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Crutzen +10: Reflecting upon 10 years of geoengineering research

Key Points:
- In the decade since Crutzen's seminal essay, the field has developed and diversified
- This 10th anniversary special issue takes stock and reflects on possible future developments in geoengineering research
- Contributions from a wide range of authors reflect the future-orientation and socio-political dimensions of geoengineering discussions

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Reflecting upon 10 years of geoengineering research: Introduction to the Crutzen + 10 special issue

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Abstract Ten years ago, Nobel laureate Paul Crutzen called for research into the possibility of reflecting sunlight away from Earth by injecting sulfur particles into the stratosphere. Across academic disciplines, Crutzen's intervention caused a surge in interest in and research on proposals for what is often referred to as "geoengineering"—an unbounded set of heterogeneous proposals for intentionally intervening into the climate system to reduce the risks of climate change. To mark the 10-year anniversary of the publication of Paul Crutzen's seminal essay, this special issue reviews the developments in geoengineering research since Crutzen's intervention and reflects upon possible future directions that geoengineering research may take. In this introduction, we briefly outline the arguments made in Paul Crutzen's (2006) contribution and describe the key developments of the past 10 years. We then proceed to give an overview of some of the central issues in current discussions on geoengineering, and situate the contributions to this special issue within them. In particular, we contend that geoengineering research is characterized by an orientation toward speculative futures that fundamentally shapes how geoengineering is entering the collective imagination of scientists, policymakers, and publics, and a mode of knowledge production that recognizes the risks that may result from new knowledge and that struggles with its own socio-political dimensions.

1. Introduction

The year 2016 marks the tenth anniversary of Nobel laureate Paul Crutzen's seminal 2006 contribution, "Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?" [*Crutzen*, 2006]. In his essay, Crutzen noted that attempts at reducing greenhouse gas emissions to limit global warming had thus far been "grossly unsuccessful" and called for research to investigate whether injecting sulfur particles into the stratosphere could effectively reflect incoming sunlight and thereby limit temperature rise [*Crutzen*, 2006, p. 212]. He emphasized that such research should aim at assessing potential positive and negative effects of the proposed stratospheric modification schemes, stating that "if positive effects are greater than the negative effects, serious consideration should be given to the albedo modification scheme" [*Crutzen*, 2006, p. 216]. Across academic disciplines, Crutzen's intervention was followed by a surge in interest in and research on proposals for what is at the aggregate level often referred to as "geoengineering"—an unbounded set of heterogeneous proposals for intentionally intervening into the climate system to reduce the risks of climate change. The umbrella term geoengineering commonly refers to a broad set of methods and technologies designed to deliberately alter the Earth's climatic system in order to limit the adverse impacts of climate change. This encompasses proposals for reflecting sunlight away from Earth as well as removing carbon dioxide from the atmosphere at a scale sufficiently large to alter climate [*Intergovernmental Panel on Climate Change*, 2014]. The focus of this article is mainly on the development of solar geoengineering research of the kind called for by Crutzen, but this focus cannot always be strictly upheld because of the many ways in which the diverse proposals have become entangled under the umbrella term geoengineering.

As *Caldeira and Bala* [2016] point out, discussions of geoengineering have a history that stretches over several decades. However, it was during the last decade that geoengineering has developed from a fringe topic into a broad, international and interdisciplinary research endeavor: Several national and multinational geoengineering research projects have been established, a plethora of young researchers are obtaining their degrees by investigating aspects of geoengineering, and a number of governmental institutions have commissioned assessment reports on the potential implications of the proposed technologies (see Section 3).

However, while the topic has received increased attention in recent years, it has simultaneously been questioned whether geoengineering should be considered a singular topic at all. Some argue that the individual proposals subsumed under the umbrella term are too heterogeneous to be usefully referred to under a collective heading, and that the individual geoengineering proposals and their specific portfolios of costs, benefits, and risks should be considered and discussed separately in order to assess whether they can and should become part of a policy portfolio for addressing climate change [*Heyward*, 2015]. Alternatively, an aggregate term may be seen to create the image of a stable field, which can provide advantages in the competition for funding, personnel, and recognition. Yet, aggregating terminology may also feign stability when no geoengineering technology yet exists in practice. This goes to show that geoengineering is, at this stage, not a specific, stable, and coherent object or infrastructure, but rather a contested concept that unites a set of heterogeneous proposals for how a targeted intervention into the climate system might be achieved. Discussions of geoengineering are coming of age not without growing pains, and it is time to take stock and to reflect on possible future developments.

This special issue aims to do just that. To mark the tenth anniversary of Paul Crutzen's contribution, we invited experts in the field to review the development of geoengineering research over the past decade, and to reflect upon where it may be going in the next 10 years. This introduction first briefly outlines the arguments made in Paul *Crutzen*'s [2006] contribution, describes some of the key developments in geoengineering research over the past 10 years, and finally introduces and discusses the topics addressed in the contributions to this special issue. In situating the contributions within the broader discussions that are taking place, we highlight two characteristics of these discussions that, we contend, are central for how research on geoengineering is taking shape: An orientation toward speculative futures that fundamentally shapes how geoengineering is entering the collective imagination of scientists, policymakers, and publics, and a mode of knowledge production that recognizes the risks that may result from new knowledge and that struggles with its own socio-political dimensions.

2. Crutzen's Call: Breaking the Taboo

Crutzen's essay was motivated by a twofold policy dilemma, which he perceived as arising from the need to reduce global emissions of both carbon dioxide and harmful air pollutants such as sulfur dioxide (for a more detailed discussion of Crutzen's article and the commentaries which accompanied it, see *Lawrence and Crutzen* [2016]. Crutzen was concerned about the slow political progress on the former, and understood that the latter would result in more rapid warming of the Earth's atmosphere as the reflective effect of the air pollutant particles was reduced. His concerns about political inertia on emissions reduction attracted the most attention at the time of publication and formed the basis for his compelling call for geoengineering research. He argued:

> "Given the grossly disappointing international political response to the required greenhouse gas emissions […] research on the feasibility and environmental consequences of climate engineering of the kind presented in this paper, which might need to be deployed in future, should not be tabooed" [*Crutzen*, 2006, p. 214].

Crutzen argued that research on solar geoengineering was needed to investigate its potential positive and negative effects, in case emission reduction efforts were inadequate, the rate of climate change and its associated detrimental impacts accelerated, or both. However, he was also careful to point out that solar geoengineering should not be considered a substitute for mitigation, writing:

> "Nevertheless, again I must stress here that the albedo enhancement scheme should only be deployed when there are proven net advantages and in particular when rapid climate warming is developing […]. Importantly, its possibility should not be used to justify inadequate climate policies, but merely to create a possibility to combat potentially drastic climate heating" [*Crutzen*, 2006, p. 216].

Crutzen was far from the first to suggest the idea of geoengineering, but his status as a Nobel Prize laureate and a respected member of the atmospheric science community meant that his essay in Climatic Change attracted a great deal of attention among his peers. The years that followed the publication of Crutzen's essay saw a strong increase in interest in and research on geoengineering across academic disciplines [*Oldham et al*., 2014], and he is therefore often credited with "breaking the taboo" surrounding geoengineering research [*Harnisch et al.*, 2015; *Stilgoe*, 2015a]. The following sections outline the ways in which Crutzen's call for geoengineering research has been taken up by the academic and policy communities.

3. Answering Crutzen's Call: A Decade of Developments

Crutzen's publication invigorated academic discussion about and investigation of geoengineering techniques. The publication of his article was followed by a significant increase in the number of academic publications on the topic of geoengineering [*Oldham et al.*, 2014]. Several national and multinational geoengineering projects were established subsequently, including the German Research Foundation (DFG) Priority Programme on Climate Engineering, the EU-funded Implications and Risks of Engineering Solar Radiation to Limit Climate Change (IMPLICC) Project, the European Transdisciplinary Assessment of Climate Engineering (EuTRACE), the Mechanism and Impacts of Geoengineering Project (supported by the National Key Basic Research Program of China), the Norwegian Research Council's EXPECT project, the UK Research Council funded Integrated Assessment of Geoengineering Proposals (IAGP) and Stratospheric Particle Injection for Climate Engineering (SPICE) projects, and the international Geoengineering Model Intercomparison Project (GeoMIP).

Although the United States does not have a national geoengineering research program, research is being carried out at individual institutions: a research group dedicated to geoengineering has been established at Harvard University, where currently a broader research program is being set up, and researchers at several other US institutions including Pacific Northwest National Laboratory, the US National Center for Atmospheric Research (NCAR), Cornell University, the Carnegie Institution for Science, Rutgers University, the University of Montana and the University of Washington are investigating aspects of geoengineering from various disciplinary and interdisciplinary perspectives. In Germany, an interdisciplinary research group at the Institute for Advanced Sustainability Studies (IASS) has been investigating geoengineering since 2012, and more than 18 German, Swiss, and Austrian universities and research institutions continue to conduct geoengineering research as part of the DFG Priority Programme. In the United Kingdom, ongoing geoengineering research is being carried out by groups at the universities of Oxford, Exeter, and East Anglia. Researchers at Japan's Agency for Marine-Earth Science and Technology (JAMSTEC) and the University of Tokyo are likewise assessing the potential risks and benefits of geoengineering, as are academics at universities in Australia, Canada, the Netherlands, and an increasing number of other countries. The first major international, transdisciplinary conference on geoengineering, CEC14, was held in Berlin in 2014 and attracted over 350 participants from more than 40 countries. A second such global conference, CEC17, is to be held in 2017 to facilitate discussions about the future development of geoengineering research among representatives of academia, the policymaking community, non-governmental organizations (NGOs), and wider society. In addition, a Gordon Research conference entitled Radiation Management Climate Engineering: Technology, Modeling, Efficacy, and Risks is to be held in 2017 in Maine, USA.

In the last 10 years, increased research into solar geoengineering has led to an expansion of the range of approaches under consideration to include not only stratospheric aerosol injection of the kind suggested by Crutzen, but also a range of other options, including marine cloud brightening and cirrus cloud thinning. Over the years, improvements in global climate models have allowed more detailed simulations of various solar geoengineering techniques and multi-model comparisons have begun examining areas of agreement and disagreement between different models [*Kravitz et al.*, 2011; *Schmidt et al*., 2012; *Caldeira et al*., 2013; *Robock*, 2014; *Kravitz et al*., 2015; *Irvine et al*., 2016a]. Modeling and laboratory research has also begun to investigate the potential negative effects of geoengineering, including effects on ozone, ultraviolet radiation, and precipitation patterns [*Robock*, 2008; *MacMartin et al*., 2016; *Robock*, 2016]. Social science and humanities research has investigated some of the fundamental legal, economic, geo-political, ethical, and societal challenges that geoengineering research and potential deployment pose [for overviews, see *Shepherd et al*., 2009; *Schäfer et al*., 2015]. However, both natural and social science investigation of the various techniques remain in the early stages, and the call for more research into geoengineering continues to be voiced inside and outside the academic community [*Harnisch et al*., 2015; *NAS* 2015a, 2015b].

The proliferation of scientific interest in geoengineering has been mirrored by an increase in awareness of the issue within the policy space. Several governmental institutions, including the US National Academy of Sciences [*National Research Council*, 2015a, 2015b], the US Government Accountability Office [*GAO*, 2010, 2011], the US Congressional Research Service [*Bracmort and Lattanzio*, 2013], the German Federal Environmental Agency [*Bodle et al*., 2014], the German Federal Ministry of Education and Research [*Rickels et al*., 2011], the Office of Technology Assessment of the German Bundestag [*Caviezel and Revermann*, 2014], and the European Commission [*Schäfer et al*., 2015], have commissioned reports on geoengineering. The US House of Representatives and the UK House of Commons held a series of hearings on the scientific and governance challenges of geoengineering in 2009 and 2010 [*United States House of Representatives*, 2009, 2010a, 2010b; *United Kingdom House of Commons*, *Science and Technology Committee*, 2010]. The UK and German governments have stated their positions on the issue, supporting ongoing research to inform future decision making, but not endorsing the deployment of any geoengineering technologies [*German Parliament*, 2012; *UK Government*, 2013].

In the international climate change arena, the Intergovernmental Panel on Climate Change (IPCC) held a joint working group expert meeting on geoengineering in Lima in 2011, and the panel's two most recent assessment reports (AR4 and AR5) included references to geoengineering. Additionally, the IPCC Chairman Hoesung Lee was recently quoted calling for the panel to explore the technical and governance aspects of geoengineering [*The Guardian*, 2016]. The historic agreement reached at COP21 in Paris to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels has led to increased debate about what role carbon dioxide removal and solar geoengineering measures may play in achieving climate targets, especially given that the removal of large quantities of carbon dioxide is already assumed in most of the IPCC's scenarios for limiting temperature rise to 2°C [*Parker and Geden*, 2016; *Anderson and Peters*, 2016; *Geden and Schäfer*, 2016; *Horton et al*., 2016; *Nicholson and Thompson*, 2016; *Shepherd*, 2016].

The increased academic and societal interest in geoengineering has additionally led to the establishment of several geoengineering governance initiatives. The Solar Radiation Management Governance Initiative (SRMGI), which seeks to expand the discussion of SRM research governance in developing countries, was launched in 2010 by the Royal Society, The World Academy of Sciences (TWAS), and The Environmental Defense Fund. Building upon the Oxford Principles on Geoengineering Governance [*Rayner et al*., 2013], the Universities of Oxford and Sussex partnered with University College London in 2012 to conduct the 2-year Climate Geoengineering Governance (CGG) project, which focused on assessing possibilities for public participation and transparency in geoengineering decision-making. More recently, the Forum for Climate Engineering Assessment (FCEA) initiated an Academic Working Group (AWG) on International Governance of Climate Engineering, an international group of senior academics assembled to formulate recommendations on the international governance of climate engineering research and potential deployment, with a focus on solar geoengineering technologies. Responding to the Royal Society's call for the development of a code of practice for geoengineering research [*Shepherd et al*., 2009], in early 2016 the University of Calgary, the Institute for Advance Sustainability Studies (IASS) and the University of Oxford's Institute for Science, Innovation and Society (InSIS) jointly launched the Geoengineering Research Governance Project (GRGP) aimed at further developing a Code of Conduct for geoengineering research that had previously been co-published between the IASS and the University of Oxford [*Hubert and Reichwein*, 2015]. Most recently, the Carnegie Council for Ethics in International Affairs announced the commencement of the Carnegie Climate Geoengineering Governance Project, led by Janos Pasztor, senior advisor to the UN secretary-general on climate change, which aims to encourage intergovernmental dialogs on geoengineering governance.

An overview of key developments in geoengineering research since 2006 is illustrated in Figure 1.

4. Taking Stock: Geoengineering's Past, Present, and Future

As the above brief outline of developments in the field shows, investigations and discussions of geoengineering technologies have progressed considerably since 2006. Ten years after Crutzen's article encouraged

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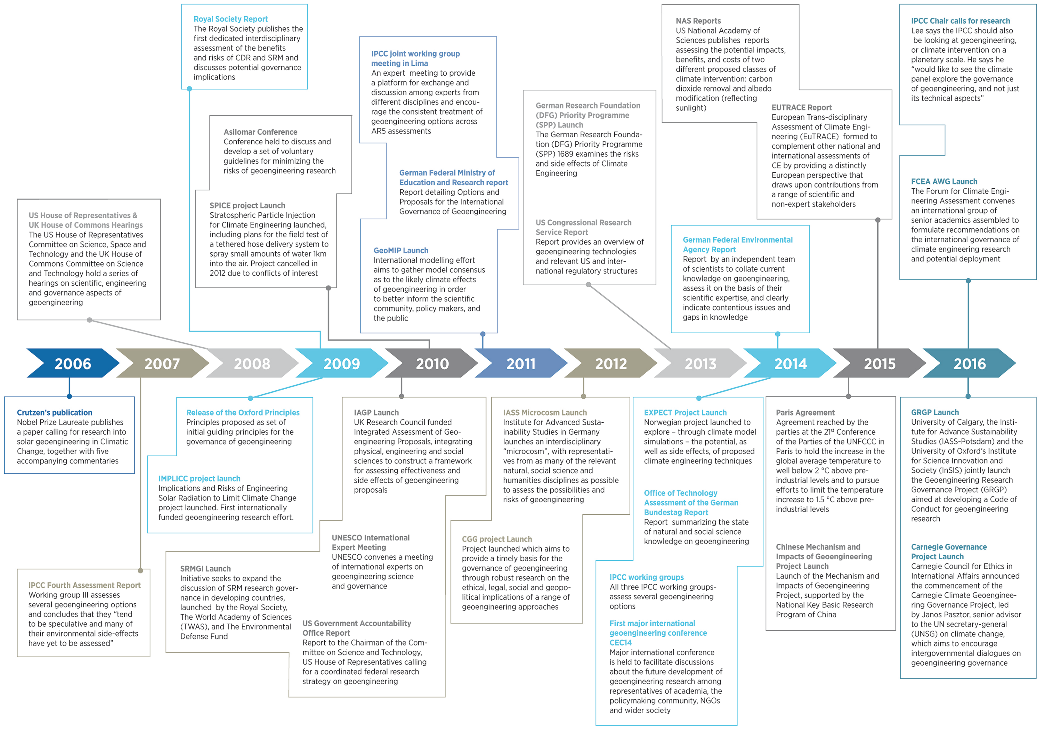

Figure 1. Key developments in geoengineering research since 2006 [for details of developments prior to 2006, see *Caldeira and Bala*, in this issue; *Lawrence and Crutzen,* in this issue].

serious consideration of geoengineering, it is time to take stock and reflect on past developments and future challenges for academia and society, and to assess the contours of the geoengineering research debate to date. In this section, we give an overview of some of the key features that characterize current thought and research on geoengineering, and present the way in which the papers included in this special issue contribute to these ongoing discussions. In particular, we focus on two interrelated characteristics that we contend are central to geoengineering research: An orientation toward speculative futures that fundamentally shapes how geoengineering is entering the collective imagination of scientists, policymakers, and publics, and a mode of knowledge production that recognizes the risks that may result from new knowledge and that struggles with its own socio-political dimensions.

4.1. Speculative Futures

A constitutive feature of geoengineering research is that the individual geoengineering proposals themselves are better understood as speculative futures than as established policy options. As such, they exist as back-of-the-envelope calculations, computer models and simulations, laboratory and field experiments, as topics for focus group discussions, questionnaires, and assessment reports, but not as operational epistemic, socio-political and material infrastructures. Any logic or metric of assessment for geoengineering is directed at a projection of the future that is modeled or in some other way narrated. The future-oriented nature of geoengineering discussions, and the epistemological, methodological, and technical implications that this temporal focus carries, fundamentally shapes how geoengineering is entering the collective imagination of scientists, policymakers, and publics.

For example, a speculative future that has received particular attention in geoengineering research and discussions concerns a scenario in which the mere consideration of geoengineering as a climate response strategy may result in societal and political unwillingness to reduce greenhouse gas emissions, or conversely, may galvanize action on mitigation. The former is often referred to as the 'moral hazard' dilemma [*Keith*, 2000]. The concept of moral hazard originates in the field of economics, and refers to a lack of incentive to take action to guard against risk when one is protected from its consequences by insurance. The moral hazard associated with geoengineering correspondingly consists of the risk that publics and decision makers may reduce their mitigation efforts due to a belief that geoengineering provides adequate insurance against climate risk.

The contributions from *McLaren* [2016] and *Burns et al*. [2016], respectively, discuss the development of aspects of the geoengineering moral hazard debate, and the results of initial empirical research into the potential effects of the consideration of solar geoengineering as a policy option on public attitudes toward mitigation. *McLaren* identifies different forms of the moral hazard effect, emphasizing that "research will need to turn from trying to prove or disprove the phenomenon of moral hazard, to much more nuanced efforts to understand when, where and how it might appear" [*McLaren*, 2016]. *Burns et al*.'s review discusses the appropriateness of the use of the term "moral hazard" in the geoengineering context and indicates that although it is a concern for various publics on an aggregate level, the 'moral hazard' often reverses on the individual level, with some studies finding that individuals are more willing to offset their own emissions when informed about solar geoengineering. In their contribution, *Lawrence and Crutzen* [this issue] reflect upon whether Crutzen's own decision to advocate for geoengineering research was a "moral hazard or moral imperative," concluding that the moral hazard risk associated with geoengineering has "thus far been largely avoided on an international political scale." However, the authors emphasize that "the verdict is still out" and therefore call for increased societal dialog and engagement to further limit the risk of moral hazard in the future [*Lawrence and Crutzen*, this issue].

Computer models and simulations often serve as generative media for constructing speculative futures, and it is therefore unsurprising that models and simulations have taken center stage in furthering understanding of the potential future positive and negative effects of various proposed geoengineering techniques. Given that the majority of geoengineering proposals involve complex global earth system processes, climate models are an obvious tool for geoengineering research. Within these models, it is possible to experimentally perturb the climate system with various patterns of stratospheric aerosol injection or marine cloud brightening, and to investigate the corresponding climate system response. The vast majority of natural science geoengineering research so far has been conducted using climate models. In particular, the GeoMIP has furthered collaboration between climate modeling groups from around the world, and provided the opportunity to compare modeling results [*Kravitz et al.*, 2011, 2016; *Robock and Kravitz*, 2013. See also *Robock* and *Lawrence*, 2016; *Crutzen*, 2016, for more details about the results of GeoMIP].

However, the difficulty of adequately representing the complexity of the earth system in models and the abstract nature of the resulting model outputs are central to the discussion as to how much, if any, predictive power such models can have. This is especially relevant when discussing the ability of models to predict the potential positive and negative effects of various geoengineering approaches on humans and ecosystems, as *MacMartin et al*. and *Robock* point out in their contributions to this collection. Additionally, both natural and social scientists involved in geoengineering research are aware of the risks of misinterpretation or reification of experimental and explorative modeling results when those results are mistaken as projections of a future reality, as opposed to useful constructs that can inform thought and action in the present. *Caldeira and Bala* specifically address this topic in their contribution to this issue, saying that those involved in the field need to be aware of the tendency to take results from a "limited number of simulations of a small set of scenarios in a single climate model, and then making very broad claims about what would happen in the real world in a much broader range of possible scenarios" [*Caldeira and Bala*, 2016].

Models and simulations have also been used for the formulation of future-oriented statements about the economic and international political implications of geoengineering. In this context, a question that has been the focus of much discussion is who, if at all, may eventually decide to deploy solar geoengineering, when, why, to what end and to what extent. Research on the future international politics of geoengineering frequently draws on climate modeling and economics — a combination of separate but epistemologically related bodies of disciplinary knowledge. This combination is a direct result of the future-orientation of geoengineering discussions: The instances in which geoengineering has thus far been addressed in international political settings are few and far apart and accordingly, the material that can be subjected to empirical analysis is limited [*Horton and Reynolds*, 2016]. Discussions of the international politics of geoengineering have therefore largely relied on game-theoretical models that combine computer modeling of the climate with political reasoning that is grounded in assumptions imported from economics [see

Barrett, 2008; *Millard-Ball*, 2012; *Moreno-Cruz et al*., 2016; *Urpelainen*, 2012; *Ricke et al*., 2013; *Harding and Moreno-Cruz*, 2016]. By modeling the future development of an engineered climate, climate models can deliver inputs with which game-theoretic and economic models of international political dynamics can simulate the development of the future international politics of geoengineering.

In this issue, *Harding and Moreno-Cruz* reflect upon the development of economic modeling of potential individual and collective geoengineering deployment behavior, detailing the use of economic cost analysis, optimal climate policy analysis, and game theoretical approaches when assessing the potential international political dynamics of geoengineering. The authors show that geoengineering has the potential to fundamentally alter climate change economics in unexpected ways, and that economic analysis has contributed significantly to generating an understanding of how this may happen. However, they emphasize that the varying ways in which economic incentives and associated policy dynamics may be shown to change as a result of the emergence of geoengineering as a climate response strategy depends largely on the economic tools and models used for analysis. As *Harding and Moreno-Cruz* point out, the methodologies used also affect the extent to which potential positive and negative effects of geoengineering in the form of social costs and benefits can be incorporated into economic analyses. The authors conclude that "much of the work done by economists has been to add an economic framework to the work of researchers in other fields", and emphasize that there is going to be an even greater need for interdisciplinary research in the future, especially with regard to incorporating "findings pertaining to the impact assessments of economic damages" [*Harding and Moreno-Cruz,* 2016].

Low's contribution to this issue outlines how scenarios and simulation exercises could be used as experimental models for thinking through the political and societal implications of geoengineering research and development, pointing out that such models can structure transdisciplinary communication and identify research and policy gaps under conditions of deep uncertainty about future developments. Taking an alternative, historical approach to assessing the potential development of state preferences, *Moore et al.*'s contribution to the issue directly addresses the possibility that China may be the first to initiate geoengineering. The authors emphasize that the philosophical traditions of the country also need to be taken into consideration when evaluating China's potential future stance on geoengineering, pointing out that China's history of 'gardening' the natural environment means it sees geoengineering in a different way than countries in the West.

4.2. Socio-Political Dimensions

A widely shared narrative of how the modes of scientific knowledge production have changed over time identifies a progression from disciplinary isolation to interdisciplinary collaborations and, most recently, a move toward transdisciplinary engagement [*Bensaude-Vincent*, 2016]. While this narrative itself is questionable on several counts—disciplinary boundaries are artificial constructs that were never fully representative of ongoing practices, and the same is true of the image of an academic "ivory tower" detached from society—it does appear that geoengineering is in some respects emerging in the mold of this latest stage, thereby responding to the widely recognized need to take into account the socio-political dimensions of geoengineering research. As the influential Royal Society report on geoengineering emphasized, "The greatest challenges to the successful deployment of geoengineering may be the social, ethical, legal and political issues associated with governance, rather than scientific and technical issues" (*Shepherd et al.*, 2009, p. xi).

Many researchers in the natural and social sciences are actively engaging with publics and policy-makers in the deliberative co-production of knowledge in geoengineering assessments. In doing so, scientists recognize—and attempt to navigate—the socio-political dimensions of their own research practices. As *Burns et al*. [2016] highlight, geoengineering researchers recognize that public views and values about geoengineering need to be incorporated in science-policy decisions. This being said, as *Burns et al*. emphasize that "the public" is, like geoengineering itself, not a monolithic, stable object; rather, publics and specific understandings of what characterizes them are defined through various means of engagement, such as opinion polls and focus groups [see also *Morris*, 2015]. Those engaging publics are thereby facilitative of the constitution of the publics that they engage, and the chosen mode of engagement preconfigures the kinds of publics that are constructed.

A transdisciplinary mode of knowledge production is also reflected at the level of research programs. The contribution by *Oschlies and Klepper* [2016a] details the development of such a research program, highlighting the move from early, uncoordinated and narrowly focused research efforts towards geoengineering assessments across a broad range of scientific, environmental, economic, social, legal, political, ethical, and communicative dimensions. The establishment of such integrated research programs may suggest that geoengineering research is developing along a "new regime of knowledge production" in which "the boundaries between academic disciplines are gradually blurred while the traditional 'linear model of innovation' (where technological development goes from pure to applied science and thence to industry) is rejected" [*Bensaude-Vincent*, 2016, p. 45]. In line with this development, the assessment framework of "responsible research and innovation", which has its roots in scholarship that helped deconstruct the image of stable boundaries and linear innovation, has played a particularly important role in discussions of what might constitute appropriate governance for geoengineering research [*Macnaghten et al.*, 2012; *Stilgoe et al*., 2013; *Stilgoe*, 2015a, 2015b].

The socio-political dimensions of geoengineering research are also visible in the recognition that geoengineering may in many respects be less of a scientific problem, and more of a design problem. While there are obviously scientific questions attached to geoengineering, such as the back-scattering effects of aerosol particles on incoming sunlight or their effects on the reflectivity of clouds, these questions are not specific to geoengineering. As *Caldeira and Bala* point out in their contribution to this issue, "Some of the most important questions facing us are not scientific questions, although scientific information is relevant to their answer: What is right and wrong and what should we or should we not do?" Many central and unique geoengineering questions are related to its objectives, and to the design of future interventions into the climate system for achieving those objectives. Computer models are thereby becoming an "inventive tool" in the design of geoengineering strategies [*Wiertz*, 2015], and further discussion on how to include publics in the decision making process on what kinds of futures are generated in computer models appears warranted.

Several contributors to this special issue highlight the design aspect of the geoengineering discussion: While *Low* discusses the potential for using anticipatory foresight as a way to engage stakeholders in visioning exercises for the kinds of futures "we" want, *Quaas et al*. [2016] and *MacCracken* [2016] discuss the potential for the design of targeted and regionally differentiated geoengineering approaches. *Quaas et al*. focus on regional scale economic incentives to undertake regional solar geoengineering and conclude that this may be attractive since it potentially provides the opportunity to target the suppression of some extreme events such as heatwaves. In a similar vein, *MacCracken* emphasizes that investigation and deployment of regional geoengineering measures may moderate severe climate impacts and provide insights about potential global geoengineering interventions. Looking at regional geoengineering effects from an alternative perspective, *Keith and Irvine* [2016] put forward the hypothesis that solar geoengineering could be designed in such a way that the aggregate risks of climate change could be reduced across regions without making any country worse off. *Irvine et al*. [2016b] point out that as geoengineering could be designed to produce different climate outcomes, it is necessary to develop ways to assess the potential impacts of such tailored approaches on natural and human systems such as agriculture, health, water resources, and ecosystems. *Suarez and van Aalst* [2016] take up the issue of the differentiated distribution of geoengineering effects from a humanitarian perspective and argue that if the exploration of geoengineering options continues, the emphasis should be on designing a framework for managing the risks to those most vulnerable to potential impacts.

A further widely recognized socio-political dimension of geoengineering research concerns the role of scientists themselves. Geoengineering researchers have often faced the call to justify their involvement, for example, because geoengineering research is seen as carrying the potential to divert attention and funding from mitigation and adaption [*Stilgoe*, 2015a]. Reflecting upon the motivation behind and the subsequent effects of Crutzen's own call to action, *Lawrence and Crutzen*'s contribution to this special issue takes up the long-running debate as to whether advocating research into geoengineering is morally responsible, concluding that researchers should actively engage in societal dialog to ensure that research is conducted responsibly. In their contribution, *Burns et al*. also emphasize that research can perform a legitimizing or performative role, and therefore argue for responsible, self-reflective social science research into geoengineering to mitigate future risks. The authors also point out that "*not* pursuing empirical research on a subject like this comes with direct risks" (emphasis in original). The role of scientists in pushing geoengineering onto the research policy agenda is additionally discussed by *Oschlies and Klepper*, who detail how a bottom-up responsibility initiative of concerned scientists led to the emergence of the national priority program for the assessment of geoengineering measures in Germany. As becomes evident throughout the contributions to this special issue, the risks and side effects associated with geoengineering take center stage in discussions of the potential viability and desirability of any geoengineering intervention. Discourse analysis has shown that in general, even proponents of geoengineering "are well aware of and seriously consider all the technology's risks" [*Anshelm and Hansson*, 2014a, p. 135].

The way in which solar geoengineering research is and will be understood may depend to a large extent on how information about the technologies is framed and communicated by privileged storytellers, such as leading academics [*Bellamy*, 2013; *Corner et al*., 2013; *Scholte et al*., 2013; *Anshelm and Hansson*, 2014a, 2014b; *Cairns and Stirling*, 2014; *Huttunen and Hildén*, 2014; *Linner and Wibeck* 2016; *Harnisch et al*., 2015]. In this issue, *Caldeira and Bala* discuss the tendency among both natural and social scientists in the field of geoengineering to present viewpoints as if they were facts, and in a similar vein, *Reynolds et al*. [2016] evaluate and critique some of the common claims put forward about solar geoengineering and call for more evidence-based discussion of the technologies.

5. Ways Forward

After 10 years of increased research into geoengineering, preceded by a much longer history of investigation, many questions still remain unanswered. As *MacMartin et al*. put it, when reviewing the development of geoengineering research, perhaps the appropriate question to ask is not "what have we learned?", but rather, "what don't we know after a decade of research?" [*MacMartin et al*., this issue]. As *MacMartin et al*., *Robock et al*. and *Keith and Irvine* all point out in this issue, despite progress in understanding the potential environmental, political, and societal risks and benefits of solar geoengineering, the current state of knowledge remains insufficient for conducting the sort of comprehensive assessment required to make future decisions on deployment. However, work on integrated, future-oriented assessment frameworks is underway. In this issue, [*Boyd*, 2016] outlines a set of geo-politically relevant geoengineering assessment criteria based on the potential transboundary effects of a range of techniques, and *Oschlies et al*. [2016b] present a call for a decision-oriented approach to identify specific indicators and metrics for assessing geoengineering involving academia, decision-makers, and societal stakeholders. In their contribution, *Irvine et al*. [2016b] detail moves toward integrating climate impacts into assessments of geoengineering. Furthermore, as both *Caldeira and Bala* and *Robock* emphasize in the contributions to this special issue, in addition to continued computer modeling and integrated assessment efforts, advancing scientific knowledge of the potential positive and negative effects of geoengineering techniques is likely to require outdoor experimentation in the future. The prospect of experimentation in the open environment is expected to lead to increased efforts toward the development of geoengineering research governance frameworks. Although geoengineering research has received increasing attention from economists, climate modelers, earth system scientists, political scientists, philosophers and beyond over the last 10 years, much work remains to be done before informed societal and political decisions on geoengineering can be made in the future.

As the above discussion has highlighted, natural and social science research into and discussions of emerging geoengineering proposals are characterized by a future-orientation that fundamentally shapes how geoengineering is entering the collective imagination of scientists, policymakers, and publics, and by a mode of knowledge production that recognizes the risks that may result from new knowledge and that struggles with its own socio-political dimensions. As geoengineering technologies are currently in the process of being defined and designed, reviewing the development of research on and discussions of geoengineering provides a timely opportunity to consciously reflect upon possible future developments. Such reflexive moments are especially relevant at the early, constitutive stages of technological emergence, when socio-technical imaginaries have not yet stabilized and science and society alike still have important roles to play in shaping their future trajectories [*Jasanoff and Kim*, 2009].

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