of minilateral forms serves to facilitate a comparative assessment of minilateralism vis-à-vis multilateralism and unilateralism. This comparison covers a range of factors such as enabling conditions, levels of compliance and effectiveness, perceptions of legitimacy, and degrees of coercion. A key question addressed by this assessment is the applicability of minilateralism to solar geoengineering. These findings are then linked to existing social science research on geoengineering. Previous work on, inter alia, public goods, "exclusive coalitions," consortium structures, the role of power, and antidemocratic tendencies is connected explicitly to the concept of minilateralism and to analysis of its suitability as an instrument of geoengineering governance. Finally, the overall appropriateness of minilateral governance for solar geoengineering relative to alternative political configurations is assessed.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Delivery systems for SRM

Hugh Hunt // Cambridge University

Climate Engineering is directed by accurate modelling of the climate. But climate modeling is full of uncertainty. Supposing we gain confidence in the modelling of climate and we are ready to try out some climate engineering at scale. Will it be possible to deliver, say, 10 million tonnes of SO_2 per year to an altitude of 20km? Or will it be possible to deliver enough salt water into the troposphere for cloud whitening? There is nothing trivial about the Engineering Systems required for SRM.

This paper will give an overview of the infrastructure and technology that would be needed to realize SRM proposals. This includes the design of new technology and the modification of existing technologies to (a) reflect sunlight, by surface albedo modification or space reflectors, and/or (b) deliver albedo-enhancing materials such as reflective aerosols and saltwater sprays.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

SRM Science Cambridge – lessons learned

Hugh Hunt // Cambridge University
Kirsty Kuo // Cambridge University

The a Solar Radiation Management Science conference (SRMS) in Cambridge, March 2015, there followed on the six months after the CEC14 Climate Engineering Conference in Berlin. The Berlin conference was themed around " Critical Global Discussions" and there was a lot of discussion around ethics, governance and social science. Many in Berlin could see the need for a follow-up meeting to focus on the science. SRMS had four themes: 1. Climate Modelling, 2. Engineering systems, 3. Atmospheric chemistry and 4. Impacts, implications and consequences. In addition there were two lunchtime perspectives sessions to allow space for discussion on the framing and ethics of climate engineering. There was also a panel discussion (linked with the Cambridge Science Festival) on the subject of "Climate Engineering - who can we trust?" with panelists Martin Rees, Amartya Sen, David Keith and Onora O'Neill, chaired by Oliver Morton.

This paper will address the outcomes of the conference and in particular it will examine the nature of a science-only conference in the context of climate engineering for which and framing, ethics and governance are so important.

4 | A COMPARATIVE VIEW ON CLIMATE ENGINEERING OPTIONS AND ASSESSMENT METRICS

Review of the Climate Impacts of Sulphate Aerosol Injection

Peter Irvine // IASS

Solar Radiation Management (SRM) Climate Engineering (CE) has been proposed as a means to reduce some of the risks posed by rising greenhouse gas (GHG) concentrations. Numerous studies have shown that whilst no SRM technique can reverse all the effects of elevated GHG concentrations in the atmosphere, they may be able to offset changes in key climate variables, such as temperature and precipitation, thus potentially reducing climate risks. Whilst there is a growing understanding of the climate response to various SRM techniques, very little work has been done to determine what the climate impacts response to these techniques would be. Whether SRM ought to be considered a partial substitute for mitigation and adaptation efforts, a potential supplement to existing climate policies, an emergency response only, or dangerously hubristic, is contested. However, central to such considerations of SRM is the question of whether and to what extent it could reduce the risks of climate change.

To investigate this question a group of climate impacts experts with a wide range of expertise were brought together with a small number of SRM experts on the 9th and 10th of March to evaluate the climate response to SRM. This presentation will summarize the findings of this workshop addressing such questions as:

1) What can be inferred about the climate impacts response from current climate model results on SRM?
2) Which uncertainties in the climate response to SRM are the most significant in terms of shaping climate impacts?
3) What can be known and what cannot be known in advance about the climate impacts of SRM?
4) What are the most pressing research questions on the climate impacts of SRM?

5 | PERCEPTIONS OF AND PERSPECTIVES ON CLIMATE ENGINEERING RESEARCH AND DEPLOYMENT

Concepts of Responsibility and their Communication within Priority Program 1689

Nina Janich // TU Darmstadt
Christiane Stumpf // TU Darmstadt

Scientists bear responsibility not only for the methods they use in their research, but also for their results. Scientists and the public are both fully aware of this fact. This responsibility also involves communicating these research methods and results both within scientific circles and to the public.
The topics of climate engineering and climate research are particularly affected by the issue of scientific responsibility given the high degree of uncertainty and anxiety that these fields of research provoke in the public. The perception of climate research conveyed in the SPP is therefore partly dependent on whether and how scientists communicate the challenges of climate engineering.
The present research project has its focus on the creation of the SPP against the backdrop of a scientific 'Responsibility Initiative' and investigates what scientists understand by the term 'responsibility'. We will first introduce a possible theoretical understanding of the concept of scientific responsibility based on philosophical and sociological approaches. In order to do this the various terms which express responsibility, collected through questionnaires and interviews and used by SPP participants with various research backgrounds, will be compared. We are interested in issues such as conscious reflection about responsibility by these researchers, public awareness of climate research and how scientists deal with the issue of uncertainty.
This project deals with themes from both Section 2 and Section 5 and although it corresponds to Barben & Matzner's presentation in content, we employ a different, SPP-internal perspective.

4 | A COMPARATIVE VIEW ON CLIMATE ENGINEERING OPTIONS AND ASSESSMENT METRICS

The Carbon Dioxide Removal Model Intercomparison Project (CDR-MIP)

David Keller // GEOMAR Helmholtz Centre for Ocean Research Kiel
Andrew Lenton // Commonwealth Scientific and Industrial Research Organisation)
Vivian Scott // University of Edinburgh
Naomi Vaughan // University of East Anglia

Continued anthropogenic greenhouse gas emissions are changing the climate threatening "severe, pervasive and irreversible" impacts. Inadequate emissions reduction is resulting in increased attention on Climate Intervention (CI) – deliberate interventions to counter climate change that seek to either modify the Earth's radiation budget, or remove the primary greenhouse gas from the atmosphere – Carbon Dioxide Removal (CDR). The majority of future scenarios that do not exceed 2°C warming by 2100 include CDR methods. At present, there is little consensus on the impacts and efficacy of the different types of proposed CDR. In response, the Carbon Dioxide Removal Model Intercomparison Project (or CDR-MIP) is proposed. This project aims to bring together a suite of Earth System Models (ESMs) and Earth System Models of Intermediate Complexity (EMICS) in a common framework to explore the potential, risks, and challenges of different types of proposed CDR. At present the proposed simulations for CDR-MIP include: Direct–air capture simulations, Afforestation and Ocean alkalinisation as well as a modified Diagnostic, Evaluation, and Characterization of Klima (DECK) experiment. These experiments are designed to answer key questions related to quantifying efficacy, feedbacks, response time scales, and potential side effects of specific CDR methods, as well as questions of climate "reversibility". Here we present details on the proposed experiments, and encourage feedback from the community on their design and implementation. It is anticipated that this will be the first stage of a continuing project exploring CDR, and as such we strongly encourage interested modeling groups to participate. CDR-MIP aims to commence in September 2015.

2 | EXPLORING CLIMATE ENGINEERING UNCERTAINTIES

Investigating the uncertainty of simulated climate engineering

David Keller // GEOMAR Helmholtz Centre for Ocean Research Kiel
Nadine Mengis // GEOMAR Helmholtz Centre for Ocean Research Kiel
Ellias Feng // GEOMAR Helmholtz Centre for Ocean Research Kiel
Andreas Oschlies // GEOMAR Helmholtz Centre for Ocean Research Kiel

Many climate engineering studies are based on the results of Earth system model simulations. However, these models are simplistic representations of reality and contain many poorly constrained parameterizations and further limitations imposed by model resolution. In addition, the data used to force the models, especially for future scenarios, is often idealized. The results of all Earth system model runs, thus, contain some degree of uncertainty even if they compare well with observations. Several approaches are commonly used to better understand model results and reduce their uncertainty. In this study we performed a parameterization sensitivity analysis to better understand idealized afforestation, artificial ocean alkalinization, and solar radiation management climate engineering during a high CO_2 emission scenario (RCP 8.5) simulation with the University of Victoria Earth system climate model, a model of intermediate complexity. The parameterizations that are individually analyzed include: biological terrestrial and marine responses to changes in temperature, CO_2 air-sea gas exchange, marine stoichiometric and terrestrial vegetation response to changes in atmospheric CO_2, oceanic vertical mixing, the response of winds to climatic change, and the absorption of short wave radiation in the atmosphere by water vapor, dust, ozone, clouds, etc.. In addition, we analyzed the effect of some of the forcing associated with the RCP 8.5 scenario by individually turning off the land use, sulphate aerosol, and non-CO_2 greenhouse gas forcing. The results of these analyzes provide a better understanding of the minimum and maximum potential of these idealized climate engineering methods. They also show that even when this range of possible effectiveness is taken into account, the methods are still, individually, either relatively ineffective and/or have potentially severe side effects.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Climatic impacts of irrigated afforestation of the Sahara in a complex Earth System Model

Tronje Kemena // GEOMAR Helmholtz Centre for Ocean Research Kiel
Katja Matthes // GEOMAR Helmholtz Centre for Ocean Research Kiel
Sebastian Wahl // GEOMAR Helmholtz Centre for Ocean Research Kiel
Andreas Oschlies // GEOMAR Helmholtz Centre for Ocean Research Kiel

Some scientists proposed afforestation of the Sahara and the Australian Outback as an applicable climate engineering method to counteract global warming. Past studies have primarily investigated the efficiency of carbon dioxide removal and estimated the realization costs. Possible impacts on climate were only treated aside and with simplified climate models.
Here we use for the first time a high-top state-of-the-art Earth system model, (NCAR's CESM-WACCM) to investigate in more detail changes in climate variability and circulation to a large-scale afforestation with fixed pre-industrial carbon dioxide concentrations. We are interested in local changes but also in particular in global teleconnection patterns.
Preliminary results of the afforestation of the Sahara show a strong increase in the precipitation rate and consistently in cloud coverage over the Sahel Zone. Strong effects on atmospheric circulation (in particular the African Easterly jet and the Tropical Easterly jet), sea surface salinity and sea surface temperatures are seen in the tropics but seem to impact global scale circulation features significantly as well. A thorough analysis of the resulting regional and global changes will be presented, and the risks and feasibility of such large-scale afforestation projects will be evaluated.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Studying the limitations of stratospheric aerosol injections by microphysical processes and interaction with radiation using the IPSL climate model

Christoph Kleinschmitt // Institute of Environmental Physics, Heidelberg University
Olivier Boucher // Laboratoire de Météorologie Dynamique, CNRS / IPSL, Paris, France
Ulrich Platt // Institute of Environmental Physics, Heidelberg University

Current studies assessing climate engineering by stratospheric aerosols injections (SAI), like those performed in the framework of GeoMIP, reveal numerous risks and undesirable side effects of this method. But they largely rely on the assumption that increasing radiative forcing by greenhouse gases can be counterbalanced by sufficiently large aerosol injections, at least on a global scale. However, there are various processes that might have the potential to severely limit the efficacy of SAI, but which are not considered in most of the participating earth system models. Among them, there is coagulation of aerosol particles leading to an increase in particle size, which reduces scattering efficiency and stratospheric lifetime through sedimentation. Interaction with infrared radiation, i.e. the aerosol's own greenhouse effect, can also limit the desired cooling effect.
In order to get a better estimate of the cooling potential of SAI from global climate simulations, all these processes were implemented in the IPSL climate model using an aerosol bin scheme. A new radiative transfer scheme is used to account not only for solar, but also for terrestrial *infrared radiation. Results from climate model experiments showing the influence of each one of the relevant microphysical and radiative processes on the cooling potential if SAI will be presented.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

The role of iron during the open ocean dissolution of olivine in a simulated CO_2 removal experiment

Judith Hauck // Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung
Christoph Völker // Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung
Peter Köhler // Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research
Dieter Wolf-Gladrow // Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung

One CO_2 removal mechanism proposed as geoengineering approach is enhanced silicate weathering. We here follow up on previous simulation experiments on the open ocean dissolution of olivine, a well-distributed magnesium-iron-silicate and focus on the role of iron. Olivine is known to contain a magnesium:iron ratio of ~9:1. Iron is a micronutrient and in various areas of the ocean marine biology is iron-limited. It is thus expected that olivine dissolution as a large-scale geoengineering application for CO_2 removal would increase the iron input into the ocean with implications for marine biology. With the numerical simulation of the marine ecosystem and biogeochemistry model RECOM-2 embedded in the ocean general circulation model MITgcm the potential changes in the marine biological productivity via associated iron fertilization were analysed. Since it is not clear how much of the iron contained in olivine will be lost by colloid formation and aggregation before becoming biologically available we show in sensitivity experiments that already the availability of 0.1% of the iron enhances the oceanic carbon uptake connected with the olivine dissolution by 20% compared to similar experiments in which the effect of iron is neglected. Results saturate at an increase in marine carbon uptake rate of 35% if 1% or more of the dissolved iron would be biologically available. For an addition of 3 Pg/yr of olivine with a 1% solubility the additional biologically available iron in the surface ocean would be 2.4 Tg/yr, which is 10x larger than the dissolved iron input by dust. The effect of such an iron fertilization would lead in certain areas to species shifts in the phytoplankton communities with diatoms being one of the winners and effects would be largest in the Southern Ocean.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Nitrogen related constraints of afforestation as terrestrial CE measure

Daniela Kracher // Max Planck Institute for Meteorology

Large scale terrestrial afforestation is discussed as one possible option to reduce man made climate change. Regrowth of forest on abandoned areas will foster the uptake of CO_2 in the terrestrial biosphere, thus reducing CO_2 concentrations in the atmosphere. Significant modifications of the landscape inherit potential for unwanted side effects. The benefits of such a drastic measure, i.e. the efficiency regarding mitigation of climate change, must be assured to justify those side effects beforehand.

One often neglected factor is limited growth of regrown forest due to limited supply of nutrients. This effect will even be more dominant with enhanced plant growth under higher atmospheric CO_2 concentrations thus restraining further CO_2 sequestration. Particularly at areas with low N supply, uptake of CO_2 by trees can be enhanced by fertilizer application. However, both N_2O and CO_2 producing microbial processes will be stimulated by higher nutrient availability and can partly compensate the achieved higher CO_2 uptake.

The magnitude of the reduction in CO_2 sequestration due to limited N supply is quantified by applying JSBACH, the land component of the MPI-ESM (Max Planck Institute Earth System Model). In simulation experiments the effect of large scale afforestation and potential fertilizer application on soil borne N_2O emissions and net CO_2 exchange is investigated. By considering interactions with N dynamics, the effect of large scale afforestation on the climate can thus be investigated more comprehensively.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Food price increases following from afforestation

Ulrich Kreidenweis // Potsdam Institute for Climate Impact Research
Florian Humpenöder // Potsdam Institute for Climate Impact Research
Alexander Popp // Potsdam Institute for Climate Impact Research

It has been shown that large-scale afforestation has a significant potential for carbon dioxide removal from the atmosphere – at the cost of agricultural land (Humpenöder 2014 Environ. Res. Lett. 9: 064029). However, the effectiveness of afforestation in cooling the planet also depends on its location. Studies with earth system models showed that the decrease in surface albedo can outweigh the cooling effect of carbon sequestration. So while afforestation in the tropics presumably leads to a net cooling effect, albedo and low carbon storage potential decrease its effectiveness in boreal regions (Arora and Montenegro 2011, Nature Geoscience 4: 514-518). Additionally, afforestation is projected to result in strong food price increases due to a competition for land with food production (Calvin et al. 2014 Climate Change 123: 691-704).

In this study, we investigated food price impacts of different afforestation scenarios with the model of agricultural production and its impacts on the environment (MAgPIE). In the model, afforestation resulted from an increasing CO_2 price until the end of the century, while the food demand of a growing population also had to be fulfilled. The scenario setting considered the latitudinal difference in afforestation effectiveness by restricting its use to certain regions. Afforestation was either allowed globally, everywhere except the boreal zone or only in the tropics. In addition, we assessed how food prices responded to trade liberalization in each of the scenarios.

All our afforestation scenarios showed an increase in food prices. The effect was strongest if afforestation was allowed globally, and slightly lower if boreal regions were excluded. Limiting afforestation to tropical regions lead to a much lower increase in the global food price, while regionally the effect was still pronounced. For all scenarios our study showed that an increase in international trade could partially alleviate food price impacts of afforestation.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Engineering the climate to address a looming crisis? A case of technologization

Judith Kreuter // University of Münster

This paper presents a theoretical framework for assessing the influence of the crisis discourse on the choice of technological means to address political issues. This technologization framework will be the basis for a systematic empirical study into the circumstances under which climate engineering (CE) measures might be developed and potentially even deployed.

The paper is divided into four parts: First, the paper discusses the underlying theoretical concept of Social Constructivism. The second part includes the theoretical framework of securitization and the claim voiced in the literature that this framework does not apply to the case of climate change. The third part of the paper presents the framework of technologization as an alternative to analyze the case of climate change. The fourth part of the paper discusses the applicability of the technologization framework to the case.

The framework of technologization is based on the theory of Social Constructivism, which states that social reality is not objectively given, but rather constructed through ideas which are produced through discourse, i.e. language. Accordingly, the way in which climate change is constructed in discourse can help explain how it is addressed. The framework describes the process in which topics are discursively constructed as a crisis which needs to be addressed through the extraordinary measure of application of technology. This contributes to addressing the puzzle that, while climate change has been declared an existential threat, no securitization of the issue has taken place. The concept of crisis consists of an objective threat that offers only limited time to act under conditions of uncertainty concerning the consequences of actions. Extraordinary technological measures are used if, simultaneously, a potentially feasible technological option exists to address the threat and a technologically progressivist scientific community supports research into this technology.

Integrated assessment of mitigation and carbon dioxide removal technologies

Elmar Kriegler // Potsdam Institute for Climate Impact Research
Florian Humpenöder // Potsdam Institute for Climate Impact Research
Jessica Strefler // Potsdam Institute for Climate Impact Research
Nico Bauer // Potsdam Institute for Climate Impact Research
Ulrich Kreidenweis // Potsdam Institute for Climate Impact Research
Alexander Popp // Potsdam Institute for Climate Impact Research

The integrated assessment of mitigation pathways to limit global warming to 2 degrees has shown the potentially important role of carbon dioxide removal (CDR) technologies (Clarke et al., 2014, Chapter 6: Transformation Pathways, IPCC Fifth Assessment Report of Working Group III). The admissible amount of future cumulative emissions (the so-called carbon budget) has become so small that negative emissions may be needed to offset excess emissions in the past or residual emissions in sectors such as agriculture and transport (Kriegler et al., 2013, Climatic Change 118: 45-57). So far, integrated assessments have mainly considered bioenergy combined with carbon capture and storage (BECCS) as the only CDR option to produce negative emissions. Land use trade-offs have given rise to concerns about the sustainability of large-scale BECCS deployment (Fuss et al., 2014, Nature Climate Change 4: 850-853). BECCS is, however, not the only option for removing CO_2 from the atmosphere.

This presentation will put the debate about the role of CDR for achieving ambitious climate targets into a broader context by considering a larger set of CDR options such as BECCS, afforestation and enhanced weathering .The presentation will review the existing literature on the use of BECCS in 2°C mitigation scenarios, and how it may be altered if afforestation or enhanced weathering are added to the portfolio of technology options. To this end, the trade-offs between BECCS and afforestation (based on the results of Humpenöder et al., 2014, Environmental Research Letters 9, 64029), and between BECCS and enhanced weathering, in mitigation scenarios will be investigated. Furthermore, the total deployment of CDR options as well as the trade-offs and synergies between CDR and other mitigation options will be analysed, and put into the broader context of the debate to what extent CDR options can be an effective, sustainable and ethically defensible strategy to reach ambitious climate targets.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Sequestration of Inorganic Carbon via Forestation

Joel Kronfeld // Tel Aviv University
Murray Moinester // Tel Aviv University
Israel Carmi // Tel Aviv University
Dorothy Godfrey-Smith // National Defence Headquarters (NDHQ)

We propose tackling atmospheric CO_2 reduction using a low-tech method to reverse the secondary processes of deforestation, specifically in semi-arid regions. These areas, which comprise over 15% of the global land mass, are characterized by erratic and low amounts (25-50 cm/yr) of precipitation. This area is marked by a thick unsaturated zone (USZ) where plants can develop deep root systems. Because plant roots respire, they continuously pump CO_2 into the USZ (along with decay of organic matter in soils which also produces CO_2), such that the CO_2 concentration in soil gas can be orders of magnitude greater than in the atmosphere. The resulting USZ aqueous solution contains dissolved inorganic carbon (DIC) compounds in dynamic equilibrium. The HCO_3– bicarbonate component in the DIC interacts with soil minerals to form and then precipitate a variety of secondary carbonate salts; the carbonate precipitation rate from soil moisture within the USZ, as measured so far in Israel, is approximately 15 mg/L/ year. Considerably more of the CO_2 released as soil gas is flushed downwards in the form of the soluble bicarbonate anion by percolating recharge water. This is added to the groundwater in the underlying aquifer. Planting trees and appropriate shrubs over semi-arid areas will increase sequestration of atmospheric CO_2 into USZ groundwater and sediments, and into underlying aquifer groundwater. Provisionally, we use the Israeli data to make a rough estimate of how much atmospheric CO_2 may thereby be vacuumed out globally, and then stored at depth via forestation. Our very rough global sequestration estimate is ~1 Pg CO_2 yr-1 via inorganic storage in the USZ and in the underlying groundwater. This value is the same order of magnitude as the rate by which the CO_2 in the atmosphere is increasing. This represents a rather sustainable possibility to retard the rate by which CO_2 is increasing in the atmosphere. Estimates from other semi-arid regions are needed for comparison.

5 | PERCEPTIONS OF AND PERSPECTIVES ON CLIMATE ENGINEERING RESEARCH AND DEPLOYMENT

What if we could cure climate change?

Tim Kruger // University of Oxford

The field of climate engineering is populated with technological imaginaries - proposed technologies that are characterised by great uncertainty as to their feasibility, scalability and desirability. This talk explores the issue of what might constitute success for climate engineering technologies through a medical framing and examines the strengths and weaknesses of such a framing. It also considers the consequences (both positive and negative) resulting from the development of technologies that could safely, cheaply and scalably remove carbon dioxide from the atmosphere.

Synthesizing Uncertainties

Johannes Lenhard // Bielefeld University
Martin Carrier // Bielefeld University

Regarding its organization, CE is calling for contributions from several scientific disciplines. Regarding its methodology, CE will have to be based heavily on simulation modeling. A main point is that these two aspects are interdependent. More precisely, we want to address how (different) uncertainties get, or should get, synthesized when different simulation models get coupled.
Here, two issues interfere. The first is uncertainty in a conceptual sense, i.e. what are relevant types of uncertainty? The second is about the technical dimension: How can or should we deal with uncertainty when different simulation models get coupled, each bringing in their uncertainties? Our contribution will address these questions in three steps.
(i) Three types of uncertainties will be distinguished: risk where we already have in hands a probability distribution. Second, there is uncertainty, or uncertainty proper, where the location and reasons of uncertainty are known, but cannot be estimated quantitatively. Third, we have deep uncertainty where there is missing knowledge about the actual reasons for uncertainty.
(ii) In a sense, uncertainties seem to proliferate and the question then is what kind of result or statement can be upheld without a cloud of caveats around it. Robustness arguments can support statements that seem to be more certain than their conditions are. However, robustness arguments are also limited. We will argue about the power and the limitations of robustness.
(iii) The third part will draw lessons from the conceptual analysis. We will focus on pitfalls of integration, i.e. particular dangers of misapprehending uncertainties when integrating simulation models. Our analysis will use integrated assessment models as an example that has relevant similarities to climate engineering. This study will give us opportunity to discuss whether integrated models are synthesizing uncertainties or whether they are making uncertainties disappear.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Risks and Conflicts of Climate Change and Climate Engineering – Governing Pathways and Path Dependencies

Jürgen Scheffran // University of Hamburg
P. Michael Link // University of Hamburg
Jasmin S.A. Link // University of Hamburg

Potential consequences of climate engineering (CE) pathways will be compared with climate change for different mitigation strategies. CE raises difficult environmental, political and ethical questions that could provoke risks, frictions and geopolitical implications, including complex conflict constellations from local to global levels, resource competition, resistance against CE impacts, security dilemmas, and power games on climate control. Exemplary cases will be discussed with regard to impacts on biodiversity, water and food, public health and social inequality, termination effects, dual-use, and conflict risk.
We analyze how path dependency will affect the likelihood of different scenarios and the scale of possible impacts. Whether CE deployment leads to conflict depends on the behavior of people affected or involved in that situation. Knowledge about the strength of path dependency with regard to sticking to a high emission path can help in estimating future human behavior. And thus, plausible or relevant consequences of a CE deployment can be determined and weighted in a social context. Simulations allow the visualization of potential dynamics and feedback loops within the networks of potential impacts of such an SRM deployment, help to reconsider the potential costs of failed climate mitigation and may reshape the calculations of humankind's switch to a low emission path.
The presentation provides a mapping of the problem landscape and identifies knowledge gaps and research questions. Expected outputs are a comparative assessment of CE pathways regarding risk and conflict dimensions as well as risk avoidance, conflict resolution, security and cooperation in an anticipative and adaptive governance framework under uncertainty. Such framework is based on the evolving state of knowledge, possible perceptions and responses of affected groups, as well as guardrails and adaptive mechanisms for risk prevention.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Simulating a Climate Engineering Crisis. Climate politics simulated by students in Model United Nations

Nils Matzner // Alpen-Adria University

This poster is based on experimental teaching methods in Political Science classes. It presents scenario, method, and results from three participatory simulations.
Climate Engineering (CE) technologies are of high risk and therefore controversial. We employed the concept of CE to build a crisis scenario for a participatory simulation of international climate politics. This paper reports an example of student simulations with Model United Nations (MUN). It also provides some insights into how international conflicts affected by CE could be handled. Material from three simulation runs indicate that students tried experimental learning that went beyond instructional teaching of international politics. We recorded, observed, and evaluated the simulation with the students. For interpretation of the materials we had a closer look at the following categories: (1) divergent interests, (2) power struggle, (3) technical and political ignorance, (4) risk politics, and (5) deciding with a lack of knowledge. Moreover, crucial problems of CE, such as technical/social ignorance and risk politics, are highlighted and compared with recent studies.

5 | PERCEPTIONS OF AND PERSPECTIVES ON CLIMATE ENGINEERING RESEARCH AND DEPLOYMENT

Responsibility and governance in the climate engineering discourse of science and policy

Nils Matzner // Alpen-Adria University
Daniel Barben // Alpen-Adria University

This presentation is based on the research project "How to Meet a Global Challenge? Climate Engineering at the Science-Policy Nexus: Contested Understandings of Responsible Research and Governance" (AAU Klagenfurt and TU Darmstadt) funded by the DFG's Priority Programme 1689.

The overall objective of the project is a better understanding of how CE has emerged, and will continue to emerge, as a field of research and technology development that has the potential to change the ways in which the global challenge of climate change has been addressed both scientifically and politically, by investigating the ways in which actors concerned with CE articulate and value its challenges and opportunities both within (TUD) and beyond (AAU) the PP. By situating the PP in the broader landscape of debate and decision-making, we also aim at advancing capacity building in the PP, enabling it to better understand, and operate in, the unfolding network of CE-related controversies, interactions and strategies.

We will first argue that with regard to climate change the science-policy nexus is of key strategic importance because of the interrelations between scientific assessment of climate research, science-based policy advice, and policy making. Outlining preliminary results of the Work Package on "CE, responsible research and governance: discourses in scientific and policy arenas", second, we will present our approach to a both quantitative and qualitative discourse analysis across various domains (i.e. science, policy making, and civil society). Based on a comprehensive corpus of CE-related publications compiled in the project, we will outline the conceptual significance and articulations of responsibility and governance in light of fundamental challenges, such as uncertainty and risk. Against this background, third, we will interpret the findings with regard to the discursive configuration of CE as a "third option" of climate policy and provide an outlook on further research.

4 | A COMPARATIVE VIEW ON CLIMATE ENGINEERING OPTIONS AND ASSESSMENT METRICS

Climate consequences of large-scale herbaceous biomass plantations employed as climate engineering tools

Dorothea Mayer // Max Planck Institute for Meteorology
Daniela Kracher // Max Planck Institute for Meteorology
Christian Reick // Max Planck Institute for Meteorology
Julia Pongratz // Max Planck Institute for Meteorology

Enhancing terrestrial carbon sinks is much-discussed as a climate engineering method both in politics and science. The debate focuses mostly on its potential for carbon sequestration and fossil-fuel substitution, whereas other effects such as changes in heat and water fluxes are often ignored. We assess potentials and side-effects of two different land-use types suggested as climate engineering tools, forest and herbaceous biomass plantations.

We integrated herbaceous biomass plantations as new plant functional types into the land component (JSBACH) of the Max-Planck-Institute Earth System Model (MPI-ESM). Herbaceous biomass plantations alter surface albedo, carbon and water cycles compared to forests. We adapted the JSBACH carbon cycle (assimilation and respiration) to reflect a highly productive biomass grass and the phenology to increase the realism of harvest dates. Where possible, the model was validated using yield measurements and water-use efficiency calculations available from literature data.

The potentials and side-effects of afforestation and herbaceous biomass plantations are compared in a plausible global scenario: under the representative concentration pathway (RCP) 4.5, large areas of agricultural lands are abandoned as food production intensifies on the most productive soils. We model the climatic consequences of using these abandoned croplands for afforestation or biomass plantations, under an RCP 8.5 forcing (high CO_2 emissions). We emphasize differences between biogeochemical and biogeophysical effects of land-use on climate and how these factors interact on the local and global scale. Apart from direct climatic effects (energy, water, and carbon fluxes), we consistently account for fossil-fuel substitution effects of biomass plantations in a coupled model.

4 | A COMPARATIVE VIEW ON CLIMATE ENGINEERING OPTIONS AND ASSESSMENT METRICS

What is the best measure of justice in climate engineering assessment?

Duncan McLaren // Lancaster University

Advocates and opponents of climate engineering both support their positions with arguments about justice. Such arguments draw on a range of – often contested – philosophical and cultural conceptions of justice. This paper seeks to review the merits of different approaches to justice as a means of supporting judgements about climate engineering. It addresses a range of approaches: including distribution, recognition, capabilities, rights, procedural, utilitarian, restoration, egalitarian and sufficientarian; and the metrics each might involve, to make an initial assessment of their practical capacity to assist with policy making on climate engineering.

The paper will examine each approach against three basic questions. First, how far do they help us to meaningfully compare or contrast the justice of climate engineering in comparison with mitigation and adaptation responses to climate concerns? Second, how far do they help us to meaningfully compare or contrast the relative justice of different proposals for climate engineering (including different categories, techniques and applications)? Third how well do they encompass or reflect public or political concerns about the potential justice implications of climate engineering?

The paper will test the various justice conceptions against both carbon dioxide removal and solar radiation management forms of climate engineering. It will consider both international and intergenerational dimensions of justice. It will draw conclusions on the appropriate framing of debate and assessment of climate engineering by policy makers and researchers; the implications for institutions and governance for climate engineering research and deployment; and on the next steps in development of a multi-dimensional assessment metric of justice, including further research to fill information gaps regarding public views and cultural variations in conceptions of justice, and more widespread public engagement and deliberation.

2 | EXPLORING CLIMATE ENGINEERING UNCERTAINTIES

Comparative assessment of detectability and robustness of Climate Engineering impacts

Nadine Mengis // GEOMAR Helmholtz Centre for Ocean Research Kiel
David Keller // GEOMAR Helmholtz Centre for Ocean Research Kiel
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Julia Pongratz // Max Planck Institute for Meteorolog
Christian Reick // Max Planck Institute for Meteorolog
Tatiana Ilyina // Max Planck Institute for Meteorolog

For the comparative investigation of Climate Engineering (CE) impacts, simulations of the University of Victoria Earth System Climate Model (UVic ESCM) and the Max Plank Institute Earth System Model (MPI-ESM) are used.
Both modeling groups performed three CE simulations (Reforestation, Ocean Alkalization and Radiation Management) under the RCP8.5 emissions scenario with the target of reaching the radiative forcing of the RCP4.5 emissions scenario. In addition to these simulations, the UVic ESCM modeling group performed various sensitivity analyses with respect to temperature and CO2 sensitivities of badly constrained model parameters. These included variations in model parameters such as the sensitivity of marine and terrestrial biological production to temperature and CO2 levels as well as air to sea gas exchange coefficients or the vertical diffusivity. These analyses should provide the basis for a better understanding of uncertainties inherent in model-based assessments of CE schemes.
Using this data, the robustness of the models response to CE is evaluated by comparing the reactions of the two models to the same forcing. Thereby, the parameter sensitivity range of the UVic ESCM gives information on the uncertainty in the future development concerning badly constrained model parameters and the MPI-ESM shows the sensitivity of the future projections to internal model uncertainty from noise.
By comparing the differences of the CE simulations to the reference RCP8.5 simulations, we can obtain information on the detectability of the respective CE measure.

Selecting Indicators from Earth System Metrics to assess Solar Radiation Management and Afforestation

Nadine Mengis // GEOMAR Helmholtz Centre for Ocean Research Kiel
Wilfried Rickels // Kiel Institute for the World Economyl
David Keller // GEOMAR Helmholtz Centre for Ocean Research Kiel
Andreas Oschlies // GEOMAR Helmholtz Centre for Ocean Research Kiel

Measured, calculated, and forecasted quantitative variables (metrics) are used to assess the complex reality by indicating the state of a specific matter. For the specific matter of current climate change, most attention is usually devoted to global mean temperature, making it the most commonly used indicator among the various earth system metrics for climate change assessment.

Besides practical and social aspects for selecting global mean temperature over other possible indicators, its selection is justified by the aspect that other earth system metrics are often correlated with global mean temperature. However, in an engineered climate prevailing relationships between earth system metrics may no longer remain valid. Consequently, assessment of CE for climate change mitigation requires a comprehensive discussion of the indicator selection process from the earth system metrics.

The (implicit) selection of indicators for the assessment of CE is not based on any set of agreed guidelines or a comprehensive discussion and is therefore, even though in a kind of scientific consensus, a normative choice in the assessment of CE.

Based on a parameter sensitivity analysis of the UVic ESCM (University of Victoria Earth System Climate Model), correlation between the most commonly used Earth system metrics are calculated. These analyses give information about the physical connection of the Earth system metrics during the historical period, under climate change, and the changes of these connections in case two different CE measures are implemented.

An exemplary aggregation of metrics that are found to be uncorrelated, form a set of indicators, which are used to evaluate the different CE methods against the climate change simulation.

5 | PERCEPTIONS OF AND PERSPECTIVES ON CLIMATE ENGINEERING RESEARCH AND DEPLOYMENT

Does knowledge of stratospheric sulphate injection change individual efforts to mitigate climate change?

Christine Merk // Kiel Institute for the World Economy
Gert Pönitzsch // Kiel Institute for the World Economy
Katrin Rehdanz // Kiel Institute for the World Economy

The injection of sulphate into the stratosphere might develop into an effective measure against global warming in a few decades. Scientific knowledge about the technology, however, is currently limited and its many risks caution against its use. A major risk is that knowledge about the potential climate effect of sulphate injection or its actual deployment could make people reduce their mitigation efforts. This counter-argument is called risk compensation, moral hazard, or mitigation obstruction. If sulphate injection reduced the risks from climate change while at the same time causing only minimal side-effects this response would be individually rational. However, today's consumption level would be maintained at the risk of a technological lock-in of future generations. In our paper, we analyse how learning about sulphate injection changes people's short-term willingness to mitigate climate change. We use data from a framed field experiment. The control group receives only information on climate change. The treatment group additionally receives information on sulphate injection and its risks. All subjects have the opportunity to buy CO_2-certificates after they have received the information. If treated subjects buy less certificates than subjects in the control group this would support the hypothesis that information on sulphate injection as a measure against climate change leads to risk compensation, i.e., mitigation obstruction. If the treated subjects buy more certificates this would support the hypothesis that knowledge of sulphate injection increases mitigation efforts. The fieldwork will be finished by April 2015.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Navigating Complexity in the Governance of Climate Engineering Technologies

Ina Möller // Lund University

Underlying not only the issue of governing climate engineering technologies but also climate change in general (and any other policy area of global relevance) are the methods of governance and, more concretely, the interaction and cooperation of actors involved. While governments have been trying to reach a binding agreement at the international level for over twenty years, the overall climate regime and it's participating actors has become a complex network of institutions trying to address the problem at different levels and from different perspectives. Its complexity has led onlookers to term the current global governance regime as 'congested' and confused, with a whole strain of academic literature evolving around the capture, description and analysis of such complex governance systems. It is within this field that I position myself and from where I start my analysis of climate engineering governance. Using Social Network Analysis as my principle method, I will map and analyse the policy area, its actors and their interactions as one entity. By looking at the case of climate engineering governance I not only hope to provide important insights to the development of governance in this particular policy field, but also to contribute more general knowledge and understanding about processes of interaction and cooperation in situations of fragmentation and uncertainty. In this presentation, I will outline my research project, the questions that I am after and the research design I will apply in my analysis.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Understanding the slippery slope argument against further climate engineering research

David Morrow // George Mason University

The "slippery slope" argument against small-scale outdoor climate engineering experiments is, roughly, that such experiments are a bad idea because they will inevitably lead to undesirable outcomes, such as unwise deployment of climate engineering technologies. Despite its importance for pressing questions about the conduct and governance of small-scale outdoor experiments, the slippery slope argument has received far less attention than other arguments against further research. As a result, most discussions of the slippery slope argument are too vague to provide helpful guidance for researchers, funders, or policymakers. By collecting what we think we know about the slippery slope and providing a framework for thinking further about it, this talk provides a launching pad for in-depth discussion of the slippery slope argument within and beyond the climate engineering research community. To that end, this talk will explain the logic needed for a cogent slippery slope argument against small-scale outdoor experiments; collect and expand on existing suggestions for why small-scale outdoor experiments of one kind or the other might put us on a slippery slope to somewhere undesirable; identify special complexities in climate engineering, mainly related to uncertainty and dynamic preferences, that make it difficult to evaluate the slippery slope argument; and highlight some norms and institutions that might make the slope less slippery.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Model simulations of the potential for stratospheric ozone loss under conditions of enhanced water vapour and sulphate aerosol

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Bärbel Vogel // Forschungszentrum Jülich
Simone Tilmes // National Center for Atmospheric Research

Solar radiation management through stratospheric sulphate aerosols would lead to enhanced surface area densities of stratospheric aerosol. It has been suggested that together with enhanced water vapour, convectively injected into the stratosphere, this aerosol could lead to increased risks of ozone loss, potentially substantially enhancing UV dosage levels in summer over populated areas (Anderson et al., Science, 2012). It has also been suggested to conduct a stratospheric controlled perturbation experiment to allow a better assessments of these risks associated with SRM to be made (Dykema et al., Phil. Transact., 2014).

Here we report on results of a three-dimensional model study addressing the issue. We use the Chemical Lagrangian model of the Stratosphere (CLaMS), a three-dimensional chemistry transport model, which is well suited for the description of stratospheric mixing and for the preservation of transport barriers (like the tropopause) in simulations. Further CLaMS simulates the full stratospheric chemistry, including the heterogeneous chemistry on cold sulphate aerosol. We will present preliminary results for the impact of enhanced water vapour and sulphate aerosol on the stratospheric ozone in summer. These results will also allow and assessment of the benefits and potential problems of the proposed stratospheric experiment.

5 | PERCEPTIONS OF AND PERSPECTIVES ON CLIMATE ENGINEERING RESEARCH AND DEPLOYMENT

Climate Intervention in Africa: Perspectives based on Analogies from International Conventions on Response to Climate Change

Cush Ngonzo // Kenyatta University
Rose Akombo // Kenyatta University
Mary Mutiso // Kenyatta University

Global warming is steadily threatening ecosystems and their biological lives across the globe. Though life the equatorial and tropical regions is associated with hot temperatures rather than cooling, the drastic decrease of forest cover and major vegetations in the last century may be an argument for adoption of the principle of large-scale Climate Intervention (also known as Geoengineering) through Carbon dioxide removal (CDR) and albedo modification technologies. CDR may especially be scaled up as a "plan B" to climate mitigation to supplement African governments' efforts to reduce planned GHG emissions and avoid suicidal climate mitigation and adaptation strategies. These schemes may be cheap and effective climate "mitigation" options but they may be dangerous, the safe options being expensive or useless. Besides, most of the countries in the African continent do not have the ability to invest in what are considered as "harebrained schemes, which impacts are yet to be ascertained". Hence, African countries' position vis-à-vis CI deployment is likely to follow the trend of their ratification of the Kyoto Protocol, UNFCCC, UNCBD and REDD+ Agreements. This paper simulates different responses to CE deployment based on the practice of international law in Africa, depending on expected funding for research and institutional capacity development to improve the quality of life.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Climate extremes in multi-model simulations of stratospheric aerosol- and marine cloud brightening climate engineering

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Martin Quaas // Kiel University
Ulrike Niemeier // Max Planck Institute for Meteorology
Helene Muri // University of Oslo
Johannes Quaas // University of Leipzig

Simulations from a multi-model ensemble for the RCP4.5 climate change scenario for the 21st century, and for two solar radiation management schemes (stratospheric sulfate injection, G3, and marine cloud brightening, G3SSCE) have been analyzed in terms of changes in the mean and extremes for surface air temperature and precipitation. Study involve three ESM namely, MPI-ESM, NorESM and IPSL. The climate engineered (SRM 2060s - RCP4.5 2010s) and termination (2080s - 2060s) periods are investigated. During the climate engineering period, both schemes, as intended, offset temperature increases by about 60% globally, but are more effective in the low latitudes and exhibit some residual warming in the Arctic (especially in the case of marine cloud brightening that is only applied in the low latitudes). In both climate engineering scenarios, extreme temperatures changes are similar to the mean temperature changes over much of the globe. The exception is in Northern Hemisphere high latitudes, where high temperatures (90th percentile of the distribution) of climate engineering relative to RCP4.5 rise less than the mean and cold temperatures (10th percentile) much more than the mean. Temperature extremes by fixed thresholds, namely number of frost days and summer days, it is found that both climate engineering experiments are not completely alleviating the changes relative to RCP 4.5. The reduction in 2060s dry spell occurrence over land region in G3-SSCE is mostly similar to that for RCP4.5. Experiment G3 experiences a slight increase in the length of dry spells. A strong termination effect is found for the two climate engineering schemes, with large temperature increases especially in the Arctic. Mean temperatures rise faster than the extremes, especially over oceans, with the exception of the Tropics. Conversely precipitation extremes rise much more than the mean, even more so over the ocean, and especially in the Tropics.

2 | EXPLORING CLIMATE ENGINEERING UNCERTAINTIES

Buying time with climate engineering? Analyzing the different notions of the Buying Time and Peak Shaving argument.

Frederike Neuber // Karlsruhe Institute for Technology

We seem to run out of time when dealing with climate change. Climate Engineering might just be the device to buy us that extra time. That reasoning gives rise to the so-called "Buying Time Argument", which has been among the commonly used arguments in favour of Climate Engineering for years. Surprisingly, however, the buying time argument has not yet been spelled out in much detail. Just how does a CE technology buy more time and what are we to do with this extra time?

Another similar idea is expressed in the "Peak-Shaving-Argument" that has been evoked in recent literature. Climate Engineering could be used to shave the peak off dangerous climate change, thus giving us more time to change society towards low-carbon. But what peak is that and how long will it take to shave it off?

Here I whish to explore the notions underlying the Buying Time and the Peak Shaving Argument. It seems that there are a few very distinct CE-deployment scenarios (or policy mixes) that would support the idea of "buying time" via CE. Those need to be evaluated carefully concerning effectiveness, costs and side-effects, as well as ethical issues. However straightforward the Buying Time Argument might seem, its underlying reasoning is not.

2 | EXPLORING CLIMATE ENGINEERING UNCERTAINTIES

Is there a Limit of Sulfate Injections for Climate Engineering?

Ulrike Niemeier // Max Planck Institute for Meteorology

The injection of sulfur dioxide into the stratosphere to form an artificial stratospheric aerosol layer is considered as an option for the reduction of solar radiation to counterbalance the impact of anthropogenic climate change. The related reduction in radiative forcing depends upon the injected amount of sulfur.

Studies of the microphysical evolution of sulfate concentration show a decrease in efficiency with increasing injection magnitude, however, none of these studies consider injection strengths above the 10

Mt(S)/y necessary to counteract the strong anthropogenic forcing expected if 'business as usual' conditions continue throughout this century. For this numerical study we calculated the forcing of strong sulfur injections up to 100 Mt(S)/y, and estimate the reliability of the given results by varying the injection strategy and compare the results to previous studies. Our calculations show that the efficiency of the aerosol layer, expressed as the relationship between sulfate aerosol forcing and injection strength, has the form exponential decay. This result implies that the solar radiation management strategy required to keep temperatures constant at that anticipated for 2020, whilst maintaining 'business as usual conditions', would require atmospheric injections of the order of 60 Mt(S)/y which amounts to 5 - 10 times that emitted from of the Mt.~Pinatubo eruption each year.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

The ISA method

Franz D. Oeste // gM-Ingenieurbüro

Reverse of global warming (GW) is possible by controlled application of the Ice Age climate cooling process. Natural refrigerant during the glacial epoch had been the loess dust particles coated by soluble iron salts. Modifying this nature process we created the Iron Salt Aerosol (ISA) method (IM). Virtual causes of the global warming problem are combustions. Instrumentalizing combustions as ISA emitters change them from CO_2 emitters to CO_2 decomposers.

Ship engines, jet turbines, power works, combustion-free wind and sunshine power generation can act as process components in the order to generate ISA. IM acts as multi-stage cooling in the environments troposphere (T), dry solid sunlit surfaces (D), ocean (O), and ocean sediment (S):

- T Cloud reflectance, CH_4 oxidation, and black carbon oxidation increase
- D CH_4 oxidation increase
- O CO_2 conversion to organic carbon increase
- T DMS-dependent cloud reflectance increase by phytoplankton fertilizing
- S (O, T) CO_2 conversion increase by phytoplankton fertilizer emission increase
- S CO_2 absorption increase by CH4 hydrate, dolomite, and lime precipitation
- S CH_4 emission decrease by iron ferment supported CH4 sulfate oxidation

The actual global aerosol input of 250,000 t soluble iron per year presents the maximum ISA emission size, fitting an economical feasible order, easy to realize by mankind over decades. IM has Ice Age verification by realizing temperature drops (TD) up to 10 °C without doing irreversible harm to the environment. GW reversal needs a TD of 1 °C only.

Continuing the common use of fossil carbon resources by sustained conversion of flue gas CO_2 into fossil carbon resources is IM's main opportunity.

Global fixing regulations of the price values of CO2 and CH4 emission certificates and ISA CO_2 and CH4 destruction certificate credits are simple but effective measures to quickest world-wide implementation of IM.

Simulated impacts and side effects of multi-centennial climate engineering

Andreas Oschlies // GEOMAR Helmholtz Centre for Ocean Research Kiel
David Keller // GEOMAR Helmholtz Centre for Ocean Research Kiel

Whether referred to as a potential emergency operation or prudent precautionary measure, climate engineering would, if ever deployed, almost certainly be carried out for many decades and probably many centuries in order to have a lasting impact on climate. Most modeling studies performed so far focused on simulations covering this century, corresponding to the time scale typically considered by international climate policy and the IPCC. However, stopping potential climate engineering at the end of this century would, in the absence of drastic CO_2 emission cuts, probably not be a safe option for at least some of the currently discussed methods. Longer-term consequences of committed changes and exit strategies have to be accounted for in any comprehensive assessment of climate engineering. Here we report results of simulations with an intermediate complexity Earth system climate model (UVic ESCM), in which we extend climate engineering deployment until the year 3000, for an RCP/ECP 8.5 business-as-usual CO_2 emission scenario with emissions peaking in the year 2100, ramping down to a few GtC/yr by 2250 and to zero emissions by year 3000. The climate engineering schemes tested include a reduction in solar irradiance, ocean alkalinization, ocean iron fertilization, artificial upwelling, and afforestation. We find that their efficiencies, side effects and termination effects exhibit considerable differences on the millennial time scale considered here with respect to earlier studies restricting the analysis to the 21st century.

2 | EXPLORING CLIMATE ENGINEERING UNCERTAINTIES

The high-latitude impact of climate engineering using tropical stratosphere sulphate aerosol

Scott Osprey // NCAS, University of Oxford
Lesley Gray // University of Oxford
Jim Haywood // University of Exeter
Andy Jones // University of Exeter

Discussions of our response to climate change invariably involve issues of adaptation and mitigation. The former presupposes unavoidable climate consequences and recognises a need to lessen their impact. The latter attempts to lessen the effects of increasing greenhouse gases (GHG) by (1) reducing GHG emission, (2) creating CO_2 sinks (e.g. carbon sequestration) or by blocking the effects of solar radiation (solar radiation management - SRM).
The SPICE project was set up to investigate the feasibility of implementing a practical method of SRM using the stratospheric injection of aerosols. SPICE remit includes: engineering design for the delivery of stratospheric aerosol, laboratory measurements for characterising the properties of optimal aerosol, and modelling studies looking into the parameterisation and impact of stratospheric aerosols within a state-of-the-art global climate model. The project has also pressed for the need for governance of climate engineering research.
We describe idealised experiments investigating the environmental impact following sulphate aerosol injection into the tropical low-mid stratosphere. We compare a geoengineering scenario (GeoMIP G4), which includes a constant injection rate of SO_2 (5Tg/year) beginning at 2020, against a control simulation of increasing greenhouse gas forcing, as outlined by the CMIP5 RCP4.5 scenario. We use the well-documented stratosphere-resolving Hadley Centre model, which has been employed in previous CMIP5 and climate engineering studies. We examine for high-latitude impacts following tropical aerosol injection, and in particular the Holton-Tan effect observed in the wintertime extratropical stratosphere. These dynamical sensitivities provide an important link, bridging tropical stratosphere forcing with the near-surface response often seen at high latitudes.

Exploring the 'termination shock'

Andy Parker // IASS Potsdam
Peter Irvine // IASS Postdam

If deployment of SRM were stopped suddenly it could lead to a rapid rise in global temperatures, which would probably be even more damaging than the slower warming from unchecked climate change. This effect – known as the 'termination shock' – is an influential idea in SRM discussions, and for some commentators it is one of the greatest potential threats from the development of geoengineering. This presentation will outline the science behind the termination shock, but its main focus will be the socio-political dimensions, and the drivers that might cause sudden termination, such as terrorism, economic collapse, natural disasters, or the discovery of damaging side effects. It will explore the pathways by which each of the drivers might lead to SRM being stopped, reviewing where technical and political responses might help avoid termination or reduce its impacts. Based on the analysis of the different pathways, the presentation will question whether the risk of termination shock has been overplayed in geoengineering commentary.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Climate Engineering, Liability Regimes and Information

Tobias Pfrommer // Heidelberg University
Timo Goeschl // Heidelberg University

Large scale trials or actual deployment of CE requires an international legal framework. One important task of such a framework is the regulation of compensation between States for damages associated with CE interventions. Liability regimes are a traditional means to organize compensation. Besides considerations of equity, such compensation also serves economic efficiency: Without liability agents would only have to consider the costs of CE interventions being incurred by themselves, neglecting costs and risks to third parties. The prospect of liability leads to the internalization of these otherwise external costs.
The two principal liability rules are strict liability and negligence. Under strict liability an injurer must compensate victims in any case he causes harm, whereas compensation under negligence requires a misconduct of the injurer, the failure of taking due care. Since an injurer does not have to compensate in all cases under negligence, strict liability is superior to negligence if only the injurer's risk externality is of interest. For CE this is not the case: Since CE is a novel technology with poorly understood risks, deployment leads to learning about these risks, hence to the possibility of better decision-making regarding CE in the future. As this information is public, everybody can make use of it, giving rise to a positive information externality on top of the negative risk externality. We show with the help of a simple two-stage model, that under dynamic considerations the superiority of strict liability is no longer guaranteed. We analyze what incentives strict liability and negligence provide for agents today, as well as which trade-offs between the well-being of deployers, victims today, and future generations they can address. We cautiously conclude that the optimal liability rule might depend on whether CE is undertaken in a way that provides information or not (e.g. by facilitating data collection through full transparency in advance).

5 | PERCEPTIONS OF AND PERSPECTIVES ON CLIMATE ENGINEERING RESEARCH AND DEPLOYMENT

Informed and Uninformed Opinions on New Measures to Address Climate Change

Gert Pönitzsch // Kiel Institute for the World Economy
Carola Kniebes // Kiel Institute for the World Economy
Christine Merk // Kiel Institute for the World Economy
Katrin Rehdanz // Kiel Institute for the World Economy
Ulrich Schmidt // Kiel Institute for the World Economy

Climate engineering (CE) and carbon capture and storage sub-seabed (CCS-S) are currently controversially debated options to address climate change. Our paper provides empirical evidence on the public perception of two different CE measures, namely, stratospheric sulphate injection (SSI) and afforestation, as well as CCS-S. Using data from a novel large-scale survey, we analyse the determinants of acceptance of these measures in Germany. We also provide experimental evidence on how additional information on these measures changes the respondents' acceptance. We show that the acceptance differs strongly between the three measures. Afforestation is strongly favoured over CCS-S and SSI. This ranking holds independent of the amount of information provided. For all three measures, we find that, on average, additional information decreases acceptance. However, the sign and the strength of the information effect strongly depend on personal characteristics, such as gender and risk attitude..

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Challenges Posed by Carbon Capture and Storage to the Environmental Policy and Legislation in China

Tianbao Qin // Wuhan University
Meng Zhang // Ghent University

Carbon capture and storage, a new climate engineering technology, aims at realizing low-carbon utilization of fossil fuels in a large scale. Recently based on some cooperation programs with the EU, despite the late start, China has made considerable progress in the development of CCS technology and projects. However, there are still many significant problems hindering its development. For instance, the energy penalty and cost are high; and the safety and reliability of long-term CO2 storage are to be demonstrated. As any coin has two sides, if it is out of regulatory control, CCS technology, just like a double-edged sword, may causes environmental damages.

Since 2006, the London Protocol has already opened a window to the development of marine geological carbon storage; Since the CCS directive was formulated in 2009, as the pioneer to address climate change, the EU has already established a sound regulatory framework for the governance of the CCS technology and projects. But as for China, compared to its remarkable progress of CCS practices in technical level, the formulation of the CCS legislation is still not on the government's agenda. Thus from a comparative perspective, an interesting phenomenon can be found that the EU has already established a legal framework for CCS, while in some member states, you even still cannot find a running CCS project. However on the contrary, in China, the country with the largest-scale demonstration CCS projects, there is even no CCS legislation or regulatory framework at present. As a country where the ruling communist party operates in a central planning mode, the Chinese government and ruling party's like and dislike can make or break the future of the development of CCS. In the context of lack of legal governance and clear national policy and strategies on CCS development, it may expose the development of CCS to a "scissor-style" pressure and risk: from above, from the central government's ambitions and from below, from the large-scale demonstration projects without legal control. Thus based on China's cases and experiences, there is an urgent need for emerging countries to take actions to minimize the gaps between the legislation and the technical development of CCS in order to guide the development of CCS on a sustainable and safety path.

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1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Revisiting ocean carbon sequestration by direct injection: A global carbon budget perspective

Fabian Reith // GEOMAR Helmholtz Centre for Ocean Research Kiel
David Keller // GEOMAR Helmholtz Centre for Ocean Research Kiel
Andreas Oschlies // GEOMAR Helmholtz Centre for Ocean Research Kiel

Marchetti [1977] proposed that CO_2 could be directly injected into the deep ocean to mitigate its rapid build-up in the atmosphere. Although previous studies have investigated biogeochemical and climatic effects of injecting CO_2 into the ocean, they have not looked at global carbon cycle feedbacks and backfluxes that are important for accounting. Using an Earth System Model of intermediate complexity we simulated the injection of CO_2 into the deep ocean during a high CO_2 emissions scenario. At seven sites 0.1 GtC yr^{-1} was injected at three different depths (3 separate experiments) between the years 2020 and 2120. After the 100-year injection period, our simulations continued until the year 3020 to assess the long-term dynamics. In addition, we investigated the effects of marine sediment feedbacks during the experiments by running the model with and without a sediment sub-model.
Our results, in regards to efficiency (the residence time of injected CO_2) and seawater chemistry changes, are similar to previous studies. However, from a carbon budget perspective the targeted cumulative atmospheric CO_2 reduction of 70 GtC was never reached. This was caused by the atmosphere-to-terrestrial and/or atmosphere-to-ocean carbon fluxes (relative to the control run), which were effected by the reduction in atmospheric carbon. With respect to global oceanic carbon, the respective carbon cycle-climate feedbacks led to an even smaller efficiency than indicated by tracing the injected CO_2. The ocean also unexpectedly took up carbon after the injection at 1500 m was stopped because of a deep convection event in the Southern Ocean. These findings highlighted that the accounting of CO_2 injection would be challenging.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Leveraging a solar climate engineering patent pool for international regulation of field experiments

Jesse Reynolds // University of Tilburg

Solar climate engineering (SRM) field experiments warrant some form of international regulation, even in the absence of expected transboundary impacts. This is presently difficult because no existing international legal institution has the clear authority and support to do so; because the relevant states have divergent interests; because SRM remains highly uncertain and dynamic; and because the scientists who would be both the regulatory targets and integral to regulation's development are resistant to potentially restrictive policies. This paper suggests a possible innovative means to overcome these challenges by linking the international regulation of SRM field tests to a voluntary intellectual property (IP) regime. Indeed, concerns over personal IP interests in SRM have been expressed inside and outside the SRM research community. There appears to be an emerging consensus that SRM should not be a for-profit enterprise and that researchers and scientific institutions should forego IP claims. However, that would not prevent problematic IP claims by outlying scientists and other actors. I suggest that a voluntary patent pool could act as a lever to induce participation in an emerging, broader, and responsive regulatory regime. Once a pool is established and seeded with key patents, scientists, institutions, funders, and state regulators would have incentives to join, while agreeing to abide by an array of broader research standards and best practices regarding e.g. public engagement, transparency, assessment, monitoring, and international coordination. Notably, such a mechanism does not require national governments or intergovernmental institutions in order to begin; transboundary private regulation may suffice. These standards could subsequently be gradually legalized. The presentation considers existing cases of international patent pools and of using IP access as a regulatory incentive, as well as potential legal, economic, and political impediments.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

Regulation of Radiation Management: Uncertainty and Incentives

Wilfried Rickels // Kiel Institute for the World Economy
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Spreading sulfur into the stratosphere or brightening marine clouds to reject incoming sunlight are discussed as measures to counteract extreme or even catastrophic climate change. These measures are examples for radiation management (RM)---low-cost, high leverage measures with the potential to influence the climate within the time span of a year. However, such a potential application would not allow compensating all aspects of climate change equally at the global and in particular at the regional level and would imply an uneven distribution of cost and benefits. Accordingly, a compensation scheme would be an essential element to achieve an international consensus on RM application, however, would have to deal with the attribution problem resulting from the highly variable climate system with stochastic events. We show that the regulation of nonsource point pollution can be extended to regulate RM application and that basing the tax and subsidy payments not on the level of RM but on observed changes in climate variables achieves the first-best level of RM application. We derive a mechanism to implement the RM compensation scheme and provide a quantitative example of its application in the year 2100.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

The Best of Both Worlds: Maximising the Legitimacy of the EU's Regulation of Geoengineering Research

Janine Sargoni // University of Bristol Law School

This paper argues that by adopting an 'incorporated' approach to assessing the risk of Solar Radiation Management (SRM) real-world research, the EU can import elements of Sabel and Zeitlin's 'directly deliberative polyarchy' into its otherwise orthodox constitutional regulatory approach, thereby maximising the possibility of securing legitimacy. The argument is new in so far as it juxtaposes two conceptions of procedural legitimacy – one institutional and the other functional – in the context of scientific uncertainty in the technocratic regulatory paradigm of the EU. The significance of the work is that it draws on these conceptions of legitimacy to advance a pragmatic model of institutional design which comprises procedures that maximise legitimacy with minimal disruption to the EU's institutional balance of powers.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

International Liability for Transboundary Damage Arising from Stratospheric Aerosol Injections?

Barbara Saxler // Trier University
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Modelling studies show that the implementation of stratospheric aerosol injections – be it for a large-scale experiment or actual deployment – could, by causing changes in the climate system, lead to considerable damage. Who would be liable for such damage? Is there a basis in international law for the equitable and effective compensation of victims?
In order to find answers to these questions, we have assessed the applicability of existing norms on State liability for damage arising from stratospheric aerosol injections. First, the customary rules on State responsibility would be applicable if a breach of international law was linked to an aerosol injection. However, we argue that in most cases these rules would not be capable of providing for the equitable and effective compensation for victims of harm caused by aerosol injections. In particular, it would already be hard to establish a breach of international law. Second, there are no liability rules that would cover damage resulting from internationally lawful aerosol injections. Due to that, a State deploying this CE technique would not be liable if an aerosol injection was carried out in compliance with international law. A central problem of the attempted application of any liability regime consists in that causation between an aerosol injection and the damage would be required. Such causation, due to scientific uncertainty, would be extremely difficult to prove. Altogether, the international rules on State liability are, in their current form, not eligible to compensate damages resulting from stratospheric aerosol injections.

1 | SCIENTIFIC FEASIBILITY OF CLIMATE ENGINEERING IDEAS

Investigating the Limits of Marine Cloud Brightening (MCB)

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Marine Cloud Brightening (MCB) is proposed as one method of climate engineering. The basic idea is to artificially release particles (e.g. sea salt) which then can act as additionally CCNs, which lead to higher cloud droplet numbers, which increases cloud albedo and reflect more shortwave radiation (Latham et. al, 2008).

Previous investigations suggested the Southeast Pacific as one of the most favorable region for climate engineering (Korhonen et al., 2010). This region is known to be characterized by a persistent layer of stratocumulus clouds. Their existence is a result of a complex chain of interactions between several processes. Due to the complexity of the system and that processes take place on very small scales atmospheric models encounter difficulties in capturing this cloud layer in a realistic way. Additionally there are still uncertainties in the outcome of this method due to uncertainties in cloud aerosol interactions.

The impact of cloud seeding via additionally emitted sea salt particles is mainly investigated within global circulation models (GCM), or on smaller grid scales but very small domains (LES). Therefore to close the gap we use our regional model system COSMO-ART (Vogel et al., 2009) to quantify the effect of climate engineering in the south east pacific region.

Simulations showed satisfactory results to describe stratocumulus clouds in the model. Increase in horizontal resolution is capable to represent small scale variability of these types of clouds. The impact of artificially released sea salt particles showed a general reduction of shortwave radiation, but also on precipitation. On the other hand it showed that in areas with anthropogenic emissions the effect of MCB is reduced due to the competition between anthropogenic particles and the additionally released sea salt particles and showes the importance not to neglect anthropogenic emissions when examining the effects of MCB.

2 | EXPLORING CLIMATE ENGINEERING UNCERTAINTIES

How good is the volcano analogy for sulfate climate engineering?

Hauke Schmidt // Max Planck Institute for Meteorology
Matthias Bittner // TUM
Ulrike Niemeier // Max Planck Institute for Meteorology
Claudia Timmreck // Max Planck Institute for Meteorology

The suggestion of injecting sulfur into the stratosphere to cool the climate is motivated by the response of the climate system to large volcanic eruptions. But can we expect that the effects observed after eruptions accurately describe the effects of sulfate climate engineering? Here we discuss the response of stratospheric dynamics to both types of forcing as simulated in state-of-the-art climate models.
The cooling observed after volcanic eruptions is not homogeneous in space and time. An anomalous warming has been observed after several big tropical eruptions during boreal winter in northern Europe and Asia. In general, this warming is attributed to a strengthening of the stratospheric polar night jet, related to the stratospheric effects of volcanic aerosol, and a subsequent downward propagation of this dynamical signal. Here we use the Geoengineering Intercomparison Model Project (GeoMIP) G3 and G4 simulations where sulfur is injected to reduce warming during the 21st century to study the potential response of stratospheric dynamics to this type of climate engineering and compare it with the response to volcanic eruptions simulated by the same models in the CMIP5 historical simulations. Unfortunately, in general the CMIP5 models do not reproduce the strengthening of the polar night jet well. Potential reasons for this will be discussed. Furthermore we show that due to the different time scales involved in volcanic eruptions in comparison to assumed climate engineering the dynamical responses may differ.

4 | A COMPARATIVE VIEW ON CLIMATE ENGINEERING OPTIONS AND ASSESSMENT METRICS

Comparative assessment of land-, ocean-, and atmosphere-based climate engineering using the Max Planck Institute Earth System Model

Sebastian Sonntag // Max Planck Institute for Meteorology
Miriam Ferrer Gónzalez // Max Planck Institute for Meteorology
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Julia Pongratz // Max Planck Institute for Meteorology
Christian Reick // Max Planck Institute for Meteorology
Hauke Schmidt // Max Planck Institute for Meteorology

Previous model studies on potential impacts of climate engineering (CE) have focused mainly on comparing effects of individual CE methods as simulated by different climate and Earth system models. Here we assess land-, ocean-, and atmosphere-based climate engineering measures with respect to their mitigation potential, side-effects on the Earth system, and uncertainties. For the first time a comprehensive Earth system model with prognostic carbon cycle is used to consistently compare two carbon dioxide removal methods – afforestation and ocean alkalinity enhancement - and solar radiation management by stratospheric sulfur injection. We perform simulations using the Max Planck Institute for Meteorology Earth System Model (MPI-ESM), each including one of the three CE methods and all forced by anthropogenic CO_2 emissions according to the Representative Concentration Pathway (RCP) 8.5. Our results show that the different CE methods differ vastly in terms of climatic effects, driven by different target variables - CO_2 reduction for afforestation and ocean alkalinity enhancement, radiative forcing for solar radiation management. We find that mitigating feedbacks may emerge: as a response to the solar radiation management temperatures are reduced leading to a reduction of CO_2. In addition, unintended side-effects become clear: For example, global terrestrial net primary production (NPP) is substantially reduced due to ocean alkalinity enhancement, while afforestation has no large net effect on global NPP due to counteracting effects of reduced CO_2-fertilization and larger forest area. Lastly, regional patterns of climate change differ despite similar global mean changes in our simulations, highlighting the need for sufficient spatial resolution in evaluating consequences for adaptation.

4 | A COMPARATIVE VIEW ON CLIMATE ENGINEERING OPTIONS AND ASSESSMENT METRICS

The normative evaluation of CE techniques

Harald Stelzer // University of Graz

The paper is based on work done within EuTRACE and CEMICS. It is tackling the subject of session 3 from the normative side. Instead of asking what normative principles would individual metrics interfere with, it will present normative criteria for the evaluation of CE techniques. Of course, such criteria need to based on already well-established metrics as the underlying aims of techniques like the reduction of global mean temperature or the removal of greenhouse gases, the potential side-effects, the estimated costs, or questions of encapsulation, reversibility and scalability. At the same time approaching those metrics from the normative perspective shifts the focus to certain questions that are of use for establishing more normative oriented criteria. For example the estimated impacts ¬– understood as intended and unintended potential consequences - can be evaluated in respect to their spatial and temporal distribution. This brings them into the context of global and intergenerational distributive justice. Other examples are questions raised by decision-making and governance. Here CE techniques can be viewed from the perspective of procedural justice, looking at the legitimacy of decisions or political feasibility constrains. This indicates that setting up such normative criteria is not a one-way street, but also leads to the further reflection of our normative assumption. Such feedback processes can be understood in the context of the debate of ideal and non-ideal theory. The usefulness of the normative criteria will be demonstrated for one or several climate engineering options in the context of CEMICS. Until July the normative criteria should have been discussed with scientist from economics and natural sciences, elucidating their potential inclusion for the evaluation of results of Integrated Assessment Models (IAMs) as well as their possible future integration in those models.

5 | PERCEPTIONS OF AND PERSPECTIVES ON CLIMATE ENGINEERING RESEARCH AND DEPLOYMENT

Geoengineering as collective experimentation

Jack Stilgoe // University College London

As research has begun into geoengineering proposals, controversies over the politics of experimentation have proven surprising and, for social scientists, enlightening. In this talk, I will discuss the blurring of experimental boundaries in and describe some experiments in governance that have been proposed as a way to being a new discussion about responsible science and innovation. I use the term ‚collective experimentation' to both describe what is going on and offer constructive ways forward.

Enhanced weathering and BECCS - are carbon dioxide removal technologies complements or substitutes?

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Nico Bauer // Potsdam Institute for Climate Impact Research (PIK)
Thorben Amann // University of Hamburg
Elmar Kriegler // otsdam Institute for Climate Impact Research (PIK)
Jens Hartmann // University of Hamburg

In its fifth assessment report, the IPCC stated that scenarios which "are consistent with a likely chance to keep temperature change below 2°C [...] are characterized by [...] emissions levels near zero $GtCO_2eq$ or below in 2100" (Edenhofer et al., 2014, SPM of WG III, IPCC AR5). To reach such low CO_2eq emissions, net negative emissions will be necessary in some sectors. In this study we focus on two options for negative CO_2 emissions: The combination of bioenergy with carbon capture and storage (BECCS) and enhanced weathering (EW), the deployment of finely ground minerals over forests and crop lands.
EW faces neither the technological nor the social risks of the other options. However, olivine, the mineral that is best suited, might be contaminated by potentially harmful trace elements. Other sources like basalt can have lower harmful element concentrations, but show lower CO_2 sequestration potential.
Our research questions are: What are the optimal design parameters for EW? How does EW as a mitigation option interact with BECCS?
An important parameter that determines costs as well as carbon removal rate is the grain size. We first calculate an optimal grain size that maximizes profits, taking the dependency on carbon removal rate and costs into account. Second we implement EW into the integrated assessment model REMIND and show preliminary results of EW as a mitigation option.
When EW is available as a mitigation option, it provides net negative CO_2 emissions which allow for higher CO_2 emissions earlier in the century. The slower reduction of CO_2 emissions results in a lower CO_2 price and therefore lower mitigation costs. We analyze under which conditions EW is used as a substitute or complement to BECCS. In addition, we analyze scenarios where CCS is not available. In combination with a stringent climate target, these scenarios often show very high mitigation costs or become unachievable. We will investigate to what extent EW can substitute BECCS in this case.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

The Role of Human Rights in Considering Climate Engineering Research

Michael Thompson // Forum for Climate Engineering Assessment
Wil Burns // Forum for Climate Engineering Assessment
Brian Citro // University of Chicago
Patrick Smith // Stanford University

How do we ensure decision-making processes around climate engineering research are inclusive and transparent? How should we understand and anticipate the potential social and economic impact of this research? What mechanisms will ensure accountability for impacts and provide protection and remedies for those affected? How do we frame these questions in the first place?

This paper will make an argument that human rights have a role to play by providing a concrete legal foundation and valuable framing mechanism to understand the procedural, distributive and consequential concerns associated with CE. This includes both procedural and substantive protections accorded under human rights law. The paper will further argue that human rights offer unique tools to highlight the impact of CE research, and potential deployment of CE technologies, on vulnerable and marginalized groups.

The paper will also explore the limitations of a human rights approach, acknowledging that different people will suffer different kinds of human rights violations because of policy decisions on both climate change and CE. As a result, we are not likely to be in the position of choosing between a policy that violates human rights and one that does not. Rather, we may find ourselves in the position of violating human rights no matter what we do. We therefore ask, what principles and institutions ought to guide the distribution of burdens and costs? And, when balancing interests, how should we weigh historical responsibility for climate change impacts and how much should we prioritize economic development for the global poor?

Human rights offer a more robust normative framework for considering the procedural, distributive and consequential concerns associated with CE than what currently exits. They provide a legal and normative baseline for the conversation, but their limitations leave the door open for a role for moral and political philosophy in the conversation.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

A Survey of Dynamic Games in the Exploration of Global Geoengineering Governance

Weili Weng // Chinese Academy of Social Sciences
Ying Chen // Chinese Academy of Social Sciences

Climate geoengineering, a suite of hypothetical technologies with the potential to dramatically cool the climate, could cause fundamental interventions to the ecosystem and create problems with high uncertainty and uneven distribution around the globe. The research on the science and regulation of geoengineering is not evenly developed across the world either, nor transparently disclosed. Speculations of other countries' progress in geoengineering research could lead to a race of actions. Apart from physical effects, risks and benefits analysis of climate engineering depends largely on political and social elements. The paper intends to imply game-theoretic analyses in geoengineering issues in a dynamic context and explore political and social driving forces that are likely to shape a global governance regime within which decisions on the use of climate engineering technologies could be taken.

EVENING ORAL PRESENTATION

Understanding the Intangible: Perceiving Climate Engineering through Art and Design

Josh Wodak // University of New South Wales

This paper explores how art and design may articulate novel perceptions of and perspectives on Climate Engineering research and deployment. If humans are inadvertently engineering the entirety of the Earth, and Climate Engineering is the manifest of that acknowledgement, are we now looking at a proposed climate by design, in contrast to the Holocene's climate-as-given and the Anthropocene's climate-by-accident?

Art offers a discrete lens through which to probe the reversal of agency implicit in Climate Engineering: from being shaped by things to come, to how humans may shape things to come through Climate Engineering interventions. The notion of 'climate by design' is garnering increased international interest, with the 2014 exhibition Strange Weather at the Science Gallery, Trinity College Dublin, being the world's first large scale exhibition on Climate Engineering.

The presentation discusses how such art practice opens up new realms of understanding the issues at stake in Climate Engineering, including an overview of the author's art on Climate Engineering in the context of the manifesto of CoClimate, the curators of Strange Weather, that "we have always been geoengineers, but we have not been very good at it" and their response to this contention in forming their think tank to "study the technologies and tactics used for sculpting the biosphere of planet Earth."

Such artistic responses are contextualized in a discussion of the role of museum exhibitions on Climate Engineering, drawing on the author's current exhibition in 'Welcome to the Anthropocene' at the Deutsches Museum, and current collaborations with Rachel Carson Centre, LMU, München and 'The Anthropocene Kitchen' project at HU, Berlin.

The paper situates theses practices in ethical considerations of Climate Engineering, drawing on the author's co-convened conference 'Fighting Fire with Fire - Climate Modification and Ethics in the Anthropocene' at the University of New South Wales, in 2014.

4 | A COMPARATIVE VIEW ON CLIMATE ENGINEERING OPTIONS AND ASSESSMENT METRICS

Solar geoengineering reduces carbon concentrations

Claire Zabel // Stanford University
David Keith // Harvard University

Proposals to manage the climate risks using solar geoengineering have been intensely controversial. Perhaps the most commonly cited disadvantage of solar geoengineering is that it does nothing to address the accumulation of carbon dioxide and its resultant ocean acidification and ecological disruption. We draw on existing literature to point out the falsehood of this assumption: by preventing temperature rise and so slowing carbon emissions that result from warming, solar geoengineering would significantly reduce the accumulation of CO_2 in the atmosphere. Compared to a business-as-usual baseline, extensive solar geoengineering implemented in the near future could prevent 250-300 GtC in emissions by 2100. This effect is largely due to solar geoengineering preventing increasing temperatures' impact on the carbon cycle (Matthews and Caldeira, 2007), but preventing decreases to thermal power plant and solar panel efficiency (Förster and Lilliestam, 2010), and preventing increases in air conditioning energy consumption (Isaac and Vann Vuuren, 2009), also has a substantial impact on likely reductions of atmospheric carbon burden. Additionally, solar geoengineering could prevent unlikely but potentially catastrophic carbon emissions from permafrost thaw and methane clathrate release, and subsequent rapid positive climate feedbacks. In this sense, solar geoengineering can be seen as a form mitigation or carbon removal, albeit one with a limited technical potential. As a mitigation measure, solar geoengineering is inexpensive, with costs on the order of \$1/ton-CO_2 avoided.

3 | GOVERNING CLIMATE ENGINEERING RESEARCH, POTENTIAL DEVELOPMENT AND DEPLOYMENT

A law and economic review of climate engineering costs

Jinshan Zhu // University Potsdam

After years of effort, Climate change mitigation has made some progress. Unfortunately, by no means is it certain that emission control required to stabilize the climate system will be implemented in time. Against this background, Climate Engineering (CE), a series of technologies involving large-scale intentional interventions into the climate system, started to gain more and more attention. To face the challenge of the possible deployment of CE technologies, research and proposal of an ex ante governance framework is called, where economic analysis can play one of the most important roles. Efforts have been done to make the initial try to model the least cost approach. However, what the term "cost" means in both conceptual and actual dimensions still desires a deeper understand.

This research borrows the cost theories from law and economic (L&E) discipline. First of all, it modifies the cost theories of L&E, and adopts them into the climate change and CE context. Second, it develops an overview of the various costs and put them into interactive structure. Third, it applies this cost-in-structure approach as an analytical framework to individual CE methods in order to understand the cost of CE methods in a broader and clearer view. Fourth, after the specific analysis of individual methods, it summarizes the finding and further highlight the several issues about the CE cost in overarching sense.

This research suggests several respects of any possible CE deployment that involves additional costs may still beyond current research focus, but leave them being ignored or insufficiently regarded would undermine the precise understand of the economic implication of CE technology. Such ignorance should be avoided from the early stage of CE governance design, so that later governance will have less chance making unwanted policy consequence, which would be predictable at current stage.

Furthermore, we hope this qualitative analysis can also support later quantitative analysis.

CLIMATE ENGINEERING

Risks, Challenges, Opportunities?

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