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The Evidentiary Politics of the Geoengineering Imaginary

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The Evidentiary Politics of the Geoengineering Imaginary

by

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in the

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Abstract

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This dissertation investigates the ways in which societies are coming to know and govern solar geoengineering. The question at the heart of this dissertation is not whether solar geoengineering will succeed, or even whether it should, but rather what makes it — and its governance — imaginable. To this end, the bulk of this dissertation aimed to analyze the co-production of the evidence — and governance assumptions — for a sociotechnical system that does not yet exist. To do so, I draw on work in science and technology studies (STS) and political science to elucidate and analyze the political and scientific claims underpinning expert attempts to capture the public imagination and put solar geoengineering on mainstream public policy agendas. I argue that the ability to put an emerging technology on the public agenda constitutes an exercise of power, determined neither by social structures nor entrepreneurial social actors alone, and entails its own, oft-neglected, evidentiary politics.

Decades of scholarship in the interpretive social sciences demonstrates that framing and producing technoscience requires imaginative as much as technical work. Sheila Jasanoff's concept of 'sociotechnical imaginaries' offers a useful point of entry into these dynamics. Sociotechnical imaginaries describe "collectively held, institutionally stabilized, and publicly performed visions of desirable futures" co-produced with advances in science and technology.

As a theoretical concept, imaginaries help to explain why some visions of scientific and social order are co-produced, while others are not. Coupling this work with responsible research and innovation (RRI), which is concerned with the responsible steering of technoscientific developments, draws attention to the ways these imaginaries may play a vital role in the development, assessment, and governance of emerging technologies *in the present*, making scrutiny of their content and prospects for institutionalization urgent and timely.

Any social scientific study of solar-geoengineering-in-the-making presents challenges for the analyst, some of which are shared across 'emerging technologies,' and some of which are unique to this topic, at least at this stage. For one, the supply of research on solar geoengineering — social scientific and otherwise — has outpaced any demand function. It is not yet a significant topic of research in the private sector, nor is it entangled in broader imaginaries of national identity or competitiveness, though this may change. As Steve Rayner has pointed out, solar geoengineering is at a research impasse. Moreover, the primacy of models as an evidentiary basis for contemplating solar geoengineering has contributed to its stabilization as an object of governance before we know much about what it is likely to become, or even whether it is doable. This has led to a set of assumptions about what solar geoengineering is (for example, that it is cheap and easy, or likely to make things better or worse for specific people in specific places) that may need to be revisited. In this supply-driven context, the visions of a relatively narrow set of actors — and narrow kinds of evidence — are forming the foundation for future policy regimes.

In *Evoking equity as a rationale for solar geoengineering research? Scrutinizing emerging expert visions of equity*, I examine the scientization of debates about the equity implications of solar geoengineering research. In so doing, I identify three sets of equity-related arguments advanced by sociotechnical vanguards advocating for more solar geoengineering research. The first is a call for more research as a means to shed light on the distributional outcomes of envisioned futures with and without solar geoengineering. This includes a call to reduce uncertainties inherent in scientific models examining distributional outcomes of potential deployment of solar geoengineering. Accompanying such calls is a discernible shift in the content of science itself, from more extreme to more 'realistic' modeled scenarios of deployment, and from consideration of global to regional effects. The second equity-related rationale for more research is a call for comparative risk-risk assessment, underpinned by the claim that equity demands that potential risks and benefits of solar geoengineering be compared to the risks of climate change itself, especially for vulnerable populations. The third equity-related rationale for more solar geoengineering research is the invocation of the 1.5°C aspirational goal of the Paris Agreement as requiring research on solar geoengineering, out of concern for the global poor and those most vulnerable to the consequences of climate change.

My research suggests reveals several implications of this expert-driven, outcome-oriented, and risk-based understanding of equity. First, this framing suggests that more research on solar geoengineering is the only rational choice if one is concerned with equity, since many of the relevant concerns are empirical matters, amenable to resolution through the provision of more science. Second, it sidesteps the question of whether and how diverse non-experts should have a say in research, even if it is to occur on their behalf, in part by assuming that climate-related preferences are knowable and quantifiable. Third, the focus on predicting the outcomes of any future deployment of an imaginary technology at this stage represents an exercise in speculative ethics, and risks ignoring alternative ways of thinking about equity and responsibility in the context of technological innovation. Finally, I suggest that further analysis should be directed toward whether the vanguard visions I explore reflect a broader shift in operationalizing equity within multilateral climate politics, with those bearing the greatest responsibility now recast as 'risk managers' on behalf of the global poor and the vulnerable. I argue that those characterized as 'the vulnerable' in expert discourses should regain their status as agential subjects, rather than remain undifferentiated objects in expert discourse. Empirical research suggests that publics have a set of concerns not captured in the approach to equity I analyze in this dissertation, including issues around moral responsibility, historical global injustices, the ability to be included in, and benefit from, technological development, and concerns around lack of agency and self-determination in shaping innovation pathways.

In *The Politics of Climate Models for Solar Geoengineering Research*, I argue that there is an oft-neglected politics of evidence around attempts to put emerging topics on the formal public agenda, which has the potential to shape future policy regimes. In this chapter, I analyze the mutual construction of solar geoengineering modeling and policy framing. Climate models have been understood as important nodes at the interface of climate science and policy, and as capable of shaping societies' understanding of, and responses to, climate change. As Mahony and Wynne point out, less has been said about the development of this relationship over time, which can help explain how it is that the intersection of modeling and politics takes on the form that it does[156].

There are at least two issues around uncertainty and representation in the use of climate models for knowledge about solar geoengineering, which raise questions at the intersection of modeling and politics. The first is that models are being used to represent technologies which do not yet exist, black-boxing the engineering in geoengineering ideas. As one interviewee stated, "In the model, you can just *make geoengineering work*. You can just assume that the oceans have a higher albedo because of ocean bubbles, whether it's possible or not." This results in discussion of the management of the representation of a technology in models, rather than of the development of the technology itself. In addition, the displacement of technology with models has the effect of eliding important near-term questions around the complexities of technology development and the structure of responsible research programs, and stabilizing solar geoengineering as an object of governance. Secondly, there is significant debate about whether these models can usefully predict outcomes at all; uncertainties that may be less relevant to models of and for climate science and mitigation policy may become 'matters of concern' when it comes to predicting or promising regarding the effects of geoengineering.

I argue that imaginaries of solar geoengineering technologies — despite not serving current regulatory demands, and despite the non-existence of the technologies themselves (perhaps because of it) — are engaging directly with policy needs (both current and predicted). With regard to current needs, the focus on *models* as proxies for actual *deployment* of these imagined technologies has the effect of making it seem as though societies 'know' more about whether and how to develop these techniques than they do, which is resulting in debates about the management of the *representation* of a technology which does not yet exist. This has contributed to the current research impasse, in which "technologists await a green light from social scientists before proceeding with research, while social scientists are limited to commenting on highly speculative ideas about how geoengineering might turn out in practice."[192] Policymakers are avoiding decisions regarding the advisability of a research program aimed at answering societally-relevant questions about technology development, but are content to fund indoor modeling studies and speculate about the impacts of future deployment. Alternatively, one might argue that the existing settlement, at least in the US, between governments, non-governmental organizations (NGOs), and scientists, in which governments seem willing to fund indoor modeling studies but accept an informal moratorium on everything else, may itself be a kind of clumsy solution, the stability of which depends on its non-articulation [256].

There is a broader question around displacement in the realm of climate policy raised by this research. Several scholars and commentators have raised questions about the role of imagined technologies in the present, especially since the 2015 Paris climate agreement.[7, 177, 198] As Steve Rayner has pointed out, the agreement maintains the belief that global temperature targets are achievable via the inclusion of imaginary technologies, which represents a kind of 'magical thinking.' [198] Noting that the line between ambition and delusion is not always sharp, Rayner argues that the reality seems to be that the world is already likely to exceed the temperature limit agreed to absent some form of geoengineering. Despite this reality, the inclusion of climate engineering technologies in modeled scenarios has the effect of making political targets seem achievable. This is true even without any instrumental action — and potential near-term political costs — to policymakers when it comes to actually funding research and development on these imagined technologies, and assessing their impacts and implications.

Finally, in *Climate Researchers' Views of Solar Geoengineering: Benefits, Risks, and Governance*, I present the results of the first survey of climate change researchers' views of solar geoengineering research and its appropriate oversight. I argue that definitions of 'expert' in emerging domains is itself a contested political category, and far from straightforward, particularly when the technologies under consideration do not yet exist. Respondents in this survey, much like surveys of general publics, report concern about the moral hazard operating at the level of political decision-making. Nevertheless, respondents generally support research on solar geoengineering, including small-scale outdoor studies — despite both a general concern that research may result in lock-in and slippery slopes to deployment, and skepticism about the advisability of ever deploying these techniques. I find strong support for some form of novel or supplementary governance arrangement(s) for research, and a belief that scientific self-regulation is insufficient to manage risks. There seems to be less agreement, however, on particular governance approaches; I find mixed responses regarding the desirability of a 'physical thresholds' approach to governing geoengineering experiments, for example.

Despite the fact that most respondents express skepticism about the desirability of future deployment, respondents tend to support more research into these techniques, both indoor and, to a lesser extent, outdoors. This might be explained by a view that research will reveal reasons not to move forward, or because of a belief that concerns about slippery slopes are overstated (although this seems less likely, given that most respondents report concern that research may result in lock-in and slippery slopes to deployment). Alternatively, it may be the case that a substantial number of researchers surveyed here constitute an interest group, which stands to benefit from scientific research moving forward, irrespective of its strategic aims. Respondents express skepticism about prediction and controllability when it comes to solar geoengineering deployment. It remains an open question whether a desirable future world with solar geoengineering would depend upon predicting such outcomes, although most respondents do report a belief that uncertainty in our understanding of the climate system means we should never deploy solar geoengineering.

I raise several candidate predictors for risk perception among climate researchers, including cultural worldview, gender, geography, familiarity, political ideology, and climate catastrophism. Cultural worldview was only a significant predictor for one of the five factors used as response variables in the regression models (delegation to experts). My sample was highly skewed relative to surveys of the general public; relative Hierarchical-Individualists (HIs) in my sample might actually be absolute Egalitarian-Communitarians (ECs) in a sample of the general public (including climate researchers). HIs and ECs in my study, therefore, might be more similar to one another than my division suggests. This finding also raises some question about cultural and political diversity in the academy — in climate research, and potentially beyond [274].

Gender emerged as a significant predictor for three of the five factors in this study (research, deployment, and governance). While one study of risk perception of scientists regarding nuclear power did find gender differences [5], a more recent meta-analysis of gender and risk by Julie Nelson raised some doubts about such findings. She concluded that women are not more 'risk averse,' or only marginally so, and only in certain contexts. Even then, the differences between men and women are small. Nelson finds that, in general, there are more differences within men or within women than across genders [166].To the extent that women researchers do, on average, tend to view solar geoengineering research and its governance differently than their male counterparts, this finding does not explain the *sources* of these differences. Research suggests that these differences, where they exist, are likely to be due to social facts and/or norms [68, 175] or to particular contexts (e.g., risks to identity and/or concerns about stereotypes have been found to amplify differences across genders in some instances).

Irrespective of the source of the variation, the analysis here suggests that it may be important to consider gender explicitly, both in the conduct of future empirical social science on solar geoengineering and in the design and conduct of solar geoengineering research programs and governance institutions. One early study of gender and geoengineering finds very low representation in scientific publications on geoengineering, at expert meetings on the topic, and in media accounts [24]. In terms of the impacts of this under-representation, as Buck *et al.* point out, an important concern relates less to women missing out on careers in geoengineering, but rather "in the framing and decision-making powers that participation in geoengineering research implies." This is not just a normative concern (women are vulnerable to climate change and also geoenginering, so should have a say) but also a substantive one: when confronting 'wicked problems' [204] like geoengineering, the deliberate design of pluralistic institutions which seek to include multiple rationalities and perspectives can help facilitate the development of 'clumsy solutions' [256].

Arguments for inclusion also apply to geographical differences. My study used binary categories (inside/outside of US), and thus cannot address important country-specific differences. However, comparative work in STS on the role of political culture in shaping sociotechnical choices supports the view that this may be an important variable when it comes to considerations of risk and regulation. Other potentially interesting geographic divisions could have been used, but the relatively small sample size limited the statistical power of alternative breakdowns.

Climate catastrophism (or 'perceived climate risk') was a significant predictor for moral hazard (where those who see the risks of climate change as greatest also see the risks of moral hazard as highest), deployment (where catastrophists were associated were more negative perceptions of deployment), and governance (where catastrophists tended to favor novel governance arrangements).

Given low awareness of solar geoengineering, participation by a narrow set of actors — including scientists, but also those who claim to represent the views of civil society — can close down discussion of this imaginary technology, rather than open it up. In this way, the views of relevant but disempowered publics are assumed before most people have even heard of these ideas. It remains to be seen whether and how early visions of solar geoengineering will cohere or acquire collective stability, or whether they will be radically disrupted. My hope is that the data and analysis in this dissertation may prove useful in tracing the evolution of solar geongineering and its governance over time.

For Nancy and Julia.

Contents

List of Figures

List of Tables

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Chapter 1

Introduction

> What else do we find? Certainly there is awe, it is all awe, it transcends previous categories of awe, but we dont know whether we are watching in wonder or dread, we dont know what we are watching or what it means, we dont know whether it is permanent, a level of experience to which we will gradually adjust, into which our uncertainty will eventually be absorbed, or just some atmospheric weirdness, soon to pass. [55] p. 373

> There have been great societies that did not use the wheel, but there have been no societies that did not tell stories. [147] p. 22

1.1 Overview

Grounded in science and technology studies (STS) and political science, this dissertation examines debates over the governance of solar geoengineering research. Drawing on the concepts of 'sociotechnical imaginaries' and responsible research and innovation (RRI), I elucidate and analyze the political and scientific claims underpinning expert attempts to capture the public imagination and put geoengineering on mainstream climate policy agendas. The ability to put an emerging technology on the public agenda constitutes an exercise of power — determined neither by social structures nor entrepreneurial social actors alone.Decades of scholarship in the interpretive social sciences demonstrates that framing and producing technoscience requires imaginative as much as technical work. Sheila Jasanoff's concept of 'sociotechnical imaginaries' offers a useful point of entry into these dynamics. Sociotechnical imaginaries describe "collectively held, institutionally stabilized, and publicly performed visions of desirable futures" co-produced with advances in science and technology ([116], p. 6). As a theoretical concept, imaginaries help to explain why some visions of scientific and social order are co-produced, while others are not. RRI, which is concerned with the responsible steering of technoscientific developments, draws attention to the ways these visions of the future may play a vital role in the development, assessment, and governance of emerging technologies in the present (see also [28], p. 233), making scrutiny of their content and prospects for institutionalization urgent and timely.

My research brings work in STS on sociotechnical imaginaries into conversation with political scientific studies of agenda setting. Research in political science on the early phases of policy development tends to underestimate the role of scientists and experts in shaping the contours of policy debates. When these issues are examined, scholars tend to focus on later stages of the formal agenda setting process (e.g. congressional hearings), with some notable exceptions [133, 248]. Since scientists are key actors in the framing of technoscientific issues, and because these framings have the potential to influence the scope of issues worthy of consideration and the kinds of representations (of nature and social orders) that are treated as authoritative in the development of future policy regimes, scrutiny of these imaginaries is an important analytical task.

In so doing, I argue that imaginaries of solar geoengineering are functioning as a kind of 'proto-regulatory science.' Regulatory science is generally defined as a social space wherein the construction of stable and credible factual claims is especially challenging due to: political pressure which tends to deconstruct those claims because of concerns about particular *future* regulatory actions; over-ambitiousness of science, particularly regarding prediction; its necessarily interdisciplinary nature; short-time scales; and/or high decision stakes [228]). However, evidence in this dissertation, in particular *The Politics of Climate Models for Solar Geoengineering Research* suggests that imaginaries of solar geoengineering technologies — despite not serving current regulatory demands, and despite the non-existence of the technologies themselves (perhaps because of it) — are engaging directly with policy needs (both current and predicted). With regard to current needs, the focus on *models* as proxies for actual *deployment* of these imagined technologies has the effect of making it seem as though societies 'know' more about whether and how to develop these techniques than they do, which is resulting in debates about the management of the *representation* of a technology which does not yet exist. This may have contributed to the current research impasse, in which "technologists await a green light from social scientists before proceeding with research, while social scientists are limited to commenting on highly speculative ideas about how geoengineering might turn out in practice" [192]. Policymakers are avoiding decisions regarding the advisability of a research program aimed at answering societally-relevant research questions in a pluralistic manner. Alternatively, one might argue that the existing settlement, at least in the US, between governments, NGOs, and scientists, in which governments seem willing to fund indoor modeling studies but accept an informal moratorium on everything else, may itself be a kind of clumsy solution, the stability of which depends on its non-articulation [256].

With regard to anticipated needs, it is important to note that there is remarkably little engineering in geoengineering, and yet studies of the technology's potential consequences have proliferated in the last ten years. Evidence in this dissertation, in particular *Evoking equity as a rationale for solar geoengineering research? Scrutinizing emerging expert visions of equity* suggests that the focus on predicting possible futures and their consequences may be eliding near-term issues relevant for responsible innovation, including around the kinds of evidence that might be needed to understand the merits of imagined future worlds, which understandings of equity are relevant to whom, and the need for inclusive knowledge production [172]. In this way, my research engages directly with questions of 'anticipation' and 'speculative ethics' in STS and RRI, in particular. While acknowledging that to not engage the speculators and speculations means that we may allow the 'hype-or-horror prognosticators' to dominate the discussion, set the terms of debate, and the research agendas to be pursued [84], the data and analysis in this dissertation suggest that there are risks in focusing on the prediction (perhaps even the anticipation) of plausible future worlds at the expense of attention to the present. The question of whether efforts to anticipate the futures of solar geoengineering may potentially undermine societal agency over technological futures, in part by distracting from choices that are made in the present, remains an open one [171, 172].

Related to the issue of the politics of speculation is a question around what paradigms of risk assessment and management are invoked in debates about solar geoengineering research, and by whom. Much of the empirical social science on actors' perceptions of the benefits, risks, and governance architectures appropriate for solar geoengineering research focus on the public. If, as research suggests, experts and policy entrepreneurs have the power to shape the early contours of these debates with implications for the development of future policy regimes [133, 248, 227], the lack of attention to these actors and their views is a significant gap in existing research. One might explain this asymmetry by a common misunderstanding in risk politics: that publics are deficient in their understanding of scientific and technical matters, and that this is the source of policy controversy. This assumption can result in pathologizing the public [273], and focusing on public education in lieu of issues like trust in institutions, representation, and agency. In *Climate Researchers' Views of Solar Geoengineering: Benefits, Risks, and Governance*, I argue that climate researchers may be more homogeneous in their cultural worldviews than general publics, that gender and geography may be important drivers of differences in researchers' views of the benefits, risks, and governance of solar geoengineering, and that climate researchers generally support near-term research on solar geoengineering, despite skepticism around whether deployment will ever be advisable. Moving forward, assumptions that 'expertise' is straightforward in an emergent domain need to be questioned, as do assumptions that more science will yield agreement about the benefits and risks of research and appropriate oversight.

While it may be too early in the emerging domain of solar geoengineering to say anything decisive about the stability of these early visions, I argue that it is important to attend to the development of potentially policy-relevant epistemic frameworks underpinning early decision-making on solar geoengineering. This is especially important if societies seek to develop governance mechanisms capable of reflecting on these early assumptions and framings, and opening them up to broader democratic scrutiny. This is the central project of my dissertation.

1.2 Research Design

Research questions

This dissertation seeks to address several research questions motivated by the intersections of RRI and 'sociotechnical imaginaries.' Following the idiom of co-production [242], I center my analysis on identities, institutions, and discourses that accompany representations of solar geoengineering ideas and practices. I pay particular attention to policy discourses and processes of issue framing and agenda setting [83, 223, 88, 164], including by scientists. More specifically, I focus on how these narratives frame and define the public good with respect to solar geoengineering, how they seek to delimit or contain risks, how they (re)configure geopolitical boundaries, and how they refer to the past and future as sources of authority. I also examine policy and scientific documents and media articles and debates to understand framings of desirable or undesirable futures, tropes, and/or analogies that identify elements of an imaginary of solar geoengineering.

The research herein addresses the following questions:

How do future visions of 'sociotechnical vanguards' — of responsibility and agency, in particular — inform solar geoengineering debates and/or policy? Who are the key actors? How is the public good defined, and by whom? (See *Evoking equity as a rationale for solar geoengineering research? Scrutinizing emerging expert visions of equity*).

What kinds of evidentiary thresholds are constructed and contested, and by whom, in the early stages of policy development? (see *The Politics of Climate Models for Solar Geoengineering Research*).

What paradigms of risk assessment and management are invoked/co-produced in debates about whether and how to move forward with research? How do climate researchers view the benefits, risks, and appropriate governance architectures for solar geoengineering research? What are potential sources of variation? (See *Climate Researchers' Views of Solar Geoengineering: Benefits, Risks, and Governance*).

How do early framings/imaginaries cohere, acquire collective stability in an emerging domain (or not)? (See *Conclusion*).

Research methods

This study employed a mixed methods approach with a focus on qualitative data gathered through interviews and participant observation. Quantitative data were also gathered through a survey of climate researchers.

I conducted participant-observation over the course of five years at conferences, meetings, academic programs, and listservs involving geoengineering research advocates, opponents, activists, and a range of publics.

Using a snowball sampling method, I conducted ten semi-structured interviews with climate modelers. (See appendices for list of questions).

Data were also collected during a deliberative exercise with 45 mid-career environmental practitioners from the Global South in July of 2014.

I conducted a web-based survey of climate change researchers between January and March of 2017. The survey was pilot tested with graduate students and researchers, and the survey was administered online using Qualtrics. Invitations to participate in the survey were sent by email, which included a description of the research, institutional review and consent information, and a link to the survey. In total, 460 surveys were completed. Of those for whom a usable email address was identified, 15.3% responded.

Documentary analysis included examination of peer-reviewed publications, white papers and grey literature, publications produced by key actors and NGOs, and representation of geoengineering in media.

Table 1.1: Participant Observation Conducted for Dissertation

Event	Date	Location
Berkeley Workshop on Climate Engineering	Jul-14	Berkeley, CA, USA
Climate Engineering Conference 2014	Aug-14	Berlin, Germany
Workshop on the International Governance of Climate Engineering	Oct-15	Bellagio, Italy
Meeting of Academic Working Group, Forum for Climate Engineering Assessment	Mar-16	Washington, DC, USA
Harvard University Solar Geoengineering Residency	Jul-16	Cambridge, MA, USA
Meeting of Academic Working Group, Forum for Climate Engineering Assessment	Sep-16	Tarrytown, NY, USA
Meeting on Emerging Technologies, Forum for Climate Engineering Assessment	Feb-17	Berkeley, CA, USA
Forum on US Solar Geoengineering Research	Mar-17	Washington, DC, USA
Geoengineering Research Governance Project: Workshop on Code of Conduct for Geoengineering Research	Jun-17	Oxford, UK
Gordon Research Conference on Climate Engineering	Jul-17	Newry, ME, USA
Meeting of Academic Working Group, Forum for Climate Engineering Assessment	Sep-17	Washington, DC, USA
Climate Engineering Conference 2017	Oct-17	Berlin, Germany

1.3 Solar Geoengineering

Geoengineering is broadly understood as a set of ideas to intentionally intervene in, and alter, the climate at a global scale [23]. These approaches are generally divided into two broad categories: carbon dioxide removal and solar geoengineering [23]. Solar geoengineering options aim to alter the energy balance of the Earth by, *inter alia*, reflecting incoming solar radiation [178]. These currently remain speculative, with very little scientific research funded to date beyond indoor modeling studies and observations of volcanic eruptions, although some scientists have expressed interest — and acquired funding — to conduct small-scale outdoor experiments. *Explicit* policy demand for this supply of science is minimal, evinced by the lack of publicly-funded research on the topic. Despite the lack of significant research and development on the topics, the idea of geoengineering is receiving some attention in mainstream climate *discussions*, most recently in its inclusion in the scoping report for the forthcoming Intergovernmental Panel on Climate Change (IPCC) Special Report on the impacts of 1.5 degrees of warming, and pathways for achieving it [143].

The mounting risks of climate change impacts, compounded by the slow pace of international efforts at mitigation, led to the release of a seminal report on climate engineering by the UK Royal Society in 2009. Since then, a number of policy and scientific bodies have called for research on the topic [224, 38, 173]. More recently, some analysts have argued that the Paris climate agreement "facilitates the eventual inclusion of" solar geoengineering, in particular ([98], p. 5). This set of proposals has received significant attention, at least within certain expert circles, since Nobel prize winner Paul Crutzen's 2006 article calling for research into techniques to add sunlight reflecting aerosols into the stratosphere [54]. These ideas — variously termed 'solar geoengineering,' 'solar radiation management,' and 'albedo modification' — would aim to enhance the reflectivity of the planet to cool the global temperature. Early evidence from models and some observations of volcanic eruptions suggests solar geoengineering approaches could be effective at cooling the planet, "but at a currently unknown environmental price" (*ibid*, viii).

The idea of large-scale intervention into Earths systems is not new. Historically, societies promised to negotiate with heavenly powers to control the weather, including, for example, via attempts at ritualistic rainmaking. With the rise of modern science came a new set of promises. The idea of weather control has a long modern history, which historian Jim Fleming divides into three periods: (1) 1839-1946: western rainmaking to enhance crop growth (i.e., pluviculture); (2) 1946-1978: cloud seeding, commercial rainmaking, and attempts to weaponize weather (especially in the Cold War and Vietnam); and (3) 1978-present: climate modification to counter the effects of climate change [72]. Among advocates of geoengineering research, there has been some attempt to draw a boundary between attempts at weather modification and *climate-scale* geoengineering. From the early 20th century, interest in weather control reflected economic concerns regarding adequate rainfall for crop productivity, and military interest in the international race to weaponize weather. By the mid-20th century, research into weather control was considered an economic and geopolitical imperative, marrying meteorological research with the national security complex. Henry Houghten, chair of the MIT meteorology department in 1957, stated: "I shudder to think of the consequences of a prior Russian discovery of a feasible method for weather control. Fortunately for us and the world we were first to develop nuclear weapons. International control of weather modification will be as essential to the safety of the world as control of nuclear energy is now [...] Basic research in meteorology can be justified solely on the economic importance of improved weather forecasting but the possibility of weather control makes it mandatory" ([128], citing Henry Houghten, p. 252). The military also expressed the fundamental need for weather control research. General George C. Kenney, commander of the Strategic Air Command argued, "The nation that first learns to plot the paths of air masses accurately and learns to control the time and place of precipitation will dominate the globe" ([72], p. 10).

US funding for weather and climate modification reached 10 million US dollars in 1970, with limited investment in other countries (excepting Russia). However, public outcry in response to a campaign of weaponized weather control in Vietnam, pessimism about the effectiveness of cloud seeding, and the growing environmental movement led to a sharp decline in US research into weather modification by the late 1980s [72]. While China and the US have the largest investments in operational weather modification programs today (often aimed to increase precipitation or decrease hail), federal funding levels are far below their peaks in the late 1970s [3].

Geoengineering promises to be different from earlier attempts at weather control, with advocates of research drawing sharp boundaries between the two. In a review of geoengineering written in 2000 by one of the world's leading geoengineering researchers, David Keith focuses on the history of these ideas only beginning in the post-World War II period. While he acknowledges the shortcomings of this approach, it may have the effect of sharpening the distinction between pseudo-scientific or ritualistic promises to control the weather, and climate-related discussions of science-based interventions. Even within the post-World War II period, Keith draws a boundary between weather modification and climate modification: 'The correspondence between the 1960s concern with weather and climate modification and current discussion of geoengineering is less precise in that the aim of weather and climate modification was improvement of the natural state or mitigation of natural hazards, whereas the aim of recent geoengineering proposals is the mitigation of anthropogenic hazards' ([128], p. 250). This boundary-drawing can also be found in institutional reports and grey literature. The Royal Society report on geoengineering in 2009 traces the history of interest in geoengineering only to the 'earliest studies of climate change,' implying that the roots of geoengineering lay in an understanding of climate science, and not in earlier promising around control of weather ([23], p. 4). While there is, of course, a rationale for this boundary work [79], it has strategic dimensions, and is not without political effects — drawing a distinction between 'science' (climate science and geoengineering) and 'non-science' (ritualistic or magical attempts to control weather) can be interpreted as an attempt to confer legitimacy on the former. This may also affect discussion of governance approaches; as just one example, attempts to draw sharp distinctions between climate-related geoengineering and weather modification may result in an unwillingness to examine regulatory schemes for cloud seeding experiments as relevant for thinking about the governance of geoengineering experimentation.

1.4 STS Literature on Solar Geoengineering

The modern rise of geoengineering as a 'matter of concern' [146] has coincided, to some extent, with demands for the greater social accountability of science and technology in modern societies ([244] p. 853). In the second half of the 20th century, prevailing beliefs in the internal accountability of science (as accountable to nature, intra-scientific norms and standards, and/or to the production of societal benefit), were complicated by the pervasiveness of science in modern democracy [213], and growing concerns about the undesired dimensions and consequences of technological development [8, 39]. Recent and persistent public controversies over the societal implications of technologies such as nuclear power and biotechnology, as well as broader debates over the distribution of the benefits and costs of innovation, can be read as an implicit acknowledgment of the complex linkages between — indeed, the co-production of [111, 242] — science and society [86]. The seminal 2009 Royal Society report on geoengineering reflects this interest in the political foundations of innovation in its conclusion that The acceptability of geoengineering will be determined as much by social, legal, and political issues as by scientific and technical factors, and its recommendation to develop and implement governance frameworks for research and development, as well as potential deployment ([232], p. 57).

Building on decades of scholarship in science and technology studies (STS) and practical experience, which has demonstrated that science and technology are not just bits of hardware, but are socially and politically co-produced [242, 267], recent STS-inflected research on geoengineering — including on its governance — has sought to account for much more than the downstream consequences of a self-governing scientific enterprise. This has involved shifting scholarly attention from the governance of risk to the governance of innovation itself [246, 66], and to address questions such as: "what is the purpose; who will be hurt; who will benefit; and how can we know?" ([113], p. 240). STS-inflected scholarship on geoengineering has critically analyzed the politics of science and expertise in the early constitutions and representations of geoengineering and its governance. In addition to critical analyses addressing these questions, a number of frameworks have been put forward to govern geoengineering research in recent years, including anticipatory governance and responsible research and innovation (RRI). This diverse body of research shares a commitment to probe the processes and purposes of innovation — not just its consequences — and to reclaim decisions about geoengineering research as a space for collective ethical reflection and imagination.

The inclusion of STS analyses of geoengineering upstream in the research process has raised concerns by some that such scholarship may have an 'outsized' role in shaping the future of the field of geoengineering, either by prematurely stabilizing geoengineering as a policy option [12, 244], or by inhibiting valuable scientific research, by giving decision-makers and scientists the impression that social scientists and ethicists must sort out the governance issues before any research can or should move forward. There are, of course, other possibilities, including that upstream inclusion of social scientific expertise has not significantly affected decisions by research funders regarding the pursuit of climate engineering research, or that it has altered trajectories in more complex ways.

From the governance of risk to the governance of innovation

One approach to addressing the social dimensions of science and technology broadly has been to support inquiry into the ethical, legal, and social consequences of large scientific initiatives. However, as some scholars has argued with regard to the Human Genome Project, this approach to technological governance is often not well-integrated into research itself early enough to steer innovation in meaningful ways [89, 46]. Moreover, these endeavors are often expert-driven, in which "science proposes, society disposes" ([86], p. 96): broader societal engagement is limited to scientists informing society about how to respond to the consequences of innovation. Relatedly, the governance of innovation has tended to focus on products, especially those which are found to be unacceptable, rather than steering the innovation process itself, or probing the purposes of research [246]. This has often resulted in formal risk-based regulation, which sometimes fails to anticipate matters of concern early on [39], ignores them, or captures only certain risks as relevant. The prevalence of this approach has also been critiqued for bolstering a 'predict-then-act' paradigm, rather than building capacities for flexibility, reflexivity, and anticipation [258]. At an organizational level, where technological assessment bodies exist, such bodies are often constituted as advisory to parliaments or legislatures, requiring a "political trigger" for the initiation of assessment activities, and therefore remain isolated from the research and innovation process itself [86, 18].

An important contribution of STS broadly has been to question technological determinism, or the idea that innovation is natural, inevitable, or uncontrollable. STS scholars contend that science and innovation are not politically neutral, although there is some debate about the degree of indeterminacy of particular technologies. Some researchers argue that technologies have particular forms of political life inscribed in them from the very beginning, while others believe that political effects are a matter of design choice, and still others afford more interpretive flexibility to the political life of technologies [268, 39, 118]. This raises at least two relevant points for conceiving of responsible innovation, including in geoengineering: first, technologies are not politically neutral, hinting at the imperative to steer technological development toward socially desirable ends upstream in the innovation process itself; second, because the political life of technologies can become 'locked in' as technologies develop, societies seeking to govern emerging technoscientific developments are faced with what has come to be known as the Collingridge (1980) dilemma [39]: how can technologies by deliberately governed, when they are flexible but too inchoate in early stages, but too 'locked-in' to existing economic and social interests further downstream?

STS research on the governability of geoengineering has grappled with these issues in several ways. Some scholars have argued that solar geoengineering as it is being constituted is not amenable to democratic governance [252, 102], while others suggest that it is simply too early to know how this sociotechnical system — which does not yet exist — is likely to develop [244]. These understandings imply different prescriptions: if (some forms of) geoengineering are inherently undemocratic, an extremely precautionary position, perhaps a ban on innovation in this domain altogether, might be desirable; if geoengineering is politically undetermined, governance arrangements might be imagined which steer technoscientific development in more socially robust directions.

STS-inflected governance frameworks for geoengineering innovation

Research in STS has turned explicitly to practical questions regarding the governance of geoengineering research. This has involved directly addressing concerns related to the Collingridge dilemma (described above), path-dependence and socio-technical lock-in [29], slippery-slopes with respect to research and deployment: the notion that, in some cases, research may lead "unreflectively to development and ultimately deployment," [109, 25], and irreducible uncertainties and the potential desirability and democratic governability of certain forms of geoengineering altogether [102, 252] Analysts have also focused on how boundaries are drawn (and by whom) around what makes geoengineering a matter of concern in the first place — is it intent, or the unbounded nature of experimentation, or something else? — and how this boundary work influences governance frameworks [244].

The Oxford Principles — the first national-level policy statements on geoengineering (Great Britain, Department of Energy and Climate Change 2010) — were derived by a group of researchers with experience in the governance of emerging technologies broadly, and include insights from STS [199]. The principles rest on the assumption that issues associated with geoengineering are at least as much political and social as they are technical: the principles include the regulation of geoengineering as a public good, public participation in decision-making, disclosure of research plans and open publication of results, independent assessment, and governance before deployment. In addition, the framework is intended to guide the development of a system of governance from the earliest stages of research [199]. The Oxford Principles also underlie a set of principles agreed to by a group of geoengineering researchers at the Asilomar Conference on Climate Intervention Technologies in 2010.

Similarly, one of the only solar geoengineering field experiments funded to date was governed by a framework informed by STS insights (in this case, RRI). In 2010, the UK Research Councils funded a low-physical-risk outdoor experiment (the Stratospheric Particle Injection for Climate Engineering, or SPICE) aimed to generate knowledge about solar geoengineering. The Research Councils implemented a stage-gate approach for the funding and governing of the SPICE Project to ensure that public dialogue and consideration of ethical and political issues preceded the conduct of the experiment. Social scientists, including STS scholars, were engaged in developing the five criteria that were used by an advisory panel at each stage of the proposed experiment (see [246]). The criteria included questions about risk identification and management, regulatory compliance, communication of the purposes of the project, clear description of potential impacts and mechanisms to review them, and mechanisms to understand public and stakeholder views. Jack Stilgoes 2015 book Experiment Earth, which chronicles the SPICE project, argues for the adoption of RRI in geoengineering more broadly: the dimensions of responsible innovation are anticipation, inclusion, reflexivity, and responsiveness [244].

Several geoengineering researchers and policy bodies have suggested that research in this domain be governed on the basis of physically-defined thresholds: lawyer Ted Parson and geoengineering researcher David Keith call for physically-defined experimental thresholds in order to enable small-scale outdoor research, and ban research where there is a discernible effect on the environment [179]; for Alan Robock, research indoors should move forward, while outdoor research requires additional scrutiny [205]. These calls have been echoed elsewhere, in policy reports and scholarly literature. Stilgoe argues that empirical evidence from a proposed experiment in the UK suggests that such framings of the experimental system will be insufficient to quell broader societal concerns [244]. Moreover, attempts to contain the experimental system were co-produced with attempts to contain relevant publics — but NGOs critical of the experiment implied that due to broader societal concerns, relevant public for this particular experiment encompasses the worlds population (ETC Group).

Winickoff & Brown [263], building on the work of the US Bipartisan Policy Centers Task Force on Geoengineering [38], recommend an advisory commission to guide national geoengineering research. The authors assert that the development of substantive standards, or '(dis)allowed zones' for triggering additional oversight of geoengineering research only address part of the problem, because such approaches do not attend to the procedural dimensions of governance: who defines these standards, and according to what criteria? An advisory commission to "recommend principles, policies, and practices" in order to facilitate responsible research, which is "independent, transparent, deliberative, publicly engaged, and broadly framed" ([263], p. 81).

In addition to these formal institutional approaches to governance, STS looks for governance in unexpected places — this includes examination of the patent system/intellectual property regimes [181, 174] and analyses of the structuring power of knowledge production in geoengineering research [252, 174]. Parthasarathy et al. identify trends in the current patent landscape in the US, arguing that while relatively few patents have been granted, a few trends — including broad patent language, growing numbers of patents, and the concentration of patent ownership — suggests that patents will play an important role in the development of geoengineering technology, and perhaps threaten innovation and the public interest. The authors explore the possibility of the development of a *sui generis* patent system, not unlike the system for nuclear technology in the US [181]. Oldham et al. (2014) conduct a bibliometric analysis to examine how scientific and intellectual property practices can de facto shape the development of the field of geoengineering, arguing that mapping the landscape in this way can aid in the development of anticipatory governance [174].

Framing & the Futures of Geoengineering

An interest in framing, a central matter of inquiry in co-productionist accounts of STS, including research on 'sociotechnical imaginaries [60], has generated a diverse body of literature on framings of geoengineering in media [185, 222], academic literature [14, 105], public discourse [155], in key texts and policy documents [76, 151] and at various formative moments in ongoing geoengineering activities and discussions [218]. Despite methodological and epistemological diversity, some common themes and points of tension have emerged, not least of which is an understanding that "representations matter as much as whatever we may choose to call reality in shaping social behaviors" ([112], p. 25). There has been much discussion of whether framings of geoengineering are narrowing or 'opening up' over time [247, 24, 14, 222], the importance of 'climate emergency' as a framing device [169, 77, 158], cross-national comparison of policy framings [151], the emergent narrative around climate engineering as contrasted to narratives around other emerging technologies [218, 244], analyses of frames/framings as discursive phenomenon, actively constructed and negotiated by a range of actors [30], and the need to attend to the power of framing — including in empirical social science on public views of geoengineering [101, 14].

Markusson et al. examine the 'pre-emptive, emergency frame' of geoengineeringthe notion that solar geoengineering, in particular, offers a potential response to possible future climate emergenciesarguing that this frame tends to close down the possibilities for deliberation, that climate emergencies are poorly defined, vague, can justify action in the present on the basis of unpredictable futures, and needs to be actively defused [158]. Several scholars have noted that this frame for can bolster technocratic approaches to environmental management [94]. Others have argued that declarations of emergencies can foster a 'state of exception [221, 1], which carries inherent risks [33], cited in [234]. Moreover, as geographer Mike Hulme has argued: "Climate emergencies are made, not discovered, and what matters most is who announces them and for what purpose" ([102], p. 134-35). Flegal and Gupta trace the emergence of a 'risk-risk' framework in the wake of the 'climate emergency' frame among advocates of solar geoengineering research, arguing that this frame implies that risk assessment is an epistemic issue (weighing the scientifically-defined risks of solar geoengineering against those of climate change), which seeks to tame uncertainties and ignorance, and can bolster a moral division of labor where normative and political concerns are pushed downstream of scientific ones [71].

Scholars have also examined metaphors as framing devices. Nerlich and Jaspal [169] examine the use of metaphors in promotional discourse related to geoengineering, and argue that the catastrophe frame is used to sell geoengineering to the public, which contributes to closing down debates about geoengineering. Luokkanen et al. widen the scope of analysis, pointing to diversity in the use of metaphors beyond those which support the climate emergency/catastrophe argument. Their work traces "how geoengineering metaphors are used in a variety of contexts with implications for both positive and negative views and perceptions of geoengineering" [151], p. 973).

A central theme has also been whether framings of geoengineering — in mass media, public engagements, and elsewhere — have been 'opening up' [247] (i.e., becoming more wide-ranging and diverse), or closing down. Scholte et al. map the framing of geoengineering in English-speaking newspapers from 2006-2011, arguing that framings have widened, not narrowed in recent years [222]. In contrast, in a review of geoengineering appraisals, Bellamy et al. (2012) argue that geoengineering has often been evaluated in isolation of broader contextual information, and that appraisals have been dominated by technical expertise, and therefore close down upon particular sets of problem definition, values, assumptions, and courses of action. Concerns about this narrowing can also be found in the literature and practical experience with public engagement on geoengineering (see below). Sikka, in her critical discourse analysis of geoengineering advocacy, argues that particular institutions and actors advocating for geoengineering research have strategically framed geoengineering to "limit, shape and mould the current debate surrounding geoengineering" ([233], p. 173).

Cairns and Stirling warn of the dangers of co-option via strategic framing devices which can be used to garner support for a particular view. The authors analyze geoengineeringand its attendant frames/framings — as a discursive phenomenon, actively constructed and negotiated by a range of actors [30]. In contrast to Scholte et al. (2013), who argue that the ambivalence frame of geoengineering is likely to be less powerful than other pro or con frames [222], Cairns and Stirling argue that geoengineering encompasses (perhaps unavoidably) ambiguous and multivalent sets of meanings, and that additional framings outside of the bipolar pro/con axis exist among certain actors.

The futures of geoengineering

A smaller body of literature, building on research in sociology and STS [227, 60, 43, 21], has examined the politics and sociology of expectations, including how appeals to the future shape near-term geoengineering-related activities (for a brief review, see [150]). Some of this work has focused on the role of climate modeling in producing visions of solar geoengineering [261, 93], and credibility contests [62] around global climate models for geoengineering purposes [244, 264]. Flegal & Gupta analyze how particular visions of equity are embedded in the discourse and practices of advocates of solar geoengineering research (or 'sociotechnical vanguards' [95], which potentially narrow the set of concerns and actors deemed relevant and/or authoritative [71]). Beck & Mahony analyze the politics of anticipation at the Intergovernmental Panel on Climate Change (IPCC), arguing that the development of pathways for achieving temperature targets are more than technical artifacts, and in fact may work to hasten particular futures into being — futures with wide-ranging political and societal implications, as well as scientific and technical ones [7]. Steve Rayner, in his anthropological account of the 2 degrees C goal agreed to at the Paris climate conference, argues that the inclusion of an imaginary technology (in this case, negative emissions technologies) to meet politically-negotiated expressive goals, without instrumental commitment to achieving them, constitutes 'magical thinking' [198].

Jack Stilgoe has called into question the stabilization of geoengineering as an object of governance, arguing that it has been naturalized by its researchers, treated as a thing in the world to be understood rather than a highly controversial, highly speculative set of technological fix proposals [244]. He advocates, instead, for engaging with the collective experimental nature of geoengineering research and its governance — including, perhaps, by adopting inter- and multi-disciplinary research approaches in the realm of field experiments ([244], citing [119]). In his book Experiment Earth, Stilgoe points to the dynamics of hype and promising that often accompany emerging technologies, while noting that geoengineering would seem distinct from other domains, like nuclear power and genetics, in that "Few people interested in geoengineering imagine that it will be an unalloyed good" ([244], p. 35). Nevertheless, Stilgoe argues that narrow promising on the basis of predictions of the future should be supplanted with a more inclusive practice of anticipation, which aims to "think through various possibilities" and responsibilities related to innovation. (*ibid*) Steve Rayner has warned of the 'novelty trap,' for emerging technologies broadly, which can lure researchers into overselling the newness of their innovations to attract research funds, and downplay those same dimensions as mundane when they attract the eye of regulators [195].

Inclusion

Another central matter of concern in STS analysis of technological politics is the relative role of experts in modern democracies. In more technocratic arrangements, decisions about technoscience are delegated to experts, who have the political privilege of determining whether and how innovation proceeds. In more participatory models, wider publics have a greater say in these matters. Funtowicz & Ravetz have argued that when facts are uncertain, values are in dispute, stakes are high, and decisions are urgent, society is firmly operating in the context of 'post-normal science' [74]. By these criteria, many of today's societal problems — including climate change and geoengineering — are post-normal. In such contexts, the traditional mechanisms of peer review are unlikely to be sufficient to resolve controversies and compel policy action.

Research has analyzed how social, political, ethical, and cultural assumptions are interwoven with technical work, including in the production of knowledge about geoengineering [264, 159]. This would suggest that appeals to the universality and objectivity of science are unlikely to quell concerns about the legitimacy and credibility of geoengineering research, and that there is a risk that even ethical experts may miss some salient issues for diverse publics. Winickoff et al. (2015) based on an engagement exercise with 45 environmental practitioners from the Global South, argue for the importance of inclusion and representativeness in knowledge production, as well as governance institutions, for normative as well as substantive reasons [264]. Wylie Carr and Christopher Preston draw on in-depth interviews with 'vulnerable populations' to examine ethical concerns about geoengineering, finding that issues linked to "legacies of colonialism and imperialism" and concerns with self-determination — often missed in existing ethics literature on geoengineering — represent an overarching concern for vulnerable populations [36]. Peter Frumhoff & Jennie Stephens argue for the co-production of research priorities and standards for governance through a governance process that involves a wide range of potential stakeholders — including civil society organizations from regions of the world that are particularly vulnerable to climate risks [73].

Studies in STS which leveraged cross-national comparison to identify differences in political cultures help explain how and why innovation and its governance varies across national jurisdictions [22, 257, 112] — and the challenges this may pose for global and increasingly complex governance [265]. These findings suggest that political culture, and particular cultural modes of knowledge-making (or civic epistemologies), shape what constitutes an (in)tolerable risk or (un)desirable benefit. We might expect divergences in national approaches to the governance of geoengineering innovation, as well. Further comparative research on geoengineering could elucidate some of these issues.

Public engagement

In the last ten years, over 30 studies investigating public views of geoengineering have been undertaken, mostly in the global North [26], even as natural and physical scientific research on geoengineering has largely been confined to indoor modeling studies. This empirical social scientific research can be interpreted as a response to the recognition of a broad public interest in anticipatory (or 'upstream' [262]) stages of geoengineering research. Such an interest has been articulated by scientific and policy advisory bodies, as well as by natural scientists, social scientists, ethicists, international legal experts, and even members of various publics. For example, the 2009 Royal Society report argued that "geoengineering research [...] should not proceed in the absence of a wider dialogue between scientists, policymakers, the public and civil society groups" ([232], p. 42). In the US, the 2011 Bipartisan Policy Center report recommended that 'mechanisms for public engagement' be established as part of geoengineering research programs to promote accountability, build trust in institutions, and to align research with social values and concerns ([38], p. 14). More recently, the 2015 US National Research Council reports on geoengineering recommended a deliberative process with civil society representatives to examine research governance needs ([52], p. 153, 156).

As illustrated briefly above, the rationales for greater public engagement with science and technology, and geoengineering in particular, vary widely. These rationales are sometimes considered in three categories: normative, instrumental, and substantive [69, 247]. From a normative perspective, the argument is that the governance of science and innovation without meaningful participation from interested stakeholders is contrary to democratic ideals.

Citizens ought to have a say in whether and how science and technology affect their lives, the argument goes, in accordance with principles of transparency and informed consent. The instrumentalist argument is concerned with public acceptance of science and technology: engaging the public upfront on questions of controversial science and technology policy may stave off public outcry, and enhance trust between scientists and lay publics (this instrumentalist justification is highly contested, see [78], p. 128). The goal of public engagement is not to create public acceptance, but about giving stakeholders an opportunity to engage on these issues, and encourage participation. Finally, substantive arguments state that public engagement, and in particular the incorporation of non-expert views, can enhance the quality and relevance of the knowledge produced, as well as the utility of technologies. Public engagement can take many forms, and is often a part of more formal processes of technology assessment, and/or about building trust in the scientific enterprise more generally.

As there are different rationales for engaging publics on geoengineering, so, too, there are different formats for eliciting and analyzing public views. Scholars have warned of treating these approaches similarly, given different aims and epistemologies [27]. For example, the aims of public opinion polling are often distinct from those of public deliberation (for a review of empirical social science on solar geoengineering, see [26]).

While the trend toward adoption of public engagement policies within innovation policy — and in geoengineering in particular — suggests that it may be perceived by some countries as beneficial, there are some challenges to its effective implementation. First, previous engagement efforts and scholarly work suggests that engagements are most effective at achieving stated objectives when policymakers do not view the public as having deficient knowledge with respect to science and technology [272]. In addition, constructing representative publics through such exercises can prove challenging. Some public engagement processes are only viewed as legitimate for those publics directly engaged in them. This has been termed a 'fundamental problem of scale,' ([149], p. 483, [243]) and points to the need to consider engagement exercises as only one element of more responsible innovation policy. Another challenge relates to making geoengineering-related decisions responsive to the outputs of public engagement efforts. There is some risk that weak public engagements do not facilitate true deliberation, and instead serve to legitimate existing policies, especially if these activities adopt a 'managerial discourse' [193]. Furthermore, these mechanisms of engagement are most likely to be impactful when technologies are further upstream, or before they are locked-in [39]. This means that, while especially effective in cases of emerging technologies, public engagements can be more challenging for technologies that are already deeply entrenched. It also means that it can be difficult — though certainly not impossible — to engage publics on technologies that are at early stages of development, and therefore inchoate [85].

Critical reviews of the first round of public engagement efforts on geoengineering argue that the topic was perhaps too narrowly construed [47, 14], and as a result more recent efforts have worked to 'open up' dialogues. Corner et al. (2011) articulate two issues related to this concern. Firstly, the notion of a climate emergency was frequently used to introduce geoengineering in early engagements, which potentially "artificially enhanced the acceptability of conduct research" ([47], p. 14), and favored proposals which could be fast-acting and operate at the global scale [12]. Secondly, characterizing certain proposals as 'natural' resulted in the favoring of those techniques among some publics [49]. Moreover, a reliance on expert assessment of the potential risks and benefits of specific technologies potentially limited the ability of participants to consider a broader range of issues about geoengineering, including those potentially missed by technical experts [47]. The issue of presenting climate engineering in isolation of other approaches to addressing climate change has also been raised as potentially 'closing down' policy options, or stabilizing geoengineering as a policy option [247, 12].

More recent engagement exercises have tried to tackle these issues, by, for example, changing the 'inputs' provided to the assembled mini-publics. This included, for example, a weaker role for STEM experts in facilitating discussions during public engagements [12], expert self-restraint in answering questions, and an attempt to shift geoengineering from noun to verb (e.g., referring to approaches as 'ideas,' or 'proposals,' and not 'technologies,' see also [245]). Lastly, recent engagements have tried to take a broader approach in an attempt to situate climate engineering in broader discursive fields. Bellamy & Lezaun (2015) trace a few specific strategies employed by more recent engagements: The workshops conducted by IAGP introduced geoengineering in the context of climate change more broadly, rather than as a separate object of discussion [51]; the Deliberative Mapping project forced consideration of geoengineering symmetrically alongside mitigation and adaptation [12]; and solar geoengineering focus groups decoupled geoengineering from climate change entirely [155]. In 2017, Bellamy et al., rather than seeking to unframe geoengineering, *per se*, engaged in self-reflective experimental manipulation of deliberative exercises — both its participants and rules for deliberation — seeking to generate insights into whether and how cultural worldviews affect public views on geoengineering and its governance [13].

While the aims of public engagement efforts are not to derive generalizable conclusions, a few key themes have emerged across some activities: general unfamiliarity with geoengineering among many publics; the importance of framing; nuanced views of research and deployment; the importance of risk and uncertainty; and complicated concerns related to the moral hazard hypothesis (the notion that research on geoengineering might distract from mitigation).

Evaluating and/or assessing public engagement is a difficult task, in part because of a lack of clarity about its aims. However, if engagements are conceived as part of building a practice of responsible innovation, and not as a panacea for the irreducible uncertainties and challenges associated with technoscientific developments, then evaluations of the 'impact' of individual exercises may be ill-advised [85]. Scholars of public engagement with science and technology have warned against assessing the value of engagements on a case-by-case basis, particularly if the goals of such efforts are to "contribute to bending the long arc of technoscience more toward humane ends" [85], and not as panacea for all of societies' problems in governing technology.

Boundaries

STS analyses of the governance of geoengineering tend to challenge attempts to draw sharp distinctions between science, on the one hand, and governance, on the other. STS research has long attended to attempts to purify the 'hybridity' of modern life, for example into the categories of 'natural' and 'social'-work which is seen by Bruno Latour to be so central to modernity so as to be termed 'constitutional' [145]. Steve Rayner has drawn attention to the definitional politics in geoengineering discourse, in which engaged actors disagree about which technologies should or should not be included in the category of 'geoengineering' [192]. As I argue in *The Politics of Climate Models for Solar Geoengineering Research*, there is also boundary work [79] around what makes geoengineering a matter of concern, which shapes whether and how we conceive of the governance of this topic: is geoengineering a matter of concern because of its physical effects, suggesting that research inside the laboratory should be exempted from democratic scrutiny? Or does intent matter? In the introduction to solar geoengineering above I point, also, to attempts by early advocates of geoengineering research (and the Royal Society) to draw distinctions between weather control and geoengineering, perhaps as a strategy to enhance the credibility of the idea of geoengineering by contrasting it with non-scientific claims of weather control. This may help explain the dearth of work on the application of governance regimes for weather control to ideas around geoengineering experimentation (for an exception, [91]).

1.5 Dissertation Outline

First, in *Evoking equity as a rationale for solar geoengineering research? Scrutinizing emerging expert visions of equity* I argue that a small group of experts advocating for more research into solar geoengineering — what I term, following Stephen Hilgartner, 'sociotechnical vanguards,' — are justifying a call for more research, sometimes on equity grounds. I argue that what experts say and do to define and address issues of equity matters, because such boundary-drawing affects who is authorized to speak with regard to the advisability and contours of solar geoengineering research, and because the emerging visions of a smaller configuration of actors may have the potential to coalesce into widely-shared and collectively-held imaginaries. These early visions thus have implications for the potential development, assessment, and governance of emerging technologies. For these reasons, I analyze the content of expert understandings of equity and raise some questions about who and what gets excluded from expert discourses of equity in the context of solar geoengineering research.

In *The Politics of Climate Models for Solar Geoengineering Research*, I argue that there are at least two issues around uncertainty and representation in the use of climate models for knowledge about solar geoengineering, which raise questions at the intersection of modeling and politics (particularly around regulatory science and responsible innovation). The first is that models are being used to represent technologies which don't yet exist. As one interviewee stated, "In the model, you can just *make geoengineering work*. You can just assume that the oceans have a higher albedo because of ocean bubbles, whether it's possible or not." This elides important near-term considerations about geoengineering, including the complexities of technology development and the structure of responsible research programs. Secondly, there is significant debate about whether these models can usefully predict outcomes; uncertainties that may be less relevant to models of and for climate science may become 'matters of concern' when it comes to the effects of geoengineering.

Finally, *Climate Researchers' Views of Solar Geoengineering: Benefits, Risks, and Governance* reveals some potentially important trends regarding how experts are defined, and how they might come to view solar geoengineering research and its governance.

The appendices include interview guides, my survey instrument, and consent forms.

Chapter 2

Evoking equity as a rationale for solar geoengineering research? Scrutinizing emerging expert visions of equity

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2.1 Introduction

> Taking principles of global distributive justice seriously entails a moral obligation to conduct research on solar geoengineering.
> — Horton and Keith, 2016 [99], p. 80

In the above quote, Horton and Keith make an explicit justice and equity argument for undertaking research on solar geoengineering. In such a view, *not* contemplating such research is tantamount to the rich abrogating their responsibilities to helping the global poor to deal with the inequities of climate change. This article undertakes an in-depth exploration of this kind of claim-making and its implications. Such an analysis is particularly timely in the wake of the Paris Agreement and its aspirational goal to limit global warming to 1.5° C above pre-industrial levels, to be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities (CBDR-RC). A growing number of observers argue that this goal potentially opens the door to solar geoengineering in mainstream climate policy, including on equity grounds [99, 65, 231, 108, 53, 177, 187]. If so, as part of a Special Issue on Equity and 1.5° C, we interrogate how notions of equity are being evoked by experts in advocating for further research on solar geoengineering. Our analysis thus addresses a key research gap: how particular understandings of equity are constructed by, and embedded within, emerging expert visions as a way to legitimize further research into solar geoengineering.

Geoengineering is broadly understood as a set of ideas to intentionally intervene in, and alter, the climate at a global scale [23]. These approaches are generally divided into two broad categories: carbon dioxide removal and solar geoengineering [23]. Solar geoengineering options aim to alter the energy balance of the Earth by, *inter alia*, reflecting incoming solar radiation [178]. These currently remain largely in the realm of speculative technologies, with very little scientific research funded to date beyond indoor modeling studies, although some scientists have expressed interest — and acquired funding — to conduct small-scale outdoor experiments. Explicit policy demand for this supply of science is minimal, evinced also by its general absence in mainstream climate policy discussions.

In such a context, some expert advocates of research into solar geoengineering are justifying a call for more research into these technologies partly — though not exclusively — on equity grounds. The implications of this, and the potential for such expert views to become more widespread (or not) are thus important to examine. According to the standard Oxford dictionary meaning of the term, equity is "the quality of being fair and impartial" with its multiple synonyms including fair-mindedness, justice, fair play, and rightfulness. Clearly, all of these notions are subject to diverse interpretations, not least in the contested context of imagining, anticipating and governing uncertain climate futures. As such, our aim here is not to advance our own understanding of equity but rather to distill and examine notions of equity advanced by those advocating for solar geoengineering research.

This also allows us to consider how emerging expert understandings of equity resonate with, upend, or further legitimize broader trends in conceptualizing and operationalizing equity within the contested politics of multilateral climate governance writ large. As one of us has argued elsewhere, there is arguably a shift underway in practice within multilateral climate governance, particularly in the post-Paris era, from a focus on the diverging historical responsibilities component of the CBDR-RC equity principle, to the capabilities component [82]. One potential implication is that equity debates become less about ambitious mitigation by those with the greatest historical *responsibilities*, and more about enhancing the *capabilities* (or, more narrowly, the capacities) to take action of those with lower responsibilities. While a focus on capabilities/capacities, including of the most vulnerable, is a desirable element of equity, it is important to consider whether such a shift in focus could amount to a blunting of the politically contested edge of equity, and whether such a trend is also evident in the expert visions we explore here.

Our analysis focuses on a specific sub-group of experts: those advocating for more research on solar geoengineering, particularly in the United States. We rely on qualitative methods for our analysis, including participant observation, interviews and analysis of primary and secondary literature. We draw, *inter alia*, on participant observation of multiple solar geoengineering expert meetings over the last five years[1], where expert visions of the future (and the role of equity therein) are presented and discussed, as well as publicly articulated positions of scientist-advocates of solar geoengineering research as contained in websites, position papers, advocacy efforts and media debates. We supplement this with an extensive review of the published scientific literature as another key source of evidence.

We proceed as follows: the next section identifies the conceptual lens we deploy, drawing on notions of 'sociotechnical imaginaries' and 'vanguard visions', to analyze emerging expert notions of equity in the context of novel and largely speculative technologies. Section 3 then identifies and analyses key equity claims advanced by solar geoengineering research advocates. We should note here that while this may not constitute a very large group of individuals at this stage, we do assume the *potential* for outsized influence by members of the group in shaping context-specific research trajectories (particularly in the US), either because of the eminence associated with the sites wherein their visions are articulated (e.g., elite universities and/or eminent scientific publishing outlets) or because of the visibility and high-profile, including in the media, of the scientists themselves. In concluding, we consider the political implications of these emerging expert evocations of equity in justifying solar geoengineering research, and identify what gets left out of such visions as well.

2.2 Imagining Solar Geoengineering Futures: Equity in Vanguard Visions

Solar geoengineering is still confined largely to the realm of the imagination, yet climate futures that include it are ever more prominent in a burgeoning scientific literature. This proliferation notwithstanding, the imagined utopias (and dystopias) associated with solar geoengineering are not yet widely shared or institutionalized. As such, they do not yet constitute what Jasanoff and Kim term 'sociotechnical imaginaries', i.e. "collectively held, institutionally stabilized, and publicly performed visions of desirable futures" co-produced with advances in science and technology ([116], p. 6). Nevertheless, the emerging visions of smaller configurations of actors, such as expert advocates of solar geoengineering research, may have the potential to coalesce into widely shared, collectively held imaginaries. Such

[1]Formal participant observation was conducted from 2014-2017 at the following meetings: Berkeley Workshop (Berkeley, CA, US, July 2014); Climate Engineering Conference (Berlin, Germany, August 2014); Workshop on the International Governance of Climate Engineering (Bellagio, Italy, October 2015); Meeting of the Academic Working Group of the Forum for Climate Engineering Assessment (Washington, DC, US, March 2016); Harvard University Solar Geoengineering Residency (Cambridge, MA, US, July 2016); Meeting of the Academic Working Group of the Forum for Climate Engineering Assessment (Tarrytown, NY, US, September 2016); Forum for Climate Engineering Assessment, Meeting on Emerging Technologies (Berkeley, CA, US, February 2017); Forum on US Solar Geoengineering Research (Washington, DC, US, March 2017); Geoengineering Research Governance Project: Workshop on Code of Conduct (Oxford, UK, June 2017); and Gordon Research Conference on Climate Engineering (Newry, ME, US, July 2017). Ten semi-structured interviews were conducted with climate experts over the same time period.

visions may play a vital role in the development, assessment and governance of emerging technologies (see also [28], p. 233), making scrutiny of their content and prospects for institutionalization urgent and timely.

Our aim here is thus to scrutinize emerging expert visions through relying on the notion of 'sociotechnical vanguards' advanced by Hilgartner (2015) [97]. Hilgartner understands this term to mean "relatively small collectives that formulate and act intentionally to realize particular sociotechnical visions of the future that have not yet come to be accepted by wider collectives" ([95], p. 34). Following Hilgartner, we view emerging equity related visions of a specific group of experts, *viz.* advocates of solar geoengineering research, as constituting such 'vanguard visions. In deploying this notion, we do not aim to single out or identify specific individuals as belonging to this group, nor do we seek to draw rigid boundaries around it. Instead, we leave membership in this vanguard group to be ascertained *de facto* from those whose work and statements we include in our empirical analysis. In other words, we use the notion analytically rather than as a methodological tool, and deploy it here as a means to characterize as a "sociotechnical vanguard" any geoengineering researcher / expert who advocates, in his or her scientific or popular writings, media interventions or public talks, for further research into solar geoengineering, based upon identifiable contours of a vision of what an equitable future with (and without) solar geoengineering might mean.

In scrutinizing expert vanguard visions of equity, as they relate to largely speculative technologies and their role in imagined climate futures, our analysis also engages with an ongoing debate (particularly amongst researchers of responsible research and innovation, and anticipatory governance) about the political implications of engaging in so-called 'speculative ethics' [171]. According to Nordmann, the exercise of speculative ethics entails articulating ethical concerns about wholly speculative technologies manifesting in largely unknowable futures, with the danger that "an imagined future overwhelms the present" ([171], p. 32). Nordmann notes the inherent impossibility of anticipation as a way to know the future in anything more than a superficial sense, and hence the risk that (even) ethical *critique* of speculative technological futures may well serve to reify them (for further discussion and defense of this notion, see [244], p. 39-41; for a critique, see [84, 226]).

For our purposes, this debate draws attention to a well-established call within science and technology studies research, including on the sociology of expectations and sociotechnical imaginaries, to explore the political implications *in the present* of specific "fabrications of the future" (Jasanoff 2015: 337) and the performative power in the present of expectations, ideas, promises and dreams about the future [227, 21, 7, 261, 150]. Aligned with this, we interrogate here the specific content of one such set of speculative claims, those advanced by vanguards calling for more research into solar geoengineering on equity grounds. This allows us to discern the political implications of specific expert forms of engagement in 'speculative ethics' in relation to potentially high stakes solar geoengineering research.

We turn next to our empirical analysis of the diverse equity-related rationales being advanced by advocates of solar geoengineering research.

2.3 Vanguards advocating for solar geoengineering research: evoking equity

In this section, we analyze how equity is being implicated in three sets of arguments advanced by sociotechnical vanguards advocating for more solar geoengineering research. The first is a call for more solar geoengineering research *as a means to shed light on the distributional outcomes* of envisioned futures with and without solar geoengineering. This includes a call to reduce uncertainties inherent in scientific models examining distributional outcomes of potential deployment of solar geoengineering. Accompanying such calls is a discernible shift in the content of science itself, from more extreme to more 'realistic' modeled scenarios of deployment[2], and from consideration of global to regional effects. The second equity related rationale for more research is a call for *comparative risk-risk assessment*, underpinned by the claim that equity demands that potential risks and benefits of solar geoengineering be compared to the risks of climate change itself, especially to vulnerable populations. The third equity-related rationale for more solar geoengineering research is the evocation of the 1.5° C aspirational goal of the Paris Agreement as *requiring* research on solar geoengineering, out of concern for the global poor and those most vulnerable to consequences of climate change. We address each in turn below.

Equity as Distributional Outcomes: Identifying Winners and Losers in Solar Geo-engineered Futures

> You made a very strong claim that geoengineering is zero-sum. If true, I would oppose any further work on the technology. I responded that results from all climate models strongly suggest that this is not the case
> — David Keith (in [132]).

Climate modeling studies have become central to understanding posited future solar geoengineering effects and impacts [139], including distributional aspects and identification of 'winners and losers'. A major concern raised in debates about the advisability of moving forward with solar geoengineering research — and in technical studies — has been whether any potential deployment would "destabilize regional climates," exacerbating or (re-)producing climate-related inequities [132, 102, 31, 92, 106, 165, 23, 225, 206, 202, 135, 201, 138, 26].

[2] Here we refer to general circulation models, which constitute the vast majority of climate modeling studies on solar geoengineering to date [108]

These debates have played out in the climate modelling community, with the focus of modelling efforts shifting and expanding over time from consideration of global to regional effects and from more extreme to more 'realistic' modeled scenarios of deployment.

From the start, modeling and model results have been at the crux of taking proposed solar geoengineering techniques seriously. Current advocates of research claim to have been converted from skeptics to proponents of research after early modeling studies suggested that these techniques might be more effective and safer than initially assumed [80, 261, 244, 16]. While these early studies focused on the potential of solar geoengineering approaches to offset warming in an aggregate sense (i.e., compensating for changes in global mean temperature), more recent work has turned to questions of the regional impacts of potential deployment of solar geoengineering techniques ([224], p. 383).

The shift from a global to a regional focus has resulted, in part, from claims that even if solar geoengineering deployment could address climate change at the global scale, deployment could produce novel climate configurations at more localized scales, and potentially make things worse (especially regarding precipitation) for some regions of the world. This is because local discrepancies in radiative forcing as a result of deployment could lead to regional climate changes, and because the impact of solar geoengineering on precipitation and the hydrologic cycle is not well understood [224].

Such concerns emanated, *inter alia*, from an inter-model comparison project established for geoengineering (the Geoengineering Model Intercomparison Project, or GeoMIP), which aimed to "understand the robust climate model responses to geoengineering" ([142], p. 3380, referencing [141]). In addition to a global focus, early studies also tended to assume 'extreme scenarios', both of climate change itself and deployment (e.g., abrupt quadrupling of carbon dioxide emissions and aggressive solar 'dimming') (for a critique of claims based on these studies, see [131]). The 'extreme scenarios' approach is seen by some scientists as vital to serving legitimate scientific ends, with those undertaking it noting that "simulations have repeatedly been shown to be a novel method of uncovering fundamental climate behavior" ([142], p. 3380). However, some of these early studies also suggested quite negative regional implications of some scenarios of deployment, and were interpreted as evidence for legitimate equity concerns. Findings included, for example, that solar geoengineering had "the potential to drive regional climates outside the envelope of greenhouse gas-induced warming, creating 'novel' conditions" ([106], p. L18702); that solar geoengineering might weaken the Indian monsoon [206]; involve a large reduction in precipitation [67, 255]; or involve trade-offs in which there would inevitably be winners and losers [202]

In response, prominent advocates of solar geoengineering research now argue that these early studies are not acceptable evidence for making decisions about solar geoengineering research (particularly on the basis of equity concerns), because the scenarios they model are insufficiently realistic or policy-relevant [131, 201, 130]. This suggests some tension between intra-scientific standards of research (about the merits of modeling more extreme scenarios to explore fundamental climate dynamics versus more realistic scenarios to address imagined needs of decision-makers, especially regarding equity concerns).[3] Advocates of solar geoengineering research see the purpose of such research as supporting climate policy decisions and not to pursue "purely scientific goals" ([130], p. 550).

In an implicit acknowledgement that scientific studies shape the windows of political opportunity in important ways, these vanguard research advocates thus critique the early unrealistic scientific studies as responsible for producing a trope of the likelihood of *inequitable* impacts in the solar geoengineering literature (Reynolds et al. 2016). As one scientist argued, 'extreme scenarios', lead to "extrapolations about risks and about social impacts," which do not help us "study what the outcomes associated with a broader range of scenarios would be."[4] Some experts talk of 'winners and losers' from solar geoengineering deployment ([23], p. 51; [138], p. 6). In any case, the legitimacy of pursuing (or not) solar geoengineering research on equity grounds has come to rest, partly, on the extent to which we can realistically know and predict the likely physical (distributive) outcomes of solar geoengineering deployment.

Going beyond physical effects on the climate system (assessed largely through climate models), scientists are also now discussing climate impacts from deployment of solar geoengineering (assessed largely through integrated assessment modeling)[5]. Prominent researchers working on solar geoengineering have identified assessment of impacts, including (in-) equitable impacts, as central to understanding the consequences of proposed solar geoengineering techniques [93, 108]. In a detailed review of the state of impact modeling in solar geoengineering, Irvine and colleagues argue that "a thorough climate impacts assessment is needed to better evaluate *societally relevant consequences* of deploying solar geoengineering" ([108], p. 94, emphasis added). One scientist noted in an interview that a focus merely on climate effects such as "global average temperature and precipitation are fine, but they dont help people in their daily lives."[6] Even GeoMIP researchers note that future efforts will "encourage cooperation with [...] impact assessment communities" ([139], p. 13103).

While scientists readily acknowledge that modeling results (whether relating to climate

[3]Remote interview conducted with GeoMIP participant, 2017.

[4]Researcher quoted at Forum on US Solar Geoengineering Research, Washington, DC, US, March 2017

[5]Climate *effects* are assessed by climate models, defined by the IPCC as "a numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties." Thus, climate effects include, for example, increased precipitation or sea level changes. Climate *impacts* are examined using integrated assessment models, which are "a method of analysis that combines results and models from the physical, biological, *economic and social sciences*, and the interactions between these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it" ([253], emphasis added). Thus, climate impacts include integrated assessment of projected physical/biological changes to the climate systems, with social and economic aspects as well.

[6]Remote interview conducted with GeoMIP scientist, 2017.

effects and/or impacts) are not the only way to decide whether solar geoengineering is advisable, and some note major issues with integrated assessment models for these purposes (see [93], p. 2, noting the "general limitations of simple assessment frameworks" for regional disparities), many advocates of research argue that the equity dimensions of solar geoengineering demand more policy-relevant research on likely effects and/or impacts. Thus, in sum, in epistemic visions of equity, assessing distributive outcomes of solar geoengineering deployment (both in terms of climate effects and impacts) come to the fore.

Yet, a focus on anticipating 'realistic' distributive outcomes of the deployment of still speculative technologies, and privileging epistemic authority in doing so, can risk becoming an exercise in speculative ethics, particularly given pervasive scientific uncertainties. Reliance on modeled projections of global or even regional outcomes of solar geoengineering deployment may, as Szerszynski et al. (2013) point out, overpromise on what science can deliver in complex domains, with attendant risks for the democratic governance of innovation [252].

The issue of the reliability of climate models as bolstering the case for solar geoengineering, including on grounds of equity, came to the fore in a published exchange between David Keith and Mike Hulme in 2013 in *The Guardian* [132], as follows:

> I take solar geoengineering seriously because evidence from atmospheric physics, climate models, and observations strongly suggest that it could significantly reduce climate impacts to vulnerable people and ecosystems over the next half century.
> — David Keith

> [...] the point here is how much faith we can place in climate models to discern these types of regional changes. As the recent report from the UNs Intergovernmental Panel on Climate Change has shown, at sub-continental scales state-of-the-art climate models do not robustly simulate the effects of greenhouse gas accumulation on climate. What you are claiming is that we can rely upon these same models to be able to ascertain accurately the additional effects of sulphur loading of the stratosphere. Frankly, I would not bet a dollar on such results, let alone the fate of millions.
> — Mike Hulme

This discussion implicates, as well, the role that reducing scientific uncertainties plays in realizing (or not) equitable outcomes from solar geoengineering. Uncertainty and/or ignorance have become, as Steve Rayner (2014) notes, key rhetorical devices in debates about (the need for) solar geoengineering research [191]. As two prominent scientists put it, “The stakes are simply too high for us to think that ignorance is a good policy” ([32], p. 62). From this perspective, whether solar geoengineering is a viable climate policy option or not (which depends, in part, on its ability to produce equitable outcomes), is a matter that demands further research to reduce our ignorance. In contrast, opponents of research have argued that ignorance is unavoidable (“there are limits to human knowledge” [102], p. 112), and that remaining ignorant constitutes good policy. Regardless of whether or not ignorance constitutes good policy, which is a broader debate cutting across science-politics, if fundamental uncertainties about distributional aspects of solar geoengineered futures cannot be reduced through provision of more science (on this point, see [211]), then the case for more research as key to furthering equity is more tenuous.

Delimiting Risk: Realizing Equity through Risk-Risk Comparison

> It is our hope that scientific and technical research over the next decade focuses more closely on well-articulated variants of the key policy-relevant question: could [solar geoengineering be designed and deployed in such a way that it could substantially and equitably reduce climate risks?
> — Keith & Irvine 2016 [130], p. 549

Early justifications for research on solar geoengineering tended to center on the need to be prepared for its use in the event of a potential climate emergency. Several studies have analyzed the prominence of this framing [158, 14, 169, 75, 30]. More recently, however, ‘climate risk management’ has become a prominent frame for evaluating the pros and cons of solar geoengineering research among technical experts and advocates of research, as well as by prominent science advisory bodies [224, 129, 130, 148]. A recent report of an event launching a research program on solar geoengineering at Harvard University in the US argues that the interest in solar geoengineering research is a result of “the underlying realities [Paul Crutzen] described: increasingly severe risks from projected climate change, continued uncertainty about the character and timing of these risks, and increased recognition that mitigation and adaptation may be inadequate to manage the risks” ([178], p. 5).

Rather than embedding ideas about solar geoengineering in notions of planetary-scale management in the face of a global climate emergency, the risk management frame draws attention to whether and how solar geoengineering can reduce climate risks (generally meaning various climate impacts) for particular people in particular places. A commonly used diagram in solar geoengineering meetings depicts future scenarios of climate risk reduction in which solar geoengineering is posited as a potential approach to shave peak temperatures and associated impacts, in a so-called portfolio response to climate risk reduction ([153], Figure 1, p. 40).

Thus, some advocates of solar geoengineering research argue that assessing the risks — or merits — of solar geoengineering needs to be a relative endeavor. Evaluating solar geoengineering risks and benefits without considering the broader context of climate risks is nonsensical, the argument goes, since the harms of climate change could shift the terrain of assessment in important ways: if a world without solar geoengineering means catastrophic impacts on ecosystems and humans, societies might be more willing to accept some potential negative side-effects of solar geoengineering. As two prominent advocates of research put it, "[...] when managing risk is the framework for evaluation, *ethical* considerations demand that [solar geoengineering] be taken seriously (in addition to mitigation and adaptation)" ([99], p. 89, emphasis added). Understood as such, this risk-risk framework is not too dissimilar from the earlier emergency framing, given that it may also restrict the scope of technological choice by fostering a state of climate exceptionalism in which (almost) anything goes.

Vanguard advocates of this comparative risk approach are now also framing the need for research explicitly in terms of equity, arguing that a "key policy-relevant question for scientific research is whether solar geoengineering might substantially and *equitably* reduce climate risks" ([130], p. 549, emphasis added) especially for those most vulnerable to climate change [129]. One publication making the case that concern for the global poor entails a moral obligation to pursue research suggests that the key questions about solar geoengineering from an equity perspective are whether solar geoengineering can reduce surface temperature at a rate faster than mitigation, in a way that will be comparatively cheaper than adaptation, and without raising significant distributional concerns [99].

More recently, David Keith has argued that because various climate effects (i.e., sea level rise, changes in weather patterns) could be limited by solar geoengineering, and "[b]ecause these changes would have the most powerful impact on the worlds most vulnerable people, who *lack the resources to move or adapt*, one can make a strong ethical case for research to explore the technology" ([129], p. 71, emphasis added). In focusing particular attention on anticipating the distribution of future risks of climate change itself, especially for the global poor, this comparative risk-risk framework implies that an assessment of the equity dimensions of solar geoengineering *depends upon* further research on the topic. According to this vision, more empirical research on the distributional implications of solar geoengineering is not only justified for the conduct of comparative risk-risk assessment, but morally required. Furthermore, in such an approach to 'equitable' risk reduction, those most historically responsible for climate change are recast as risk managers for the global poor, aiding and building capacities (through research into solar geoengineering options) of the vulnerable to deal with inequitable impacts of climate change.

In our view, the claim that solar geoengineering deployment would address equity concerns by potentially reducing physical climate risks for those most vulnerable to climate change more optimally than other strategies (mitigation and adaptation) is another example of the exercise of speculative ethics, even as it sidesteps the value decisions implicit in such largely speculative (comparative) risk assessment [266]. As scholars of science and technology studies have long noted, decisions about the kinds of evidence seen as authoritative and choice of appropriate methodologies in processes of risk assessment are often as much political as technical [110, 81, 58]. If so, framing risk assessment as an epistemic matter can reify an assumed division of labor, where science is the institution most capable of steering technological emergence, and issues of broader governance are pushed downstream, with implications for who is empowered (or not) in shaping the terms of debate [115] and for the kinds of questions deemed relevant to ask [210]. While many scientists are careful to acknowledge that political decisions about solar geoengineering are fundamentally a matter of value choices[7], discussions of risk assessment and risk management often remain bifurcated. In short, framing solar geoengineering and any attendant equity concerns as an epistemic issue of comparative risk analysis may (re)produce a perceived dichotomy between the production of scientific knowledge, on the one hand, and the resolution of broader political and normative debates, on the other. The viability of this separation has also been critiqued in public engagement exercises that suggest that the science and governance of solar geoengineering are often entangled (for a review, see [26], and that — especially if justifications for responsible research rest on managing risks on behalf of the global poor — institutionalizing broader inclusion upstream is desirable.

Early evidence from a public engagement exercise with environmental practitioners in the Global South [264] reveals, for example, that participants were persistently concerned that models were insufficiently credible to produce meaningful knowledge about the equity implications of solar geoengineering deployment, both because of a lack of trust in scientific endeavors in which they had little say, and a distrust in the credibility of models to say anything useful at time and spatial scales that matter to managing and reducing vulnerabilities.

Equity as a moral imperative to realize 1.5° C: the end justifies (solar geoengineering) means

> Historical obligations to the global South include mitigating harms not just in the long term, but in the near future as well; this duty cannot be fulfilled by emissions reductions alone
> — Horton & Keith 2016 [99], p. 89

The Paris Agreement, with its commitment to limit global average temperature increase to ‘well below’ 2° C above preindustrial levels, and to undertake efforts to limit it to 1.5°

[7] At a recent event aimed at US policymakers, a prominent advocate of solar geoengineering acknowledged that the major issues around solar geoengineering research are about politics and values (Forum on US Solar Geoengineering Research, Washington, DC, US, March 2017)

C, avoids any explicit discussion of solar geoengineering. Some scholars argue that the agreement includes the building blocks for an international approach to climate engineering governance [53] or that Paris "facilitates the eventual inclusion of [solar geoengineering] in the post-Paris system" ([98], p. 5). Despite the fact that climate negotiators were silent on solar geoengineering, some advocates of solar geoengineering research are now arguing that the Paris Agreements aspirational temperature goal may *require* solar geoengineering research [98], since "solar geoengineering is probably the only known, plausible way to stay below 1.5 degrees of warming — if it could be made to work, that is" ([177], p. 860).

This position bolsters ongoing arguments by advocates of research that, since societies will inevitably face some degree of inequitable climate risk even if emissions stopped tomorrow, solar geoengineering might be the only way to mitigate inequitable impacts arising from these risks. In this perspective, given inertial climate change, effectively and equitably addressing climate risk — especially for the global poor — requires taking solar geoengineering seriously, even more so in a post-Paris context. In light of such arguments, it is worth considering whether Paris aspirational goals may promote a new 'tyranny of urgency' ([244], p. 199). In this instance, the urgency is less related to the need for solar geoengineering as a 'Plan B' in the face of a potential future climate emergency, given failing multilateralism (a now criticized earlier framing used to justify calls for more geoengineering research), but rather linked to the success of multilateralism, and the (unexpectedly high) ambition signaled by the Paris Agreements aspirational temperature goals.

What becomes of equity, in light of this particular rendition of the tyranny of urgency? One emerging new framing is that, in the post-Paris context, historical responsibilities require consideration of solar geoengineering as an option, as per the quotation above. Given that small island states and developing nations were central in pushing for the aspirational 1.5° C goal, at least one publication sees this as an implicit demand from such actors for solar geoengineering research [98]. However, as Suarez and van Aalst point out recently "it should be noted that many of the actors proposing the 1.5° target in the Paris agreement (especially those representing the most vulnerable), did not aim to endorse a package that included [solar geoengineering], but rather just aimed for very aggressive mitigation pathways. If in the context of the Paris agreement the most vulnerable can now be implicitly invoked in arguments for geoengineering, then we must call for a much more explicit engagement of those groups and their priorities, as well as a clearer framing of the range of implications of the 1.5° target" ([249], p. 191-92).

The overarching question in the context of an equity discussion then becomes: who will bear the burden of striving for 1.5° C, what means of doing so become tenable, and on what grounds? Vanguard advocates of solar geoengineering research zero in on the question of the *feasibility* of meeting the temperature targets agreed to in Paris, as a — if not the — central concern among experts advocating for the inclusion of solar geoengineering as an option in an international climate policy toolkit. Yet this focus on technical feasibility sidelines, to some extent, concerns over equitable burden-sharing, particularly in light of the fact that the 1.5° C goal is aspirational. Legal scholar Dan Bodansky points out, for example, that the 1.5° C target "serves not only a regulatory function, but also expressive and advocacy functions," and "provides a potent rallying cry for activists and a basis to push states and other actors to take stronger action" ([19], p. 303; see also [100]). Yet, the key question remains for whom, and how, the 1.5° C will serve as rallying cry and, in particular, the political implications of its evocation as justification for research into solar geoengineering, as potentially one of the only realistic pathways to moving towards such aspirational goals.

2.4 Conclusion: Equity in vanguard visions advocating for solar geoengineering research

We have analyzed here how equity is being conceptualized by a group of experts advocating for more research into solar geoengineering. Our analysis reveals a number of interrelated ways in which the notion of equity acquires meaning within such vanguard visions. First, we show how equity is being equated with the need to assess the potential distributional outcomes of solar geoengineering deployment, including winners and losers. Related to this is an argument that reducing scientific uncertainties around these distributive outcomes is a crucial imperative, in order to harness the equity-related potential of such research. Second, we have shown that vanguards advocate for more solar engineering research in a comparative risk-risk frame, as a moral imperative owed to the vulnerable suffering from the inequitable impacts of broader climate risks. Third and finally, we analyzed how the 1.5° C aspirational temperature goal of the Paris Agreement has given further impetus to vanguard calls for solar geoengineering research on equity grounds, as a moral obligation to those most vulnerable to climate impacts.

It is worth considering what overarching take on equity, if any, these elements of a vanguard vision represent. Most broadly, they view equity as an empirical question, answerable by (more) scientific analysis. Major concerns about equity are treated as empirical matters, requiring scientific assessment of feasibility, risks, or possible 'win-win' distributive outcomes and optimizations. This also entails delimiting risk and uncertainties, as well as particular readings of aspirational temperature targets pushed for by 'vulnerable states,' as requiring research on solar geoengineering.

This arguably narrow, expert-driven, outcome-oriented, and risk-based understanding of equity raises various questions, not least of which relate to how model uncertainties are approached, and whether and how scientific research projecting the impacts of deployment will be persuasive to those on whose behalf vanguard experts claim to speak. This is especially the case if equity is understood as more than just a 'fair' distribution of outcomes, but also more procedurally, as being about representative and inclusive knowledge production and decision-making. As others have also noted, "[...] technoscientifically mediated activities" shape lives in ways that extend well beyond concerns of a distributive nature ([269], p. 140). Aligned with this, recent empirical social scientific research on public views of solar geoengineering highlights a broader set of concerns relating to equitable engagement. These include, *inter alia*, questions of moral responsibility [264], historical global injustices and inequalities, the ability to be included in, and benefit from, technological development, and concerns around lack of agency and self-determination in determining innovation pathways [36].

Even in the distributive context, however, environmental decision-making involves the co-existence of multiple and sometimes contradictory conceptions of fairness. Thus, some might be interested in *parity*, where parties are, to a great extent, treated equally; others in *proportionality*, where burdens and benefits are distributed in proportion to certain fairness criteria; and still others in *priority*, where burdens or benefits are allocated to one community based on selected criteria (Young 1993; Rayner 1999). Early vanguard visions on equity could be said to reflect concerns relating to proportionality and priority, in their focus on the distribution of outcomes associated with novel technologies, and associated implications for the most vulnerable.

Yet this includes a problematic construction of 'vulnerability' and a privileging of epistemic authority in (implicitly) determining fairness criteria. First, plural rationalities of fairness in the contested context of climate change demand that the views of affected ('vulnerable') parties regarding the principles and criteria for fair processes and outcomes be explored upstream in the innovation process, and not to be a matter for a narrow set of privileged experts to delineate. Second, and as Sheila Jasanoff highlights, while a focus on vulnerability is certainly legitimate and desired, it is problematic if the vulnerable, particularly in expert renditions, get cast as "passive agent(s) in the path of potentially-disastrous events". Thus, if equity is to be equated with prioritizing delivery of benefits to the vulnerable, those characterized as such need to "regain their status as active subjects, rather than remain undifferentiated objects in yet another expert discourse" ([113], p. 241). In short, as boundaries are drawn between what is and is not an equity concern, so, too, are boundaries drawn around who is authorized to speak with regard to the advisability and contours of solar geoengineering research (for a meta-analysis of whether and how voices from the global South are being heard in these debates, see also [17]). Our analysis in this paper thus highlights the need to pay attention to who, and what, gets excluded from expert discourses of equity in the context of solar geoengineering research.

Finally, we also see as a point for further empirical analysis whether the vanguard visions of equity explored here reflect a broader shift in operationalizing equity now potentially discernible within multilateral climate politics, particularly in the post-Paris self-differentiation era. This is a shift away from equity as centered on 'fair' burdens for ambitious mitigation, based on differential *historical responsibilities*, to equity as delivering benefits to, and building capacities of, those most vulnerable to climate change. Implicit in the vanguard call for comparative risk-risk assessment, for example, is that ambitious mitigation is imperative (this is repeatedly emphasized) but *may not be forthcoming*, thus necessitating other fast-acting alternatives. To the extent that historical responsibility for ambitious mitigation is thus implicated in this expert view of equity at all, it takes on a new avatar, with those bearing the greatest responsibility for climate change now deemed unlikely to be ambitious mitigators but are recast instead as viable 'risk managers' for the global poor and vulnerable (see also [159], p. 152 on the 'framing out' of responsibility in climate engineering justice debates).

In concluding, we return to the notion we began our analysis with: that vanguard visions of equity and solar geoengineering are not yet widely shared sociotechnical imaginaries. If so, the immediate question becomes whether and whose (speculative) visions will be taken up, ignored or reinterpreted, including within established institutional contexts such as the Intergovernmental Panel on Climate Change (IPCC) and its forthcoming assessments, as well as the UNFCCC. The vanguard visions analyzed here are still emerging and tentative and are thus by no means guaranteed to crystallize into collectively held sociotechnical imaginaries, with the potential to shape future technological and policy trajectories. Nevertheless, questions remain about their performative power and political implications going forward, which merit continued social science and interdisciplinary attention.

Chapter 3

The Politics of Climate Models for Solar Geoengineering Research

Jane A. Flegal

> @JackStilgoe: Let me say it again. Solar geoengineering is not a thing. It. Does. Not. Exist. It does not *reduce* anything except in speculative models.
> @GernotWagner: Would you say the same about climate models projecting temperatures based on future greenhouse-gas emissions?

> [Vaclav Smil] understood the physics of the greenhouse effect and the potential for a carbon dioxide buildup to warm Earth, but models seemed too dependent on assumptions about things like clouds. Ever since, he's held models of all kinds in contempt. "I have too much respect for reality," he says.
> [**Voosen:2018**]

3.1 Introduction

Understanding how climate models of distant solar geoengineered futures gain and exercise authority in the present requires going beyond analyzing them as scientific tools, but also as 'powerful social objects' (Hulme in [90], p. 68). In this chapter, I analyze the mutual construction [228] of solar geoengineering modeling and policy framing. Climate models have been understood as key nodes in the interface of science and policy in various domains, mediating between the social worlds of science and politics, and fundamentally shaping societies' understanding of, and responses to, climate change. Less has been said about the development of this relationship over time, which can help explain how it is that the intersection of modeling and politics takes on the form that it does. (For a historical account of this process in climate change more broadly, see Mahony & Hulme 2016 [156]).

This chapter analyzes two issues around uncertainty and representation in the use of climate models for knowledge about solar geoengineering, which raise questions at the intersection of modeling and politics. The first is that models are being used to represent technologies which don't yet exist, black-boxing the engineering in geoengineering ideas. As one interviewee stated, "In the model, you can just *make geoengineering work*. You can just assume that the oceans have a higher albedo because of ocean bubbles, whether it's possible or not." This results in discussion of the representation of a technology in models, rather than managing the development of the technology itself, eliding important near-term questions including the complexities of technology development and the structure of responsible research programs. Secondly, there is significant debate about whether these models can usefully predict outcomes; uncertainties that may be less relevant to models of and for climate science may become 'matters of concern' when it comes to the effects of geoengineering.[146]

There is remarkably little engineering in geoengineering [244], and yet plenty of discussion of its impacts. The focus on *models* as proxies for actual *deployment* of these imagined technologies has the effect of making it seem as though societies 'know' more about whether and how to develop these techniques than we do. This relates to A.N. Whitehead's fallacy of misplaced concreteness: mistaking scientific maps of reality for reality itself [259]. This displacement may be resulting in dysfunctional debates (dysfunctional in that the object of management is not, in fact, solar geoengineering, but its representation in models) about the effects of a technology which does not yet exist, including in debates about responsible innovation[197]. As a research field, geoengineering is only beginning to become institutionalized, but evidence presented in this chapter suggests that models are often taken to be representative of reality, both in academic discourse and in broader representations of the technologies. As others have noted, this may contribute both to the naturalization of geoengineering and its stabilization [244]. Perhaps paradoxically, I argue that the black-boxing of the engineering in geoengineering may have the effect *limiting* robust research programs, by focusing debate on speculation over geoengineered futures, rather than whether and how these techniques might be developed, and according to what criteria and standards of evidence. Whether and how this affects the intersection of modeling, technology development, and politics over time remains to be seen, but tracing these dynamics may prove useful for future analyses of the field. This relates, also, to concerns about speculative ethics (see *Evoking equity as a rationale for solar geoengineering research? Scrutinizing emerging expert visions of equity*) and the sociology of expectations, wherein claims about an emerging technology are naturalized, masking its complexities and potentially limiting social agency in technology choice [21, 227, 244].

The second issue relates to the shifting context of use of models, from models to guide climate mitigation and adaptation, to models as a guide to geoengineering deployment. This shifting context may raise new challenges for for uncertainty and its management in climate science. As one interviewee stated, "To engage in geoengineering research, you flip the use of climate models. It is an effort to control climate to achieve certain objectives.

It's an *engineering* problem" (emphasis added). If climate models are not predictive truth machines, and accepting this does not undermine their credibility for climate policy, can the same be said of the use of models for knowledge about geoengineering? Advocates of a solar geoengineering research program often promise that ignorance around the impacts of these techniques will be reduced over time; however, one interviewee described this rationale as a kind of 'kicking the can,' avoiding thorny questions about the promises of prediction in the service of decision-making. This view appeals to a particular set of expectations around the role of science in decision-making, including one which sees the reduction of ignorance as necessary and sufficient to inform rational decision-making on environmental issues[211], instead of asking when we might know enough to act in the face of irreducible uncertainty, and how.

The use of 'uncomfortable knowledge' as a theoretical lens to examine these dynamics brings into focus the boundaries and limitations of knowledge (in particular climate models) in assessing *imaginary* sociotechnical systems [197]. I analyze debates about the futures of solar geoengineering as conflicts stemming from strategies of displacement (wherein computer models, designed to inform management of a real-world phenomenon, become the object of management themselves) implemented by organizations advocating for and against solar geoengineering research [197]. The uncomfortable knowledge in this case is both the non-existence of solar geoengineering (and issues of evidentiary thresholds), and the limits of climate models as predictive tools to guide rational action on geoengineering.

This chapter points to the importance of designing institutions capable of effectively reconciling the supply and demand of science [216]. In the absence of these arrangements, conflicts around the 'assessment' of technologies which don't yet exist, based on models known to be insufficiently predictive, has resulted in confusion about the state of the technologies and the potential for a prudent path forward. Institutional arrangements (perhaps 'clumsy' ones [197]) may help to ensure that knowledge that is crucial for addressing complex problems, but which is excluded from accepted versions of the world, can be included in policy debates. Multiple interviewees engaged in geoengineering modeling noted a lack of epistemic diversity in the field, including, for example, the underrepresentation of research on climate impacts, oceans, and engineering. Moreover, data collected during an engagement with international environmental practitioners, and in a survey of researchers, revealed skepticism about predictive models and the importance of geographically-inclusive knowledge-production in geoengineering research (see Chapter 4, as well as Winickoff et al. 2015)[264]. A responsibly-structured research program aimed at answering societally-relevant research questions in a pluralistic manner might help to identify and remedy these gaps. This is particularly true if any such program acknowledges the limits of scientific knowledge as a guide to decision-making, forcing difficult questions about appropriate standards for evidence to guide choices on solar geoengineering. Alternatively, one might argue that the existing settlement, at least in the US, between governments, NGOs, and scientists, in which governments seem willing to fund indoor modeling studies but accept an informal moratorium on everything else, may itself be a clumsy solution, the stability of which depends on its non-articulation.

My analysis is based on a review of over 30 peer-reviewed journal articles on solar geoengineering, ten interviews with climate modelers who work on solar geoengineering, participant observation over the course of five years, and analysis of media reports, public discussions, and a public engagement exercise. This evidence was coded where appropriate, and analyzed.

3.2 Solar geoengineering and climate models

Geoengineering, or ideas for "deliberate, large-scale intervention in the Earths climate system, in order to moderate global warming," ([23], p. ix) is receiving some more attention in mainstream climate discussions. The mounting risks of climate change impacts, compounded by the slow pace of international efforts at mitigation, led to the release of a seminal report on climate engineering by the UK Royal Society in 2009. Since then, a number of policy and scientific bodies have called for research on the topic [224, 38, 173]. More recently, some analysts have argued that the Paris climate agreement "facilitates the eventual inclusion of" solar geoengineering. ([98], p. 5) This set of proposals has received significant attention, at least within certain expert circles, since Nobel prize winner Paul Crutzen's 2006 article calling for research into techniques to add sunlight reflecting aerosols into the stratosphere [54]. These ideas — variously termed 'solar geoengineering,' 'solar radiation management,' and 'albedo modification' — would aim to enhance the reflectivity of the planet to cool the global temperature. Solar geoengineering can be defined as the "modification of the fraction of short-wavelength solar radiation reflected from Earth back into space," and differs from carbon dioxide removal techniques, which are often included under the umbrella term 'climate engineering' or 'geoengineering' ([224], p. vii). Early evidence (climate models and some observational studies) suggests solar geoengineering approaches could be effective at cooling the planet, "but at a currently unknown environmental price" (*ibid*, viii).

General circulation models (GCMs), which seek to capture atmospheric and oceanic dynamics and their interaction with physical processes (e.g., clouds, sea-ice, and land-surface processes), are the primary way societies are coming to understand solar geoengineering. Modelers who seek to represent solar geoengineering methods often do so be reducing the solar constant or adding a layer of aerosols to the stratosphere in models. For example, in a model intercomparison project aimed at understanding the effects of solar geoengineering, standardized scenarios either modified solar constant, or assumed a layer of sulphur dioxide into the stratosphere. GCMs have long been recognized by scientists and policy makers as the 'best tools' for simulating current and future climate. ([228], p. 223) However, while the reliability of GCMs when simulating global climate change is considered to be reasonably good, simulations of local or regional change are generally considered less robust

([253], p. 743). Key processes, which lie at the heart of many proposed solar geoengineering approaches and their potential impacts, are less well understood in GCMs. For example, the most recent IPCC assessment report acknowledges that “models tend to perform less well for precipitation than surface temperature” (*ibid*). Current limits on scientific understanding and computational capabilities lead to well-known deficiencies in the simulation of impact-relevant elements of the climate system (e.g., clouds, precipitation, major weather patterns, and the El Nino-Southern Oscillation).

Uncertainty and issues with prediction are at the core of much of the debate about the usefulness of climate models for solar geoengineering policy. This is nothing new for analysts of climate policy; climate modeling has long been at the center of debates about uncertainty and its implications for mitigation [194]. And while models have generally been more persuasive for purposes of mitigation, in the realm of adaptation, this has not been the case in consideration of models as evidence for adaptation policy [258, 56, 214, 176].

Analysts frequently debate the status of climate models as predictive, particularly in policy contexts. Some argue that their primary use is heuristic [176] or even as metaphor [189], while others argue that models ought to be viewed as truth machines for predicting future climates. But the consequences of relying on models within a ‘predict-then-act paradigm’ have been well-articulated by scholars who argue that fundamental uncertainties in complex systems mean that predictions often fuel, rather than quell, political debate [215, 104]. For solar geoengineering, the demands placed on predictive modeling appear even greater and more controversial than for mitigation and adaptation, at least among those contesting the validity of these results. While GCMs are often viewed as credible tools to advance fundamental scientific understanding of the climate system, this tends to be more highly contested where GCMs are deployed to make claims about the predicted impacts of climatic change on local scales.

Model confirmation also poses challenges for prediction. Typically, climate models are evaluated by testing how well they simulate past climates. Even then, there are issues. With short-term weather forecasting, forecasts can be tested against immediate empirical outcomes. With GCMs, confirmation of model outcomes against empirical reality is less readily available; this implies that indirect forms of confirmation are required, but independent testing of assumptions in the model are difficult, because of challenges with isolating the assumptions to be tested from the model itself. As a result, models are often evaluated by testing how well they simulate past climates, and/or by model intercomparison. The challenges may be greater with solar geoengineering, because of the absence of observations of past solar geoengineering scenarios. Acknowledging this limitation, some scientists argue that the models are most useful for investigating specific climate processes and feedbacks, and not for predicting outcomes of climatic processes as a result of deployment. However, this position conflicts with what many policy makers expect of climate models (i.e., some prediction of a possible future scenario as a result of climate engineering deployment), and even some conclusions of solar geoengineering modeling literature. As one modeler puts it, "[...] the results from GeoMIP must be interpreted with caution, as there are no observations of geoengineering with which the results can be compared. That is to say, although the results from GeoMIP are concordant with the current understanding of the physical behavior of the climate system, consistency among models does not necessarily imply that the models show the correct response. [...] The generally good model agreement in GeoMIP simulations has not been compared to model agreement for simulations of anthropogenic climate change and the associated ranges of uncertainties in climate responses to forcings" ([140], p. 13,106).

3.3 Do climate models have politics?

Co-production and climate models for policy

Scholarship in STS has, for at least twenty years, examined the role of climate models for mitigation and adaptation policy. This work has analyzed the role of models — especially GCMs — in producing stable knowledge claims and underwriting particular scales and forms of environmental governance [61, 37]. This co-productionist [242] work traces the role of GCMs in the transition from a local to a global view of climate [163], and examines how climate models gain and exercise authority across contexts [103]. Research has demonstrated processes of co-production in global climate science and politics, by which constructions of scientific and social facts are interdependent; scientific claims about the risks of global climate change (often through modeling) underpin claims of authority at the international level, just as international legitimacy and credibility depend upon stable scientific claims about global environmental risks [37, 163].

One key area of analytic concern in STS literature has been to examine the ways in which science (including climate modeling) and politics or policy are mutually constitutive. Jasanoff & Wynne demonstrate the interdependence of science and politics required to build stable and credible knowledge claims about global climate change [117]. Other research has documented a process of mutual accommodation, whereby scientists perceptions of the policy process play a role in shaping their scientific practices [228].

This work engages directly with the notion of 'regulatory science,' [114] (see also [209] on 'mandated science') which denotes a social space wherein the construction of stable and credible factual claims is especially challenging due to: political pressure which tends to deconstruct those claims because of concerns about particular regulatory actions; over-ambitiousness of science, particularly regarding prediction; its necessarily interdisciplinary nature; short-time scales; and/or high decision stakes [228].

Research on science for policy (regulatory science) and environmental controversies suggests that regulatory knowledge which is created to serve policy is sociologically distinct from other forms of knowledge, because it is produced in different institutional settings, under different criteria of validity. This research often entails a wide range of value judgments and 'boundary work,' wherein actors work to construct distinctions between science and non-science [114, 79, 133]. Moreover, research on scientific controversies has shown that regulatory science is highly contingent and contestable, and that science can sometimes make environmental controversies worse [44, 211, 41]. The construction of facts in the realm of regulatory science can be difficult as a consequence of political pressure leading to the deconstruction of the evidence underpinning regulatory decisions, a tendency toward predictive science even in the face of profound uncertainty, demand for fast information, and high political stakes [228, 114, 209, 40, 74]. Work on quantification and risk has found that in "a suspicious democratic order," quantitative analysis and appeals to objectivity can work to discourage public activism. ([186], p. 47, cited in [114]), scholars have turned to the constitution of regulatory science in the global domain, calling attention to the ways in which epistemic authority underwrites political jurisdiction in complex regulatory settings [162, 264].

Other work has shown how expertise most readily achieves legitimacy when it is implemented in ways that are transparent about assumptions, negotiations, and contingencies, and conforms to norms of openness and democratic deliberation [113]. Sheila Jasanoff has argued that epistemic claims associated with climate are "most trusted when they engage with practices that confer normative authority — not only scientific practices such as peer review (Mertons 'organized skepticism'), but also the cultural practices of democratic politics and the law" ([110], p. 236). Silvio Funtowicz and Jerome Ravetz, in their analysis of post-normal science (i.e., science performed in situations of high uncertainty and political stakes), have called for expanding the range of non-experts participating in knowledge production (extended peer review). In contemporary societies, they argue, science must cope with the proliferation of uncertainties associated with urgent environmental and technological decisions. These authors explicitly discuss dilemmas associated with computer models for environmental problems, pointing out that the management of uncertainty and quality assurance are critical in order to ensure that models produce policy-relevant knowledge, arguing that new methods ought to be adopted for "making our ignorance usable." ([74], p. 140).

Generally speaking, climate modeling has been analyzed as 'pure science,' or as directly connected to 'applied policy' problems. Noting the failure of these approaches to capture the empirical dynamics around climate modeling, Simon Shackley and Brian Wynne argue for a framework focused on the 'mutual construction' of a science-policy domain around climate modeling and policy, wherein science highlights a problem *and* embraces the means by which the problem can be tackled [228]. This is a step closer to what we see in solar geoengineering, and relates to the work Silke Beck and Martin Mahony have done on the role of modeled futures as a kind of 'regulatory science' in the context of the Intergovernmnetal Panel on Climate Change [7]).

Still, in the case of solar geoengineering, 'mutual construction' does not quite capture the ways in which modeling is relied upon as an evidentiary basis for an imagined *technology*, nor the way models are interpreted as *proxies* for the technology itself (perhaps even 'displacing' technology development) [197]. In the solar geoenginering domain, we see not just mutual construction, but the development of the supply-side of a future science-policy domain in which questions about the effectiveness and impacts of a technology are imagined to be answerable by a particular form of science (in this case, climate models).

The politics of models for solar geoengineering governance

Given the central role climate models have come to play in climate science and policy since at least the 1970s (underpinning knowledge claims and risk assessments of major scientific and regulatory bodies), (Rayner in [215], p. 272; [110]) it is not surprising that climate modeling has also become central in discussions about how societies might come to know and govern solar geoengineering technologies. In fact, in the popular genesis story of serious scientific interest in solar geoengineering, models play a central role. Current advocates of research claim to have been converted from skeptics after early modeling studies suggested that these techniques might be more effective and safer than initially assumed [80, 261, 244, 16]. Despite their central role, climate models have often been assumed to be politically unproblematic in the discussion of governance regimes for solar geoengineering research (excepting those for whom the idea of geoengineering is so problematic as to constitute a kind of 'forbidden knowledge' [230]). (For a discussion of ignorance as a rhetorical device in geoengineering debates, including on conflicts over 'forbidden knowledge' and 'undone science,'see Rayner 2014[191]).

In a notable 2010 paper, two advocates of geoengineering research, Ken Caldeira and David Keith, published an article in which they laid out a 'phased approach' to research on solar geoengineering [32]. In this model, 'Phase 1' research would consist of computer model and laboratory research, described as 'no-brainer' research. Discussion of this phase omits any considerations related to governance, which only come into play as research moves outdoors in Phases 2 and 3. This linear approach to governance and risk management associated with geoengineering research is common in published literature. For example, a more recent piece by Ted Parson and David Keith in Science put forth a framework for the regulation of solar geoengineering research, which suggested that governance considerations be contingent upon physically-defined thresholds of risk [179]. Reflecting this narrow risk framing, the article does not mention climate models, focusing instead on "small field research to operational deployment," and seems to conceive of governance mostly in its restrictive forms (i.e., scrutiny and control). The 2011 US Government Accountability Office report [173] similarly adopts a linear model of research [157]. In 2015, the US National Academy of Sciences released a report on solar geoengineering (preferring the term 'albedo modification'). In its chapter on "Governance of Research and Other Sociopolitical Considerations," the vast majority of the text is devoted to consideration of thresholds and mechanisms for small-scale outdoor research, referring at various points to indoor modeling studies as ethically unproblematic, so long as they "provides information for policy makers and the public to make more informed choices." ([224], p. 168, citing [205]).

Certainly the prospect of outdoor experimentation requires close consideration, including of regulatory frameworks. But conceiving of research in a linear model runs counter to findings from STS and innovation studies, which demonstrate that such an approach is overly deterministic, can prohibit the consideration of broader societal issues 'upstream,' and can restrict agency and technological choice [157, 203, 242, 254]. In the case of solar geoengineering research, one result has been that models are not sufficiently understood as sites of politics, and that users and potential contributors to their production are not well-integrated at these stages. Data collected from the Berkeley Workshop (a public deliberation with mid-career environmentalists in the Global South) suggests that models themselves are likely to be highly controversial, both because of concerns about their predictive abilities, and because of the absence of scientific involvement from the developing world in collecting data, developing scenarios, and contributing to research questions [264].

Despite the focus on models in debates about the merits of geoengineering, academic and policy discussions about the governance needs and societal implications of solar geoengineering research tend to focus on research as it leaves (or may leave) the laboratory. Many social scientists are quick to acknowledge that, despite their negligible physical risks, small-scale outdoor experiments warrant governance beyond existing regimes, "as they raise broader concerns that go beyond the immediate impacts of individual experiments" [218]. At the same time, policy reports and proposals for research governance have sought to define thresholds for triggering additional oversight based on physical dimensions and risks of harm [179, 100]. The assumption seems to be that indoor studies, while also producing knowledge about intentional manipulation of the climate, are not matters of concern in the same way as outdoor experiments (of any scale), and therefore should not be the object of additional scrutiny or governance ([244], p. 149). The implications of this boundary drawing are that, while anything outside of the laboratory cannot be detached from broader societal concerns, research inside of the laboratory is more easily contained from political life.

Policy-relevant research often entails a wide range of value judgments and 'boundary work,' wherein actors work to construct distinctions between science and non-science [114, 79, 133]. We can see this boundary work by a range of organizations around what is and is not a matter of public concern in the domain of solar geoengineering. As I've argued here, there is no straightforward reason why climate models of solar geoengineering should not — or will not — be subject to broader political scrutiny, or have potentially meaningful political effects, despite their low physical risks. In fact, the role of models for research and policy, including their epistemic and social credibility and what they can usefully represent, has already been the subject of some debate.

Models and the futures of solar geoengineering

The truth remains that climate models have come to play a central role in the politics of getting solar geoengineering on the public agenda; a move that would constitute a kind of political power [219]. For instance, climate model results are often framed to suggest that there is either a strong case, even a moral obligation, to pursue research, or abandon it altogether [99, 102]. It therefore seems critical to attend to the role and politics of models as an evidentiary basis for pursuing (or not) solar geoengineering research, even at this early stage. This does not mean that modeling studies should be subject to stringent regulatory requirements, but rather that, if we care about responsible innovation, we ought to explore knowledge production (and its embedded assumptions) in these early acts of world-making. As Jack Stilgoe notes, "given the power of such experiments to shape the promises and expectations of geoengineering, we might ask whether research inside the lab, involving computer models should self-evidently be free from public oversight or if there is a legitimate role for democratisation here too" [245].

A small body of literature, building on research in sociology and STS [227, 60, 43, 21]), has examined the politics and sociology of expectations, including how appeals to the future shape near-term geoengineering-related activities (for a brief review, see [150]). Some of this work has focused on the role of climate modeling in producing visions of solar geoengineering [261, 93], and credibility contests [62] around global climate models for geoengineering purposes [244, 264]. Flegal and Gupta analyze how particular visions of equity are embedded in the discourse and practices of advocates of solar geoengineering research (or 'sociotechnical vanguards' [95], which potentially narrow the set of concerns and actors deemed relevant and/or authoritative [71]). Beck & Mahony analyze the politics of anticipation at the Intergovernmental Panel on Climate Change (IPCC), arguing that the development of pathways for achieving temperature targets are more than technical artifacts, and in fact may work to hasten particular futures into being — futures with wide-ranging political and societal implications, as well as scientific and technical ones [7]. Steve Rayner, in his anthropological account of the 2° C goal agreed to at the Paris climate conference, argues that the inclusion of an imaginary technology (in this case, negative emissions technologies) to meet politically-negotiated expressive goals, without instrumental commitment to achieving them, constitutes 'magical thinking' [198].

Jack Stilgoe has called into question the stabilization of geoengineering as an object of governance, arguing that it "has been naturalized by its researchers, treated as a thing in the world to be understood rather than a highly controversial, highly speculative set of technological fix proposals" [244]. He advocates, instead, for engaging with the collective experimental nature of geoengineering research and its governance — including, perhaps, by adopting inter- and multi-disciplinary research approaches in the realm of field experiments ([244], citing [119]). In his book Experiment Earth, Stilgoe points to the dynamics of hype and promising that often accompany emerging technologies, while noting that geoengineering would seem distinct from other domains, like nuclear power and genetics, in that "Few people interested in geoengineering imagine that it will be an unalloyed good" ([244], p. 35). Nevertheless, Stilgoe argues that narrow promising on the basis of predictions of the future should be supplanted with a more inclusive practice of anticipation, which aims to "think through various possibilities" and responsibilities related to innovation (*ibid*). Steve Rayner has warned of the 'novelty trap,' for emerging technologies broadly, which can lure researchers into overselling the newness of their innovations to attract research funds, and downplay those same dimensions as mundane when they attract the eye of regulators [195].

However, much less has been said about the role of climate models in and for geoengineering policymaking. In part, this can be explained by the early stage of scientific research and policy development in this realm. Unlike canonical studies of regulatory science in STS, policymakers are not yet demanding that the scientific community produce evidence to support public regulatory decisions for solar geoengineering. This chapter attends to this gap, arguing that it is important to attend to the emergence of the mutually-constructed science-policy domain in the case of solar geoengineering, despite its status as imaginary. This is especially true if we seek to design institutions capable of more effectively connecting knowledge production with decision-making in the face of wicked problems.

3.4 Modeling a technology and the politics of displacement

Climate models are the primary tool by which contemporary societies are beginning to understand solar geoengineering and its implications. In the absence of controlled large-scale experimentation, model simulations are considered to be the current best evidence to inform policymakers about the likely effects of any future solar geoengineering deployment, despite well-known uncertainties (which I return to below) [106]. However, we should remember that geoengineering is an imagined *technology*. In light of this, it is notable that there is surprisingly little engineering in geoengineering, despite lengthy debates about its potential effects. My interviews with researchers reveals frustration with resources flowing to (certain kinds of) modeling work, while other kinds of research (small-scale outdoor experimentation, various engineering studies, and other forms of non-modeling inquiry) remain under-resourced.

Speculation about the ease and cost of technology development to achieve the goals of solar geoengineering may help explain this situation. David Keith, one of the world's leading researchers on solar geoengineering, opens his book with an assertion about the feasibility and cost of these techniques: "It is possible to cool the planet by injecting reflective particles of sulfuric acid into the upper atmosphere... it is cheap and technically easy" ([127], p. ix). A recent op-ed in the Wall Street Journal by an advocate of research made similar claims: "But one thing has become abundantly clear: The costs of implementation would be relatively cheap — perhaps too cheap." The calculations underlying this analysis have been the subject of some debate. Discussions with engineers suggest that these statements may vastly underestimate the challenges posed by developing sociotechnical systems, especially ones which deliver the optimized aims sketched out by proponents of these techniques. It is also true that most governments seem wary of funding technology development, but are content to fund indoor modeling studies. In any case, the result has been that discussion of solar geoengineering tends to center on climate models and the knowledge claims they generate about a yet-to-be-developed technology.

Modelers who seek to represent solar geonegineering methods often do so be reducing the solar constant or adding a layer of aerosols to the stratosphere in models. The realism of these techniques is far from straightforward. As one interviewee put it, "Of course turning the sun down is not the same thing as adding a layer of stratospheric aerosols." And, of course, adding a layer of stratospheric aerosols in a *model* is not the same as actually achieving this result in *reality*. The same interviewee later noted: "In the model, you can just *make geoengineering work*. You can just assume that the oceans have a higher albedo because of ocean bubbles, whether it's possible or not." The point, here, is that the focus on modeled effects masks the complexities inherent in developing the sociotechnical systems capable of actually producing those effects, even if one accepted the outcomes of models as sufficiently predictive.

There is a routine — and potentially problematic — slippage in how some experts and media outlets represent solar geoengineering (and aerosol injection, in particular), from what necessarily exploratory models of open systems suggest about these ideas [176], and what solar geoengineering, as a sociotechnical system, will or will not deliver in the real world. For example, the twitter exchange at the beginning of this chapter illustrates concern that model-based studies of solar geoengineering imply too much certainty and stabilization about a 'technology' which remains imaginary on the basis of inherently speculative and uncertain exploratory exercises.

This may reflect a desire by some geoengineering researchers to "imbue the imprimatur of consolidative knowledge upon what are inherently exploratory exercises" (Pielke Jr. in [34], p. 114), particularly at the early, agenda-setting phase of policy development, when scientists (or sociotechnical vanguards) are generally less constrained by political considerations [133, 97]. Because solar geoengineering research advocates are struggling to get public funding and/or mainstream the topic in climate policy agendas, one might expect dynamics of hype that are seen across emerging technologies. [43] Additionally, the slippage might be the result of a misplaced belief in the power of science to offer technically and politically determinative knowledge for guiding rational action. Moreover, the supply of science on solar geoengineering has outpaced demand in ways that mean Also a lack of discipline of fundamental science since there is so little policy or technology development in this space. Focusing on climate models as the object of management, and not on the non-existence of the technology itself, may make the notion of solar geonegineering research seem at once relatively benign, manageable via normal science, and not requiring a large-scale, strategic technology development program (knowledge which may be uncomfortable to the organizations advocating for research programs).

An argument can be made that this is simply an availability problem: that the absence of experimentation means that climate models are all we have. The point, here, is that the real object of governance (the potential future of solar geoengineering techniques) is lost in the discussion in debates over the governance of its representation (geoengineering in models). This slippage has become sufficiently naturalized such that discussion about the merits of research into these techniques are rather unhelpfully focused on the regional effects of a technology that is yet to be developed. As Jack Stilgoe has argued, "We shouldnt be scared of geoengineering, at least not yet. It is neither as exciting nor as terrifying as we have been led to believe, for the simple reason that it doesnt exist" ([244] p. 203). The real danger is not the modeled effects of geoengineering, but in the ceding of responsibility for steering technologies-in-the-making toward desirable ends.

How can we account for this displacement? The idea of uncomfortable knowledge, grounded in the anthropological studies of Evans-Pritchard [64], Mary Douglas [59], and Steve Rayner [196], proves useful here. The accounts of institutionalized forgetting or unknowing contained in this body of literature are rooted in an understanding that sense-making is only ever possible through practices of selective inclusion and exclusion. These practices are therefore in no way inherently dysfunctional. As Ravetz has argued, knowledge is only possible through the 'social construction of ignorance' [190].

Much has been made of Donald Rumsfeld's 2002 speech, in which he draws attention to what we know we know, what we know we don't know, and what we don't know we don't know [207]. But as Steve Rayner points out, "Rumsfeld altogether omitted what is possibly the most intriguing combination: what we don't know we know" ([197], p. 108). In a 2012 paper, Rayner focuses on a particular form of these unknown knowns: "those which societies or institutions actively exclude because they threaten to undermine key organizational arrangements or the ability of institutions to pursue their goals" ([197], p. 108). In this way, uncomfortable knowledge is often a necessary and even desirable social achievement. "To make sense of the complexity of the world so that they can act, individuals and institutions need to develop simplified, self-consistent versions of that world. The process of doing so means that much of what is known about the world needs to be excluded from those versions, and in particular that knowledge which is in tension or outright contradiction with those versions must be expunged. This is 'uncomfortable knowledge"([197], p. 107).

Rayner lays out four strategies that are implemented (not always intentionally) to manage uncomfortable knowledge: denial, dismissal, diversion (or decoy), and displacement ([197], p. 113). Denial involves the refusal to acknowledge the existence of information. Dismissal acknowledges information, and can include engaging it as irrelevant. Diversion is the use of an activity that distracts attention from an uncomfortable issue. “Displacement occurs when an organization engages with an issue, but substitutes management of a representation of a problem (such as a computer model) for management of the represented object or activity” (p. 113).

Rayner uses the Chesapeake Bay Program (CBP) to illustrate the strategy of displacement to manage uncomfortable knowledge. In this case, models of the Bay were used to simulate the effects of policy interventions, and upon this basis, the CBP claimed that it improved the water quality of main stem of the Bay. In fact, Rayner argues that field samples and analysis from the actual bay revealed that there was no discernible trend in the water quality. “Real water quality monitoring data that seemed to contradict the record of improvement constituted uncomfortable knowledge which was displaced by the more gratifying results from the modelling” [197] (p. 122).

The study of emerging technologies generally, and solar geoengineering in particular, can benefit from the application of this theoretical lens to early stages of knowledge production. In the case of sociotechnical systems which don’t yet exist, one might argue that the primacy of models is unavoidable, and not ‘displacement’ so much as it is the only way to generate knowledge on the topic. But early acts of selective inclusion and exclusion, and institutional design, can exert effects on the intersection of science, technology, and policy over time. Understanding how even these very early assessments of imaginaries selectively exclude other forms of knowledge production may prove useful for developing responsible governance architectures for research on solar geoengineering over time.

Uncomfortable knowledge — and the strategies implemented to achieve it, including displacement — is only dysfunctional when it stands in the way of addressing important policy problems (particularly those problems which are characterized by high uncertainty and decision stakes) [74, 197]. Geoengineering appears to fulfill both of the criteria for such a wicked problem. An argument can be made that, to the extent that the current research impasse is impairing the ability of a range of institutions to understand the complexities and possibilities associated with geoengineering techniques, these dynamics of displacemnet are, in fact, standing in the way of addressing important and wicked policy problems.

3.5 Winners and losers: modeling the regional effects of deployment

> The simulation models upon which aerosol injection technology would rely are like calculative cartoons when it comes to making long-term predictions.
> — Mike Hulme in [102], p. 112

The legitimacy of pursuing solar geoengineering research has come to rest, in part, on the epistemological status of models and their capacity to predict the potential effects of solar geoengineering deployment. Moreover, debates about appropriate governance architectures for solar geoengineering deployment, as well as ethical inquiries into the topic, are often based on the outputs of climate modeling studies. Nowhere is this more obvious than in debates about regional winners and losers in a future geoengineered world.

Research on the potential effects of solar geoengineering have proliferated in recent years, and have been the focus of political debate. Dozens of climate model studies have been published, including many from a model intercomparison project which seeks to evaluate standard solar geoengineering experiments, and engages over 15 climate modeling groups [130]. Some of these models aim to mimic solar geoengineering by reducing the model's 'solar constant.' However, as one interview put it, "Of course turning the sun down is not the same thing as adding a layer of stratospheric aerosols." Nevertheless, some modelers argue that even the most idealized scenarios are useful for generating knowledge about these imagined technologies. The arguments in support of this claim are that the models can help bound the set of concerns, and/or can help to 'build intuitions' using 'idealized cases,' which are useful for getting a sense for the response, as one interviewee put it. More sophisticated models simulate solar geoengineering by, for example, adding sulphur dioxide to the stratosphere. Several interviewees noted that stratospheric dynamics are, in general, not very well understood or represented in models. Nevertheless, generally speaking, modeling studies suggest that some solar geoengineering methods (as in reduction in solar constant, and/or addition of a startospheric aerosol layer) could reduce global average temperature within a few years, but that compensation of regional climatic changes would potentially vary due to differences in radiative forcing caused by greenhouse gases, on the one hand, and solar radiation, on the other [224, 140, 170].

One way that climate models are called upon to do political work is in the production of claims about who stands to benefit (or lose) from any potential deployment of solar geoengineering. Early solar geoengineering modeling research tended to focus on the global scale: could these techniques be effective (and reasonably safe) at compensating for global mean temperature changes associated with greenhouse gas emissions? More recently, models have shifted scales, turning toward questions of potential regional disparities associated with deployment. This shift has been driven, in part, by ongoing debates in academic literature and in public discussion about the likelihood that any deployment would destabilize regional climates, and perhaps make things worse for some people in some places (see [31, 92, 106, 165, 232, 225, 138, 102]). The distributional implications of potential deployment have been highly controversial within expert circles, and have been framed by advocates of solar geoengineering research as a key issue with relevance to taking these proposed approaches seriously [127]. Even if regional impacts of solar geoengineering might be uneven, the argument goes, "such effects could probably be minimized or possibly even negated through optimization" (*ibid*).

Many published articles are willing to make bold assertions about regional effects, despite well-known issues with GCMs at regional scales. As one scientist told me, "global averages are nice, but they dont help people in their daily lives." The potential for solar geoengineering to produce novel configurations of climate — and thus new patterns of winners and losers — in particular places has been a key area of concern for people on both sides of the debate about the viability of solar geoengineering. This direct engagement with distributive politics among some modelers contrasts with earlier research on modeling communities, wherein Clark Miller finds that scientists portrayed the utility of climate models as contributions to the general welfare, and specifically not in distributive terms [163]. In the case of solar geoengineering, at this early stage of agenda-setting advocates of scientific research seem particularly willing to frame the usefulness of models in terms of their ability to generate knowledge about 'winners and losers,' sometimes explicitly. In one article, researchers argue: "Related to our study is the often-stated claim that geoengineering will create winners and losers [. . .] if only moderate amounts of global-scale solar geoengineering are used, there is no model-based evidence to support this concern, provided that both temperature and precipitation changes are relevant in every region and sufficiently representative of the changes between climate changes and climate impacts." ([138], p. 6) Others have suggested quite serious negative distributional impacts, including the potential decreased precipitation over the Indian monsoon [206, 255]. As one interviewee put it, even for considering the future effects of climate change at regional scales, "climate models are wrong, which is okay, but I dont think we should trust them to look at regional trends in precipitation for 100 years."

A debate published in The Guardian in 2013 further illustrates the ways in which climate models of regional effects have become crucial to discussions of the advisability and justice implications of research, even outside the modeling community. Mike Hulme, a critic of solar geoengineering research, began his argument with a focus on model results: "First, all evidence to date — from computer simulations and from the analogies of explosive volcanic eruptions — is that deliberately injecting sulphur into the stratosphere will further destabilise regional climates. It may reduce globally-averaged warming, but that it not what causes climate damage. It is regional weather that does that — droughts in the US, floods in Pakistan, typhoon in Philippines. Solar climate engineering in short is a zero-sum game: some will win, some will lose" (*ibid*). For Hulme, modeling evidence itself suggests that regional impacts of deployment would likely be unequal. David Keith, an advocate of research, responded: "You make a very strong claim that geoengineering is zero-sum. If true, I would oppose any further work on the technology . . . While there are claims in popular press that it will 'destabilise regional climates' — presumably meaning that it will increase local variability — I know of no scientific paper that backs this up" (*ibid*).

The notion of a 'zero-sum' outcome associated with solar geoengineering deployment elides a deeper epistemic and normative concern about distribution and prediction: if deployment of solar geoengineering is likely to produce novel allocations of climatic benefits and harms, the distributive justice implications and governance challenges for solar geoengineering research and deployment might be quite daunting [251], indeed, to the contrary, models suggest that these impacts will not be any different from those under climate change itself, then the issue might be more straightforward. Anticipating these arguments, several published scientific articles have acknowledged the importance of this question for policymakers, and the usefulness of models for answering it. In one 2010 study on regional disparities of solar geoengineering deployment, scientists assert that the regional impacts of geoengineering "must be understood for adequately informed decision making on potential [solar geoengineering] implementation" [106]. Going further, some scientists are advocating for studies of the impacts of solar geoengineering on human and natural systems. While very little research has been published on these systems (i.e. agriculture, ecosystems, health, and water resources), some scientists perceive this as the next step [107]. It seems that advocates of solar geoengineering research have taken on board political considerations about winners and losers, and that these considerations have substantively shifted the scientific agenda, including in a re-scaling of climate science and politics from global to regional concerns.

The establishment of a model intercomparison project (GeoMIP), and the inclusion of its scenarios in the IPCCs fifth assessment report, further evinces the institutionalization of modeling as a key component of science and policy in this realm [270]. Furthermore, most meetings on solar geoengineering — inside expert communities and with broader audiences of publics and policymakers — frame the discussion with model evidence suggesting that solar geoengineering must be taken seriously as a climate policy option, because it has the potential to effectively manage climate risks. Increasingly, some scientists go a step further, arguing that solar geoengineering could "make things better for most people in most places." The primacy of models in solar geoengineering means that debates about the advisability and legitimacy of solar geoengineering research, even within expert communities, tend to center on the status of the knowledge claims they generate.

As research into solar geoengineering ideas has developed over the last tens of years, the framing of the problem by scientific advocates of research has shifted in at least two key ways. First, while early research focused largely on the *global* implications of potential deployment, more recent work by many modelers has turned to regional scales. Secondly, advocates of research in the modeling community advocate a shift from more curiosity-driven research — which looked at solar geoengineering as an interesting way to learn more about fundamental climate dynamics — to policy-relevant research into 'testable hypotheses' [130]. Not all scientists involved in modeling solar geoengineering endorse this shift; as one scientist revealed in an interview, there are 'two schools' in the modeling community working on solar geoengineering: those who see models of solar geoengineering as an interesting way to learn more about the climate system, and those who see these studies as valuable only insofar as they are 'realistic' and can 'inform policy.' Nevertheless, those modelers who are most actively involved in political advocacy have tended to engage in these framing approaches. It is worth considering why models carry such weight in debates about research. For one, models constitute the bulk of natural and physical science research conducted on the topic to date; it is not surprising, then, that this is the primary evidentiary basis for calls for more research. Secondly, research has shown that there is something alluring about quantification as a strategy for achieving credibility, especially in domains where distrust and skepticism abound, and especially in liberal democracies. Theodor Porter's research has found that in "a suspicious democratic order," quantitative analysis and appeals to objectivity can work to discourage contestation ([186], p. 47). Sheila Jasanoff has demonstrated this turn toward objectivity and quantification in the US, in particular, which is where some of the most well-known advocates of solar geoengineering research reside and work. Thirdly, climate models have achieved some level of stability and credibility for climate policy more generally. It makes sense that solar geoengineering ideas would rely on similar scientific tools. The establishment of a global geoengineering model intercomparison project, which mimics a global climate intercomparison project, evinces how techniques for producing climate knowledge for mitigation policy are carried over into solar geoengineering debates (GeoMIP).

There is some indication that modelers themselves are aware that they are experimenting in somewhat 'unrealistic' fashion. Early experiments conducted by modelers in the first solar geoengineering model intercomparison project involved simplified scenarios to test solar geoengineering approaches in models. These included, for example, the abrupt quadrupling of carbon dioxide, and attempts to include solar geoengineering deployment via 'turning down the sun' (or reducing solar constant) in the models. Jack Stilgoe has suggested that the adoption of these unrealistic scenarios may respond to a self-reflexive instinct on the part of modeler's: using realistic scenarios might suggest that solar geoengineering is plausible, which could perhaps lead to the view that it could substitute for mitigation and adaptation (known in the literature as the moral hazard problem) [244]. Others have argued that this approach suggests that modelers are more interested in probing the models themselves than in producing policy-relevant knowledge about climate change. Nevertheless, some modelers are calling for more realistic work, and later GeoMIP scenarios seem to be addressing this concern. As one modeler stated, "[...] more realistic experiments are required to support these findings, for instance, future transient model simulations with more realistic forcings as designed in other GeoMIP experiments (G3 and G4, described in Kravitz et al. [2011])" ([255], p. 11,053). One interviewee described idealized cases the following way: "Climate models are hopefully *similar enough* to the real earth system that lessons learned in modeling space can be applied in real world."

Even within expert circles, there is disagreement about whether models themselves are so uncertain as to undermine their predictive capacity — and whether prediction is necessary in the context of contemplating solar geoengineering deployment. For example, some scholars have argued that models cannot be relied upon to ascertain the effects of solar geoengineering at regional scales (Hulme in [132]; [135]). In contrast, advocates of solar geoengineering research maintain either that one must accept the validity of model results for solar geoengineering if one is wiling to accept them for climate change in general, or that methods of deployment might be designed to mitigate unanticipated or unintended consequences (Keith in [132]; [154]). In addition, there is some disagreement in the literature regarding whether any potential unequal distribution of impacts associated with modeled solar geoengineering deployment ought to be considered only in light of the potential distribution of impacts associated with climate change itself [200, 99], or whether the potential production of novel climates at regional scales raises its own distinct set of ethical, social, and political issues [251]. Despite these disagreements, most policy-oriented documents, including several policy reports, maintain that climate modeling is critical [23, 38, 173, 224, 63], and in some cases should precede small-scale field tests ([63], p. 106). These disputes are at once technical and political, scientific and social, and attempts to draw sharp delineations have been subject to intense scrutiny.

With the proliferation of models of solar geoengineered futures has come some debate about their credibility and uncertainty. Management of uncertainty in models for policy is nothing new to analysis of science policy, and the topic has been a central matter of concern in STS. In STS, Shackley & Wynne (1996) have shown that 'boundary-ordering devices' are common in the climate field to deal with the complicated relationship between uncertainty and authority in climate modeling; in policy contexts, scientists must explicitly manage uncertainty, but do not want to imply that uncertainty poses a challenge to the authority of scientific knowledge and its use in policymaking [229]. Other work has demonstrated the ways in which various social, political, psychological, and contextual investments in GCMs affect awareness and characterizations of uncertainties associated with models [144]. Other researchers have examined the purpose of climate models and their relationship to prediction. Some argue that the primary use is heuristic [176] or even as metaphor [189], while others argue that models ought to be viewed as predictive truth machines for predicting future climates. Sarewitz & Pielke Jr. have demonstrated the problematic consequences of operating within a predict-then-act paradigm for climate change, noting that "regardless of the sophistication of such predictions, new findings will almost inevitably be accompanied by new uncertainties — that's the nature of science — and may therefore act to fuel, rather than to quench, political debate. Our own prediction is that increasingly complex mathematical models that delve ever more deeply into the intricacies and the uncertainties of climate will only hinder political action" [215].

How do we make sense of these different expectations of climate modeling to inform political decision-making, particularly when the context shifts from exploratory modeling to models to predict the effects of technology deployment? I argue that, as currently conceived, this move requires a certain degree of magical thinking that enables an exploratory scientific model to become a tool for engineering design, attempting to answer questions such as: when, where, and how much.

The difference between models for climate change and models for solar geoengineering warrants clarification. In the former context, models aim to improve scientific understanding of the effects of greenhouse gases on climate in order to inform mitigation action. Interestingly, in this case, several interviewees (climate modelers themselves) pointed out that "climate change could be described with one simple equation without the need for large-scale models." On the other hand, models which seek to make long-term predictions about the effects of an engineering project seem to serve distinct purposes, with a potentially different set of evidentiary standards. As an interviewee argued, "Models are supposed to be wrong. But the climate models have been written so that we can simulate climate change, and not a geoengineered world where processes which are right now not relevant may become more relevant." Building on this, some social scientists have argued that the pressures that geoengineering necessarily places on long-term prediction make it essentially unmanageable [155, 102]. I would suggest that it is simply too soon to know, for certain, whether and how these systems might develop, and therefore the extent to which they might depend upon modeling predictions. Still, the use context for the models is at the core of some of the debate about the advisability of solar geoengineering.

Nevertheless, some scientists have sought to sidestep questions regarding the authority of models for solar geoengineering by seeking to transfer the authority of climate models for mitigation policymaking to this new domain. Needless to say, this transferability has not been frictionless. The point remains that differences in use context — and in the pressures of regulatory science — should not be easily dismissed by referencing the credibility of climate models for mitigation policy to shore up their authority in a new domain. For example, in David Keith's 2013 book on the topic, he argues: "But we can say that based on the same models used to predict climate change from greenhouse gases, geoengineering seems to be able to substantially reduce climatic change — and presumably climate impacts — on both a global and regional basis, despite the inherently imperfect compensation that arises because climate forcings from greenhouse gases and geoengineering are intrinsically different" ([127], p. 56).

An example of institutional efforts to manage credibility via reference to the authority of models in climate policy more generally can be found in the establishment of a geoengineering model intercomparison project. As solar geoengineering research and policy attention has expanded, the scientific community has been confronted with some of the challenges familiar to scholars of regulatory science, and to the climate modeling community more generally. For example, how should the community organize itself to maintain credibility across wide audiences? One attempt to address these challenges came in the form of an organized effort at model intercomparison, drawing on similar efforts in the climate science community more broadly. The Geoengineering Model Intercomparison Project (GeoMIP), a modeling effort funded by the Pacific Northwest National Laboratory of the US Department of Energy, the US National Science Foundation, and Rutgers University, was established in 2011 to coordinate climate model simulations of climate engineering. GeoMIP aims to "gather model consensus as to the likely climate effects of geoengineering in order to better inform the scientific community, policy makers and the public." (GeoMIP Website) GeoMIP builds upon existing approaches to model intercomparison in the realm of climate science in general, including in that GeoMIP experiments are "synergistically built upon the CMIP5 experiment framework" of the Working Group on Coupled Modeling of the World Climate Research Program. GeoMIP has resulted in over 30 peer reviewed articles, primarily authored by researchers in the global North (see Figure 3.1).

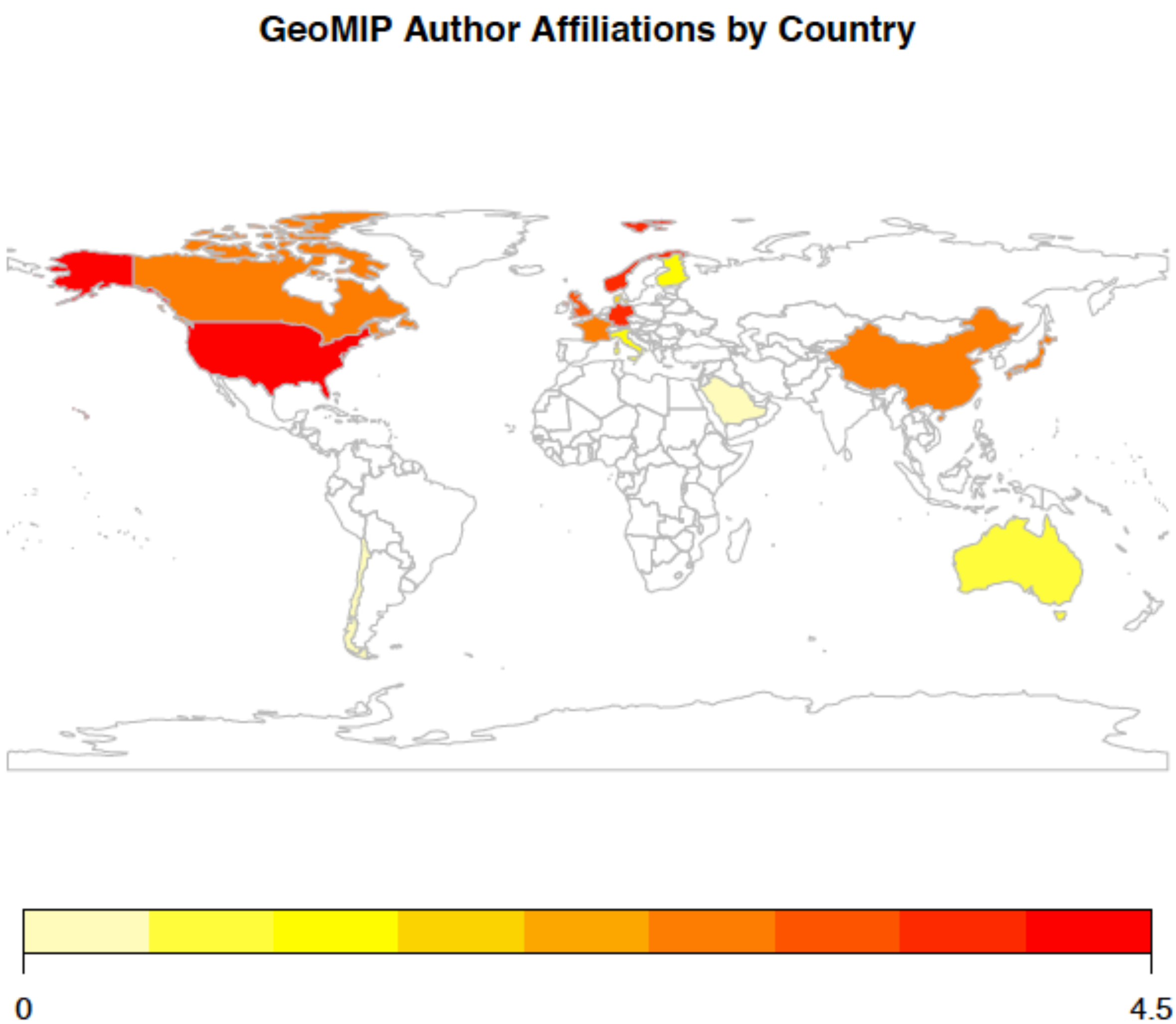

Figure 3.1: **Geographical Representation of Published GeoMIP Articles.** Colors represent log of the number of times a country appears in the author affiliations across 35 GeoMIP publications

GeoMIP, like international climate modeling efforts more generally, organizes itself around the idea that competition across models will yield improvement in knowledge about solar geoengineering. This approach is itself controversial, even within climate science generally: if GCMs are independent of and interdependent on one another, in various ways and degrees, agreement between models may be insufficient to "boost confidence that their results have ab asis in reality."[184] To this end, standardization of modeling experiments has become central to their work. There are divisions within the community of GeoMIP researchers, with some scientists more interested in using scenarios to generate greater understanding of models themselves, while others are more interested in generating knowledge about potential deployment of solar geoengineering. Standardization is essential for this kind of scientific endeavor [250]. What gets lost in this standardization, however, are more fundamental questions about for whom these models seek to speak, and the politics of representation in the production of science. At the Berkeley Workshop, many participants were not persuaded by current models as evidence suggesting that research is likely to benefit them. One repeated concern was with insufficient data collection in the Global South for climate science in general, particularly given that this data is sometimes used to validate model results. Another issue was with setting scientific priorities associated with models; participants persistently asserted that precipitation at regional scales, and impacts on crops, was far more important to them than global average temperature change, for example. Finally, acknowledging the need for capacity building, the lack of scientific collaboration in modeling efforts to date was perceived as problematic for generating useful and credible knowledge.

When it comes to models as regulatory science, research has shown that when scientists enter environmental policy debates they must work to negotiate tensions between the perception that they are neutral and objective participants with the demands of the policy process — which require, in some cases, advocacy and persuasion [133, 183]. Ann Keller demonstrates that scientific participation differs across stages of the policy process, with more explicit framing and advocacy by scientists during agenda setting — in later stages, this kind of scientific participation is both less likely to occur, and more likely to spark controversy, because of increasing formalization over the course of the policy process [133]. Due to the informality of the agenda setting phase, scientists face less pressure to appear objective. This suggests that in the agenda setting phase of policy development for solar geoengineering scientists are likely to play a greater role in framing and advocacy. What is surprising is that model results have been persistently controversial at this early stage, even in discussions within expert communities. This suggests that the framing of solar geoengineering via climate models will contend with significant political contestation. The focus on regional impacts, and the fact that some scientists themselves seem willing to use the language of 'winners and losers' in the publication of model results and at geoengineering meetings, suggests that scientists are more willing to engage in advocacy and persuasion with regard to science at this early, agenda setting stage of research. Moreover, it is clear that the transfer of one apparatus (i.e. GCMs) to a new domain (i.e. solar geoengineering) will require social and political work; the use context of a particular scientific approach shapes its epistemic authority in important ways.

3.6 Conclusion

I have argued here that climate models are playing a central role in attempts to put solar geoengineering on the public agenda, an act that constitutes a kind of political power. I have suggested further that the use of climate models to predict the effects of a sociotechnical imaginary is shaping emerging views of the governance of geoengineering innovation, evidenced, for example, in the focus on debates about the regional effects of deployment. I have suggested that the focus on models as the object of management (rather than the actual technologies) can be usefully interpreted as a strategy of displacement, whereby uncomfortable knowledge (in this case, the non-existence of the technology and the limits of prediction via climate models) is managed by a range of actors, including advocates of research.

Scholars have argued that the category of 'wicked problems' [204], "once reserved to intractable cases such as genetically modified organisms or climate, now applies to most issues where science is called to adjudicate" [208]. In the face of these wicked problems, several authors have proposed the construction of "clumsy arrangements," in which "multiple, diverse, perhaps incompatible, perspectives are brought to the bear on an issue, resulting in a settlement that is inelegant from any single perspective, but robust because it relies on more than one epistemological and ethical foundation" ([197], p. 123). In the case of solar geoengineering, construct a clumsy arrangement in the form of a responsible research program or programs; alternatively, one might argue that the existing settlement, at least in the US, between governments, NGOs, and scientists, in which governments seem willing to fund indoor modeling studies but accept an informal moratorium on everything else, may itself be a kind of clumsy solution, the stability of which depends on its non-articulation [256].

There is a broader question around displacement in the realm of climate policy. Several scholars and commentators have raised questions about the role of imagined technologies in the present, especially since the 2015 Paris climate agreement.[7, 177, 198] As Steve Rayner has pointed out, the agreement maintains the belief that global temperature targets are achievable via the inclusion of imaginary technologies, which represents a kind of 'magical thinking.' [198] Noting that the line between ambition and delusion is not always sharp, Rayner argues that the reality seems to be that the world is already likely to exceed the temperature limit agreed to in 1992 absent some form of geoengineering. Despite this reality, the inclusion of climate engineering technologies in modeled scenarios has the effect of making political targets seem achievable. This is true even without any instrumental action — and potential near-term political costs — to policymakers when it comes to actually funding research and development on these imagined technologies, and assessing their impacts and implications.

Chapter 4

Climate Researchers' Views of Solar Geoengineering: Benefits, Risks, and Governance

Jane A. Flegal

4.1 Introduction

Solar geoengineering background

The possibility of large-scale, intentional interventions in the Earth's climate system as a tool for managing climate risks has emerged as an area of scholarly attention and some policy discussion, most recently in the inclusion of these ideas in the IPCC Special Report on limiting global warming to 1.5 degrees above pre-industrial levels [143, 177]. These ideas – variously termed 'climate engineering' or 'geoengineering' – are often divided into two categories: those which seek to reflect sunlight away from Earth ('solar geoengineering'), and those that seek to remove carbon dioxide emissions from the atmosphere ('carbon dioxide removal' or 'negative emissions'). The UK Stratospheric Particle Injection for Climate Engineering (SPICE) project, one of the first attempts to conduct research into solar geoengineering outside of the laboratory, attracted significant public and media scrutiny [244]. Instrumental concerns about public backlash against these new ideas, normative interest in informed consent and democratic oversight of research, and, to a lesser extent, substantive interest in involving the public in the design of research questions, has motivated researchers to engage publics in various ways about solar geoengineering. This has included empirical studies of public views of the benefits and risks of solar geoengineering (for a review, see [26]). To date, no studies have examined the views of climate researchers or related experts when it comes to solar geoengineering research, despite the potential for experts and policy entrepreneurs to shape the early contours of scientific and policy debates [133]. This chapter attends to this gap.

Who is an expert on solar geoengineering? Everyone and no one

The question of whether one is an 'expert' in a given field is conditioned by situation and context. As an example, consider the seemingly straightforward question of who counts as an expert in climate change. Is it general circulation modelers? Oceanographers? Atmospheric scientists? Economists? Geographers? Farmers grappling with climate change? Since status and power are conferred on those acknowledged as 'relevant experts,' it is important to understand that this category itself is constructed and contested. In the case of emerging technologies, especially those characterized by high uncertainty and political stakes [74], there is a real question as to who — if anyone — can or should reasonably count as an expert [212].

Qualitative research repeatedly demonstrates that the boundary between 'expert' and 'lay' is much more porous than generally understood. As we describe in Winickoff *et al.* (2015): "There is no necessary equivalency between scientists and 'experts,' or non-scientists and 'lay public.' First, there are different forms of expertise, so a sharp dichotomy between 'expert' and 'public' fails to capture nuances in the status of participants and different forms of expertise in operation [271, 42]. Second, expertise is context dependent and can be based on experience rather than training [62, 181]." We should not fool ourselves into thinking that the views of the narrow set of participants in highly technical areas are irrelevant to risk politics. Expertise barriers have been examined in a range of domains, from breast cancer research [180] and energy policy [271], to chemicals policy [114, 96], which often work to narrow the sets of participants and concerns deemed relevant, especially to science and technology (S&T) policy. While a range of participants are sometimes able to shift the terms of debate in important ways, S&T policymaking, in particular, is often characterized by high barriers to entry for non-experts.

It is therefore surprising that much of the empirical research on views of solar geoengineering and its governance has focused on the lay public. One might explain this asymmetry by a common misunderstanding in risk politics: that publics are deficient in their understanding of scientific and technical matters, and that this is the source of policy controversy. This assumption can result in pathologizing the public [273], and focusing on public education in lieu of issues like trust in institutions, representation, and agency. More charitably, one might argue that the focus on lay publics in empirical geoengineering social science is motivated by a desire to democratize S&T decision-making, expanding early public participation, including through the use of empirical social science [69, 86, 193]. Outside of geoengineering, research which seeks to explore the drivers of risk perceptions has also tended to focus on the general public, largely omitting 'expert' views, with some exceptions.

Empirical social science on public views of solar geoengineering research & its governance

Over 30 studies investigating public views of geoengineering have been conducted to date (Tables 4.1, 4.2, 4.3). This has been motivated by instrumental concerns that public opposition to new technologies can stymie their development, normative interest in attending to public concerns around technologies with the potential to fundamentally reshape societies, and intellectual concerns in forecasting risk politics. These surveys focus mostly in the Global North (in particular, the UK, US, and Germany).

Despite methodological differences, a few common themes emerge (for a full review, see [26]). The first is consistent findings of very low familiarity with geoengineering among general publics, although it appears that public awareness has increased in recent years [50]. In 2011, Mercer *et al.* found that 8 percent of respondents in the US, Canada, and the UK could define "geoengineering" [160]. In 2014, Corner and Pidgeon found that 28 percent of respondents in the UK had heard of "geoengineering," but only 2 percent reported knowing a fair amount or great deal about geoengineering [48]. This finding was reiterated in Merk *et al.* (2015), which found that only 3 percent of German respondents had heard 'a lot' about geoengineering [161].

The second has to do with the importance of framing effects, and is related to the findings of low familiarity above. Particularly when familiarity is low, how the topic is framed in survey instruments can significantly shape responses. For example, research has shown that framing techniques as 'natural' can drive risk perceptions [182, 49]. Similarly, a narrow focus on geoengineering outside of a broader range of climate policy options can shape views of the technologies' potential benefits and risks. Recent studies have dealt with this challenge by seeking to 'unframe' the technology altogether [12], or by intentionally manipulating the framings in an experimental fashion [13].

The third finding is mixed, but discerning, views on research and/versus deployment. Mercer *et al.* report that 80 percent of respondents were in favor of lab research on solar radiation management [160]. They also found that field research was less accepted than lab research. Many studies find that publics distinguish between deployment and research, and find reluctant and conditional support for certain kinds of research [241, 160, 182, 15, 264, 10].

Empirical social science has sometimes sought to address concerns about the moral hazard: the notion that moving forward on solar geoengineering would undermine mitigation efforts (and perhaps adaptation, although this is less studied). It is not clear that studies examining *individuals'* mitigation preferences are directly related to the question of the moral hazard as it may or may not operate at the level of *political decision-making*. Studies which have sought to examine individuals' views of moral hazard have found that the risk of moral hazard is a concern for various publics [15, 2, 260, 9]. Yet, despite the concern that other people would be seduced by the prospect of geoengineering in lieu of mitigation, individuals often do not report experiencing these dynamics themselves. Merk *et al.* (2015), for example, find people are more willing to offset their own emissions when they receive information about solar geoengineering [161]. The authors attribute this behavior to subjects viewing solar geoengineering as a potential 'threat' and, thus, "increase mitigation to prevent a level of climate change that would make the deployment of SAI [sulfate aerosol injection] more likely." Others attribute the finding of 'reverse moral hazard' to an increase in concern for climate change, sparked by learning about solar geoengineering [125]. Neither type of response is universal. More skeptical publics and those endorsing 'self-enhancing' values are more likely to fall into the 'moral hazard' camp [48]. For some, knowledge of solar geoengineering may reduce incentives to mitigate; for others, such knowledge may solidify preconceived notions of the importance of climate policy action.

Very few studies have analyzed views about *specific* governance architectures for research, focusing instead on general views about the benefits and risks of research, and generating useful but high-level principles to guide research. Research from public deliberations in the UK suggested support for greater transparency in research decisions, open publication of experimental results, and new international governance and regulatory structures [182]. Focus groups emphasized the importance of public trust in climate science as: a reliable guide to policy; the ability to predict side effects; the ability of research to demonstrate the effectiveness of approaches; the existence of effective research governance; and the capacity of democratic institutions to oversee and govern solar geoengineering technologies [155, 161]. Studies have also found concerns about controllability, reversibility, and cost-efficiency of different geoengineering options [168, 13]. The most recent study explicitly addressing what might constitute a 'legitimate' experiment, and how it should be governed, found that four criteria, oriented around controllability, were important for the perceived legitimacy of experiments: the degree of containment; uncertainty around experimental outcomes; reversibility of impacts; and the scientific purity of the enterprise [13].

Surveys examining experts' risk perceptions

Some studies find correlations between positions of experts on contested risk issues and their cultural or political orientations [20, 35], although these correlations are much weaker than samples of the general public. Most of these studies examined scientists perceptions *outside* of their own domains of expertise, with one exception [240]. In contrast, studies of legal professionals found that judges and lawyers converged on responses to statutory interpretation problems regardless of their cultural outlooks (although, importantly, this convergence was confined to legal-reasoning tasks; when it came to other societal risks (e.g., climate change), they engaged in the same identity-protective reasoning as the general public) [122]. So, it might be hypothesized that scientists views on risk issues will diverge by cultural worldview *outside* of their domain of expertise, but converge *within* their domain of expertise, especially in situations where there is not already public controversy. In contrast, we could infer from existing research [136] that professional judgment will fail to insulate experts from identity-protective cognition, even within domains of expertise, when professional status becomes strongly linked with particular factual claims.

Many empirical studies aim to compare expert and public views of the risks of technologies. While these surveys tend to find differences in how experts and members of the public view risks, the picture is complicated: a study of nanotechnology experts found that while experts viewed some dimensions of nanotechnology as less risky than the general public (a finding that aligns with earlier studies, see [70, 239, 137, 217, 134, 237]), those same experts found other related issues more risky than members of the public [220]. A similar pattern was found in a 1997 study of food risks [236]. In addition, a 2002 study found that the factors that explain experts' risk perception are similar to the general public, as were overall levels of variance [238]. Barke and Jenkins-Smith, in their study of nuclear waste attitudes, found that NGOs and members of the public rate risks higher than all groups of scientists (but not accounting for sociodemographic variables); identified disciplinary differences (wherein physicists and engineers rated risks as lowest, while life scientists saw risks as greater); and sectoral differences (where scientists employed by universities gave highest risk ratings, while those employed by businesses or research labs (national weapons programs) gave the lowest ratings). These differences were associated with attitudinal measures, including: (1) severity of environmental problems in general; (2) perceived voluntariness of technological risk; and (3) values related to environmental management strategies. The authors found that people most closely associated with the risk, rated it lowest (e.g., physicists rated risks of genetic engineering higher than those involved in biomedical research, while the opposite was true for nuclear waste risk) [4]. Lynn also found that risk perception and political ideology of scientists varied as a function of where they were employed [152].

4.2 Methods

Social scientists have begun to examine what 'general publics' think about geoengineering, and the extent to which they think about these ideas at all (see Tables 4.1, 4.2, 4.3). However, there has been no large-scale empirical study of how researchers in relevant domains (i.e., climate science and policy) view these issues. Moreover, most of the existing research focuses on general views about the idea of geoengineering, and is not focused on governance architectures for research. This chapter aims to generate insights into how those researchers with the potential to shape the field of solar geoengineering (because of their subject-matter expertise, networks, and proximity to the field) view these issues, including by identifying broad areas of agreement and patterned and/or individual variations.

While much of this dissertation focuses on macro-scale risk politics (at the level of institutions and interest groups), and employs qualitative methods, both quantitative and qualitative studies of risk have shown that differences in risk interpretation among individuals may depend on a range of issues, including institutional affiliations, gender, trust in information providers/institutions, prior experience with similar situations, power/agency to influence the source of the risk, and cultural commitments. The realist model of risk analysis draws a distinction between lay (perceived) risk and expert (actual) risk [115]. In contrast, constructivist approaches understand public risk perception to be linked to assessments of institutions. In this case, rather than pathologizing lay publics as deficient in knowledge, and therefore prescribing public education, the response is to call for more inclusive and pluralistic policy processes than are considered necessary in realist models (*ibid*: 93).

Some attempts at bridging the cultures of risk analysis have already been made, with quantitative researchers deriving a set of hypotheses based on the insights from qualitative studies of risk [121, 11]. The survey developed in this chapter builds on these approaches, drawing on Mary Douglas and Aaron Wildavsky's cultural theory of risk. The basic argument of cultural theory is that individuals will form beliefs about societal hazards that reflect and reinforce their commitments to an idealized form of social ordering [121]. Cultural cognition, in particular, is one conception of the cultural theory of risk that measures individuals cultural worldviews, investigates social psychological mechanisms that connect individual risk perceptions with worldviews, and aims to enable the development and communication of public policies related to risk that can accommodate plural outlooks (*ibid*).

Leading scholars in cultural cognition hypothesize that experts will, like laypeople, be subject to conflicting views about risks in domains in which they *are not* narrowly expert, and/or where there is already persistent public controversy about policy-relevant science. For example, in a study of judges cognitive tasks, Rachlinski *et al.* find that judges sometimes make 'cognitive errors' when "something in their decision-making environment distorts or turns off their professional habits of mind," even when these issues are well within their narrow domain of expertise [188, 87]. Slovic *et al.* (1995) and Silva *et al.* (2007) find that differing cultural worldviews and values explain some expert disagreement on policy-relevant science, especially in areas where there is already public controversy [240, 235]. For the sample in this study, it might be fair to assume that solar geoengineering — as a sociotechnical imaginary — falls *outside* of most respondents' domains of expertise. Therefore, we might expect conflicting views regarding solar geoengineering, explained, at least in part, by cultural worldviews.

Respondent selection

The goal of respondent recruitment was to identify scholars actively publishing on climate-related science and policy. It is important to note that the aim of this study was not to characterize the risk orientations of geoengineering researchers, *per se*, but rather to examine the views of the wider community of experts actively contributing to climate change literature. This group was selected, in part, because the community of researchers actively studying and publishing on solar geoengineering is quite small and more amenable to study via qualitative methods (as demonstrated elsewhere in this dissertation). In addition, very little is known about how the broader climate change expert community views solar geoengineering. This is important because advocates of solar geoengineering research are actively working to mainstream the topic into broader climate science and policy discussions. It is therefore useful to understand how existing climate research communities currently perceive solar geoengineering research and its governance (understanding that this will likely change over time).

Following Cook *et al.* (2013), I searched ISI Web of Science — regarded as one of the most comprehensive and interdisciplinary scientific databases — for papers published between 1997 to 2016 on "climate change AND mitigation OR adaptation; technology OR risk; emission* OR impact*" [45]. This search resulted in 4,319 published papers. After reviewing papers for relevance, I then identified corresponding author email information for 3,371 authors. 363 emails bounced-back, resulting in a total of 3,008 emails to potential respondents. Authors were selected regardless of their country of origin or residence, resulting in a final set of respondents that contained a high proportion of international researchers (184 of 268), an issue to which I return below.

I conducted a web-based survey of climate change researchers between January and March of 2017. The survey was pilot tested with graduate students and researchers (n = 5). Invitations to participate in the survey were sent by email, which included a description of the research, institutional review and consent information (see Appendix D), and a link to the survey. Initial invitations were sent in late January of 2017. Following a modified Dillman schedule [57], two reminder emails were sent before the survey closed in March of 2017.

In total, 460 surveys were completed. Of those for whom a usable email address was identified, 15.3% responded. This was deemed a reasonable response rate when compared to similar studies [6], and resulted in an appropriately diverse sample (Table 4.4). Of the surveys completed, only 268 were used in the subsequent analyses due to incomplete responses to the cultural worldview battery and/or the geoengineering questions. Rather than imputing scores using simple means or a more complex interpolation method, elimination of incomplete results was deemed more useful in an exploratory analysis of this nature.

Questionnaire

The questions related to general risk orientations and cultural worldviews were derived from existing literature and collaboration with researchers in cultural cognition. Questions regarding climate risk and solar geoengineering were derived from my interviews with, and participant observation of, solar geoengineering researchers over the course of seven years.

The questions addressed below fell into roughly five categories: (1) partisanship & political ideology; (2) cultural worldview measures; (3) industrial strength risk perception measures (ISRPM); (4) climate catastrophism; and (5) solar geoengineering benefits, risks, and research governance (see Appendix C). The length of the survey may have resulted in respondent fatigue, perhaps reducing the overall response rate (564 surveys were started and only 460 completed).

Considering Candidate Predictors

A set of regression models were developed to determine the relative predictive power of several demographic and worldview-based traits. The candidate predictors consisted of gender (male versus female), political ideology (liberal versus moderate versus conservative), familiarity (familiar versus unfamiliar), climate catastrophism (catastrophist versus non-catastrophist), geography (within versus outside the U.S.), hierarchy (hierarchical versus egalitarian), and individualism (individualist versus communitarian). All of these predictors were reduced to dichotomies for the sake of simple interpretation. The relatively small sample means that the predictive power of the model is likely quite low, so our intent is not to present a definitive set of models in this vein. Rather, I aim to demonstrate the potential contributions of these predictors to guide future analyses of larger samples. For this reason, only the full candidate model is presented, and no subsequent model selection methods are applied. Detailed descriptions of the methods used to derive the values that were used in the regression models can be found in the Supplementary Materials.

Five regression models were built according to the broad divisions that arise from a parsimonious factor analysis of the 18 geoengineering-related questions. These categories, as reflected above, are: Research (Questions 4, 5, 6, 9, and 18), Moral hazard (Questions 1 and 2), Deployment (Questions 3, 5, 13, and 17), Governance (Questions 7, 8, 9 and 11), and Delegation to experts (Questions 8, 10, 14, and 15). The factor analysis results in a set of five continuous values for each of these response variables, making a multiple linear regression modeling approach the most appropriate as an initial investigative tool. Two of the questions (12 and 16) did not load onto any of the five factors, and thus, were not considered as components of any of the regression models. As mentioned previously, the final sample used in the regression analyses was 268 after the elimination of individuals who left incomplete responses to the worldview or geoengineering-related battery.

4.3 Results

For the purposes of this dissertation, I focus principally on descriptive elements of this survey instrument regarding climate researchers' views of solar geoengineering research and its governance. Though I present a set of regression models, the relatively small sample size suggests that the predictive power of the models may not be highly transferable. Even so, they may offer important insights into the roles of various candidate predictor variables.

General trends

The first survey of international climate researchers on solar geoengineering suggests a range of views about the potential benefits, risks, and governance arrangements for solar geoengineering research. Respondents tended to report favorable views of near-term research (53 percent), exhibiting more support for indoor studies (80 percent) than outdoor experiments (58 percent). Despite this support for *research*, the majority of respondents believe that the risks of any future *deployment* of solar geoengineering will outweigh its benefits (78 percent). In fact, most respondents report believing that deployment will likely result in unpredicted impacts at regional scales (90 percent), and that uncertainty in our understanding of the climate system means that societies should not deploy solar geoengineering (67 percent).

When it comes to governance arrangements for research, respondents express a diversity of views regarding appropriate oversight, but wide agreement that solar geoengineering research poses novel governance challenges and therefore requires new arrangements (85 percent). The majority of respondents report that self-governance by scientists is insufficient (79 percent), and that knowledge production about solar geoengineering should be inclusive and representative (86 percent). This latter finding, however, is potentially contradictory to the finding that most respondents (82 percent) believe that qualification, irrespective of geographical representation, should determine who is involved in geoengineering research programs. Most respondents report believing that wider publics should have a say in decision-making about solar geoengineering research (76 percent). The question of whether research below physical thresholds should move forward without additional oversight was more complicated: a majority (58 percent) disagreed with this approach, while 42 percent agreed.

Correlation Among Response Variables

The five response variables were derived from a factor analysis based on a battery of 18 geoengineering-related questions. It is important to define exactly what higher values of each response variable indicate. The first outcome, which is summarized as Research, consists of five questions, and higher values represents a more favorable view of research in geoengineering (including both indoor and outdoor experiments). The second outcome, referred to as moral hazard, is derived from two questions, and higher values indicate a higher belief in the risk of the moral hazard (i.e., that moving forward with solar geoengineering will reduce the probability of pursuing other mitigation strategies). The third outcome, called Deployment, consists of four questions, and higher values indicate more negative views of deployment. The fourth outcome, reduced to the term Governance, consists of four questions, and higher values represent greater support for altered or additional governance arrangements. The final outcome variable, called Delegation to experts, consists of four questions, and higher values indicate greater support for delegating decision-making to experts.

It is especially important to keep these in mind when considering the correlations between these response variables (Figure 4.1). There are several outcomes that exhibit covariance. The highest level of correlation is between the Research and Deployment factors, with a correlation coefficient (R) of -0.66. This negative correlation suggests that higher values in Research are likely to be associated with lower values in Deployment. Overall, this relationship indicates that individuals who are more supportive of research will tend to have more positive views of deployment as well. The Research factor is also somewhat highly correlated with Governance. In this case, the relationship is also negative (R = -0.42), indicating that more positive views on geoengineering research tends to align with a low perceived need for governance arrangements. Unsurprisingly, Governance is also correlated with Deployment, though in this case, the relationship is positive ($R = 0.45$). This indicates that a negative view of deployment with tend to align with a higher perceived need for governance regimes surrounding solar geoengineering. Though there are some other minor correlations ($R < 0.4$) between Delegation to experts and both Governance (R = -0.34) and Research ($R = 0.33$), the relationship is not necessarily strong enough to suggest a generalizable trend.

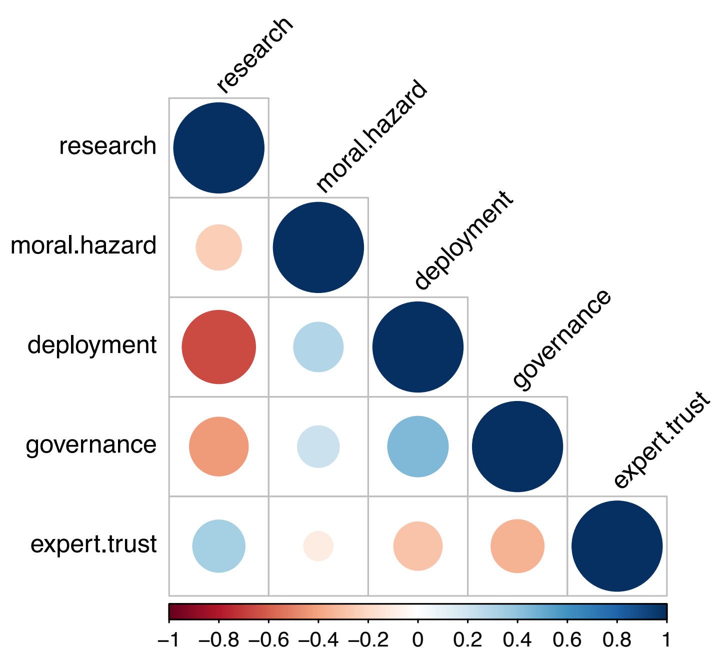

Figure 4.1: **Correlations Among Response Variables**

Correlation Among Predictor Variables

Prior to conducting a regression analysis, the correlations among the candidate predictor variables were investigated to verify that each was measuring something somewhat unique (Figure 4.2). For the sake of this analysis, all of the individuals with incomplete responses were removed (resulting in the elimination of 18 of the 268 individuals ultimately used in the regression analyses). This analysis revealed that there were no particularly highly correlated predictors, with a maximum observed correlation coefficient of $R = 0.30$ (between hierarchy and gender). To gain additional clarity, the continuous scores for hierarchy, individualism, and catastrophism were also analyzed (rather than the binary breakdown ultimately applied in the regressions). This further reduced observed correlations, with the highest coefficient associated with the relationship between catastrophism and politics ($R = 0.23$). These results imply that a regression analysis using these predictor variables will not suffer from redundant contributions and that the use of the predictors in their binary forms is justified.

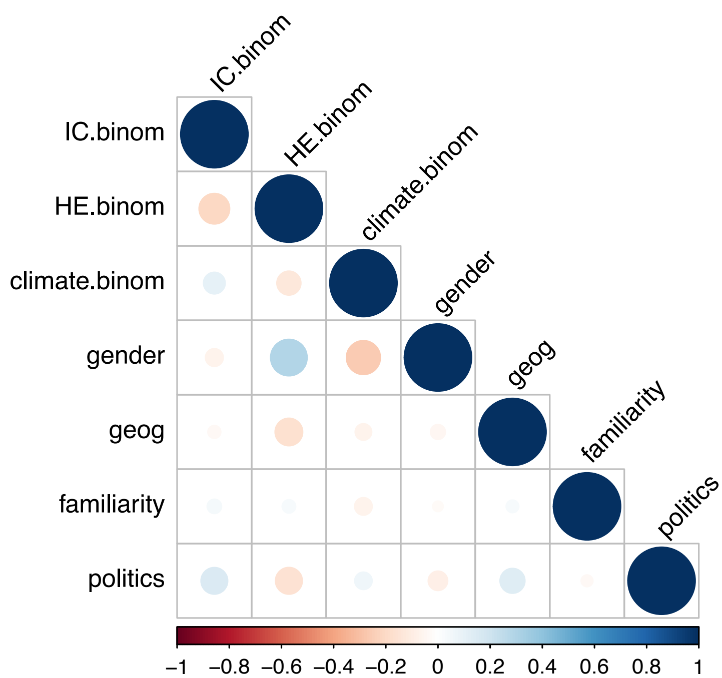

Figure 4.2: **Correlations Among Predictor Variables**

Research

The regression that treated Research as the response variable resulted in a model that explained 12.4% of the variance observed in the responses (Table 4.3). The results indicate that geography and gender are significant predictors of perceptions regarding the desirability of geoengineering research. In the case of geography, individuals within the United States were significantly more likely than their international counterparts to be in favor in research ($\beta_{US} = 1.30$; $t = 3.294$; $p = 0.00114$). In terms of gender, males were significantly more likely than females to be in favor of research into solar geoengineering ($\beta_{male} = 1.12$; $t = 2.643$, $p = 0.00877$).

Coefficients:

	Estimate	Std. Error	t value	Pr(>| t |)	sig
(Intercept)	7.6613	0.6334	12.095	<2e-16	***
Familiar	-0.2327	0.3668	-0.634	0.52652	
Conservative	1.3033	0.9105	1.431	0.15364	
Liberal	-0.5669	0.4059	-1.397	0.16377	
Within.US	1.2958	0.3934	3.294	0.00114	**
Catastrophist	-0.5007	0.3710	-1.350	0.17838	
Male	1.1155	0.4221	2.643	0.00877	**
Hierarchist	0.8233	0.5307	1.551	0.12213	
Individualist	0.1148	0.5188	0.221	0.82514	
Hierarchist:Individualist	-0.6246	0.7246	-0.862	0.38953	

Moral Hazard

The regression that treated Moral hazard as the response variable resulted in the model that explained the least variance (Multiple $R^2 = 0.049$; Table 4.3). The results indicate that climate catastrophism is the only significant predictor of beliefs regarding the risks of moral hazard. Climate catastrophists were associated with significantly higher perceptions of risk that solar geoengineering research would result in a moral hazard predicament ($\beta_{catas} = 0.69$; $t\text{T} = 2.528$; $p = 0.0121$).

Coefficients:

	Estimate	Std. Error	t value	Pr(>$\mid t \mid$)	sig
(Intercept)	6.28129	0.46518	13.503	¡2e-16	***
Familiar	-0.30240	0.26938	-1.123	0.2627	
Conservative	-0.79005	0.66866	-1.182	0.2386	
Liberal	-0.02244	0.29805	-0.075	0.9400	
Within.US	0.14283	0.28891	0.494	0.6215	
Catastrophist	0.68877	0.27242	2.528	0.0121	*
Male	-0.03459	0.31000	-0.112	0.9113	
Hierarchist	0.22831	0.38970	0.586	0.5585	
Individualist	-0.09528	0.38099	-0.250	0.8027	
Hierarchist:Individualist	-0.16590	0.53210	-0.312	0.7555	

Deployment

The regression that treated Deployment as the response variable resulted in a model that explained 12.3% of the variance observed in the responses (Table 4.3). The results indicate that familiarity, gender, and catastrophism are all significant predictors of views on the advisability of deployment. In this case, males were significantly less likely than females to hold the negative views of geoenginerring deployment indicated by high values of the response variable (β_{male} = -0.94; t = -3.365; p <0.001). Higher levels of familiarity were associated with more negative views of deployement ($\beta_{fam} = 0.56$; $t = 2.33$; $p = 0.02$). Climate catastrophism was also a significant predictor in this model ($\beta_{catas} = 0.54$; $t = 2.191$; $p = 0.03$), with catastrophists tending to have more negative views of deployment than non-catastrophists.

Coefficients:

	Estimate	Std. Error	t value	Pr(>| t |)	sig
(Intercept)	6.0846	0.4176	14.569	<2e-16	***
Familiar	0.5632	0.2418	2.329	0.020701	*
Conservative	-0.2728	0.6003	-0.454	0.649913	
Liberal	-0.0150	0.2676	-0.056	0.955333	
Within.US	-0.4028	0.2594	-1.553	0.121718	
Catastrophist	0.5358	0.2446	2.191	0.029430	*
Male	-0.9364	0.2783	-3.365	0.000893	***
Hierarchist	-0.3930	0.3499	-1.123	0.262391	
Individualist	-0.3656	0.3421	-1.069	0.286225	
Hierarchist:Individualist	0.3825	0.4777	0.801	0.424098	

Governance

The regression that treated Governance as the response variable resulted in the model that explained more of the variance in observed responses than any of the others (Multiple $R^2 = 0.157$; Table 4.3)). The results indicate that several of the candidate variables represent significant predictors of perceptions that novel or additional governance arrangements will be needed for solar geoengineering. Geography was the most highly significant predictor (β_{US} = -0.65; t= -3.230; p = 0.0014), and suggests that individuals within the United States exhibit more negative views on the necessity of governance than their international counterparts. Gender is a similarly significant predictor (β_{male} = -0.67; t = -3.23, p = 0.0023), with males also exhibiting more unfavorable views of governance regimes than females. Climate catastrophism significantly predicts perceptions of governance (β_{catas} = 0.46; t = 2.416; p = 0.016), whereby catastrophists favor governance of new geoengineering technologies more than non-catastrophists. Finally, political ideology also serves as a significant predictor (β_{lib} = 0.42; t = 2.017; p = 0.045), with Liberals exhibiting more positive views of governance arrangements than Moderates (or Conservatives).

Coefficients:

	Estimate	Std. Error	t value	Pr(>| t |)	sig
(Intercept)	5.80228	0.32508	17.849	<2e-16	***
Familiar	0.14966	0.18825	0.795	0.42739	
Conservative	0.46283	0.46728	0.990	0.32294	
Liberal	0.42019	0.20829	2.017	0.04478	*
Within.US	-0.65210	0.20190	-3.230	0.00141	**
Catastrophist	0.46002	0.19038	2.416	0.01642	*
Male	-0.66782	0.21664	-3.083	0.00229	**
Hierarchist	0.07041	0.27234	0.259	0.79621	
Individualist	-0.20307	0.26625	-0.763	0.44638	
Hierarchist:Individualist	-0.25289	0.37185	-0.680	0.49710	

Delegation to Experts

The regression that treated Delegation to Experts as the response variable resulted in a model that explained 15.3% of the variance observed in the responses (Table 4.3). The results indicate that Familiarity is a strong predictor of expert trust, as is Hierarchy. Those who were more familiar with geoengineering tended to exhibit much less willingness to delegate decision-making to a group of experts (β_{fam} = -0.81; t = -3.706; p <0.001). Where worldview is concerned, hierarchists exhibit a significantly higher willingness to delegate decision-making to experts than their egalitarian counterparts (β_{hier} = 0.71; t = 2.245; p = 0.026). The individualism component of worldview was a nearly significant predictor of this response variable (β_{ind} = 0.53; t = 1.711; p = 0.088)), with individualists being significantly more willing to delegate decision-making to experts than their communitarian counterparts. In addition, catastrophism was a nearly significant predictor (β_{catas} = -0.42; t = -1.907; p = 0.057), with catastrophists exhibiting more hesitance in delegating decision-making to experts than non-catastrophists.

Coefficients:

	Estimate	Std. Error	t value	Pr(>| t |)	sig
(Intercept)	3.5462	0.3781	9.380	<¡ 2e-16	***
Familiar	-0.8113	0.2189	-3.706	0.000262	***
Conservative	0.6127	0.5435	1.127	0.260699	
Liberal	-0.3153	0.2422	-1.302	0.194327	
Within.US	-0.2956	0.2348	-1.259	0.209285	
Catastrophist	-0.4223	0.2214	-1.907	0.057664	.
Male	-0.2158	0.2520	-0.857	0.392527	
Hierarchist	0.7111	0.3167	2.245	0.025664	*
Individualist	0.5299	0.3096	1.711	0.088316	.
Hierarchist:Individualist	-0.3999	0.4325	-0.925	0.356001	

4.4 Discussion

This paper represents a preliminary study of variables that may affect climate researchers' perceptions of solar geoengineering research and deployment. Our goal was not, and is not, to develop a predictive model to forecast the terrain of risk politics of solar geoengineering moving forward. When considering the responses to the individual geoengineering questions, we divide the group into those who agree (responding to a given question with 'somewhat agree', 'agree', or 'strongly agree') and those who disagree (responding with 'somewhat disagree', 'disagree', or 'strongly disagree'). Thus, the trends observed here are general summaries of the results that reduce some of the nuance that is maintained when the regression response variables (factors) are derived. For regression analyses, we do not divide responses into agree/disagree categories; instead, we maintain the variance in the Likert-scale responses, which helps to capture nuance. Moreover, the derivation of factors which include several questions helps to measure a more inclusive 'latent state' than the individual questions would measure in isolation of one another. Meaningful observations can be extracted from either dataset, though we emphasize the particular source of the trend in the following discussion. We raise the following findings as worthy of investigation in the future.

The responses to the 18 individual questions related to geoengineering reveal some potentially important trends. Firstly, respondents in this survey, much like surveys of general publics, report concern about the moral hazard operating at the level of political decision-making. Nevertheless, respondents generally support research on solar geoengineering, including small-scale outdoor studies — despite both a general concern that research may result in lock-in and slippery slopes to deployment, and skepticism about the advisability of ever deploying these techniques. We find strong support for some form of novel or supplementary governance arrangement(s) for research, and a belief that scientific self-regulation is insufficient to manage risks. There seems to be less agreement, however, on particular governance approaches; we find mixed responses regarding the desirability of a 'physical thresholds' approach to governing geoengineering experiments, for example.

Despite the fact that most respondents express skepticism about the desirability of future deployment, respondents tend to support more research into these techniques, both indoor and, to a lesser extent, outdoors. This might be explained by a view that research will reveal reasons not to move forward, or because of a belief that concerns about slippery slopes are overstated (although this seems less likely, given that most respondents report concern that research may result in lock-in and slippery slopes to deployment). Alternatively, a substantial number of researchers surveyed here may have an interest in scientific research moving forward in general, irrespective of its strategic aims. Respondents express skepticism about prediction and controllability when it comes to solar geoengineering deployment. It remains an open question whether a desirable future world with solar geoengineering would depend upon predicting such outcomes, although most respondents also report a belief that uncertainty in our understanding of the climate system means we should never deploy solar geoengineering.

One important note before discussing the results of the regression analyses is that the response variables in all five cases are the result of a factor analysis conducted on the responses to a battery of 18 geoengineering-related questions. The simple summary terms that are applied here are just that: simplistic. The idea of associating a single term, such as 'Research' or 'Delegation to Experts', with a factor representing a set of questions with different weights placed on each, represents a challenge. However, the idea of the factor analysis (as applied to survey results) is to reveal meaningful latent attitudes that may be borne out by multiple questions. The simplification of these complex attitudes into single terms might obscure a great deal of interesting nuance, but also facilitates interpretation at the scale of the sampled population.

Cultural worldview was only a significant predictor for one of the five factors used as response variables in the regression models (delegation to experts). There are several possible explanations for this finding. First, my sample was very international. While some work in cultural cognition suggests that the worldview scales transfer across geopolitical boundaries [125, 126], this research — on 'cross-cultural cultural cognition' — is nascent. Second, my sample was highly skewed relative to surveys of the general public (Figure 4.3); relative HIs in my sample might actually be absolute ECs in a sample of the general public (including climate researchers). HIs and ECs in my study, therefore, might be more similar to one another than my division suggests. This reveals an important consideration when conducting surveys of experts: should scales be adjusted to account for apparent biases relative to previously surveyed groups? In this instance, the scales were, indeed, treated independently from previous studies, with the median values along both the hierarchy and individualism axes used to divide the sample. This approach offers insight into the role of worldview within the community of climate researchers. However, this approach may also make direct comparisons between these results and those of surveys of the public more unclear. This finding also raises some question about cultural and political diversity in the academy — in climate research, and potentially beyond [274]. An in-depth analysis of these questions is beyond the scope of this chapter, but worthy of future inquiry. The one factor for which it was a significant predictor is directly related to the proper organization of society (the questions around delegation to experts). It makes sense, then, that cultural worldview would be a significant predictor for this factor.

Gender emerged as a significant predictor for three of the five factors in this study (research, deployment, and governance). While one study of risk perception of scientists regarding nuclear power did find gender differences [5], a more recent meta-analysis of gender and risk by Julie Nelson raised some doubts about such finidngs. She concluded that women are not more 'risk averse,' or only marginally so, and only in certain contexts. Even then, the differences between men and women are small. Nelson finds that, in general, there are more differences within men or within women than across genders [166]. Importantly, the analysis

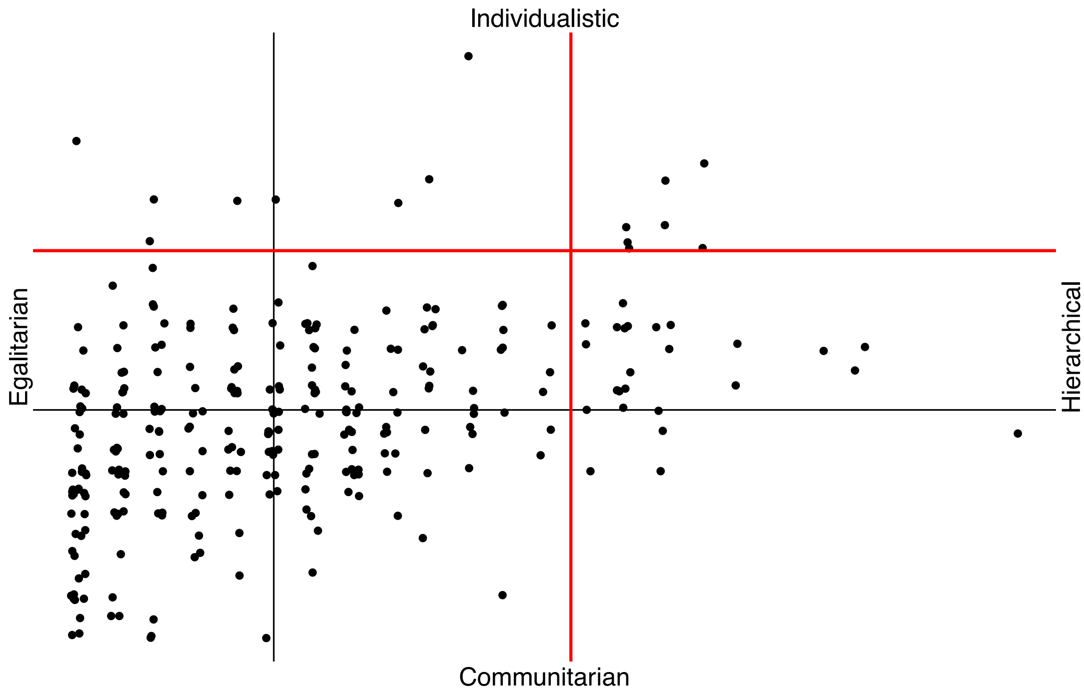

Figure 4.3: **Worldview Map:** Respondent worldviews based on the twelve-question short-form culture scales are plotted on a group-grid map (Kahan). The thin black axes indicate the means along the group and grid scales for the experts surveyed here, whereas the red axes represent the mean values obtained from a large sample of members of the general public on the same battery of questions. Note that the means on both axes shift substantially toward EC for the respondents of this study.

conducted by Nelson implies that simple group means comparisons (e.g., t-tests) or conclusions drawn from differences *on average* will obscure the true degree of difference between these groups [167]. Instead, she advocates for the application of measures of substantive difference (Cohen's d) and substantive overlap (e.g., Index of Similarity) to determine the true nature of the differences between males and females. The multiple linear regressions conducted here do not account for this shortcoming directly, which could indicate that the statistically significant differences between the genders with regard to these three factors may be somewhat misleading. To situate these results, Cohen's d was calculated for the research, deployment, and governance values associated with males and females, and the results indicate that the all three imply differences in means separated by approximately 0.5 of the whole-sample standard deviation (0.49, 0.59, and 0.54, respectively).

To the extent that women researchers do, on average, tend to view solar geoengineering research and its governance differently than their male counterparts, this finding does not explain the *sources* of these differences. Research suggests that these differences, where they exist, are likely to be due to social facts and/or norms [68, 175] or to particular contexts (e.g., risks to identity and/or concerns about stereotypes have been found to amplify differences across genders in some instances).

Irrespective of the source of the variation, the analysis here suggests that it may be important to consider gender explicitly, both in the conduct of future empirical social science on solar geoengineering and in the design and conduct of solar geoengineering research programs and governance institutions. One early study of gender and geoengineering finds very low representation in scientific publications on geoengineering, at expert meetings on the topic, and in media accounts [24]. In terms of the impacts of this under-representation, as Buck *et al.* point out, an important concern relates less to women missing out on careers in geoengineering, but rather "in the framing and decision-making powers that participation in geoengineering research implies." This is not just a normative concern (women are vulnerable to climate change and also geoenginering, so should have a say) but also a substantive one: when confronting 'wicked problems' [204] like geoengineering, the deliberate design of pluralistic institutions which seek to include multiple rationalities and perspectives can help facilitate the development of 'clumsy solutions' [256].

Arguments for inclusion also apply to geographical differences. Our study used binary categories (inside/outside of US), and thus cannot address important country-specific differences. However, comparative work in STS on the role of political culture in shaping sociotechnical choices supports the view that this may be an important variable when it comes to considerations of risk and regulation [22, 112]. Other potentially interesting geographic divisions could have been used, but the relatively small sample size limited the statistical power of alternative breakdowns. One that may warrant additional investigation is a Global North vs. Global South comparison. Given the findings presented in Winickoff *et al.* (2015) [264], it would not be surprising to see an even more stark difference among these broad geographic regions.

Climate catastrophism (or 'perceived climate risk') was a significant predictor for moral hazard (where those who see the risks of climate change as greatest also see the risks of moral hazard as highest), deployment (where catastrophists were associated were more negative perceptions of deployment), and governance (where catastrophists tended to favor novel governance arrangements). Despite its appearance in these regression models, one might expect catastrophism to play an even greater role, particularly with respect to the topic of geoengineering research. Its non-significance there could be driven by a skew in the sample surveyed here, which consisted exclusively of climate scientists, where the variance in feelings of catastrophism is likely reduced relative to a sample of the general public (i.e., most climate researchers are *absolute* catastrophists). Even so, the set of questions that give rise to this particular predictor variable could be valuable when considering experts with broader disciplinary emphases or when surveying the public.

Moving forward, studies should include variables not accounted for in this analysis, including discipline, religiosity, sector, etc. Assumptions that 'expertise' is straightforward in an emergent domain need to be questioned, as do assumptions that more science will yield agreement about the benefits and risks of research and appropriate oversight.

Table 4.1: Existing survey research on public perceptions of geoengineering (Part 1)

Authors	Sample (geography/n)	Key findings	Date conducted	Journal
Royal Society (2009)	Great Britain / n=1,000	Mixed support for OIF. More negative perception of SAI.	?	N/A
Leiserowitz (2010)	US / n=2,030	Familiarity: added one question to survey on climate change, finding that 74% of respondents had never heard of geoengineering; only 3% had correct idea about what it is	June/July 2010	Presentation to the Asilomar International Conference on Climate Intervention Technologies
NERC/Ipsos-MORI (2010)	UK / n=65	Familiarity: similar to Leiser.	March-April 2010	N/A
Spence et al. (2010)	UK / n=1,822	Familiarity: 75% never heard/knew nothing (7% knew a fair amount or more); Support: 47% support or strongly support geoengineering approaches, with 4% opposing/strongly opposing; 50% unsure or no opinion; More support for CDR (47%) than SRM (40%); Beliefs about usefulness of new tech dominate responses vs. judgments about characteristics of tech per se	January-March 2010	N/A
Bostrom et al. (2012)	Undergrad econ and biz majors in Austria; Bangladesh; Finland; Germany; Norway; and US / n=664	Support: Only 7% would vote yes to putting dust in the atmosphere; 26% would say yes to OIF; Causal thinking has a role in climate change policy preferences (e.g., perceived effectiveness)	2009-2010 academic year	Global Environmental Change
Mercer et al. (2011)	US, Canada, UK / n=3,105	Familiarity: 8% correctly define geoengineering; 45% correctly define climate engineering; Support for research on SRM; Support contingent on ideas of deployment, optimism about scientific research, valuing benefits of SRM, and SRM as natural, while opposition is associated with hands off nature	Winter 2010	Environmental Research Letters

Table 4.2: Existing survey research on public perceptions of geoengineering (Part 2)

Authors	Sample (geography/n)	Key findings	Date conducted	Journal
Poumadere (2011)	REVIEW	Naturalness/artifice; Seriousness of climate threat brings support for radical response	N/A	Wires Climate Change
GAO (2011)	US / n=1,006	Openness to research: 50-70%; More support for mitigation than geoengineering; Governance: 65-75% public support range of actors in decision-making	July/August 2010	GAO report
Bellamy & Hulme (2011)	UK / n=287	Egalitarians perceive high risks from climate change; Many believed climate change to be capricious, irrespective of worldviews; Mitigation preferences: conventional reg and market-based; Strong fatalist narrative; ON GEO (focus groups): generally against deployment; those who favored it had hierarchist bias. Egalitarian bias = extreme concern about geo, sometimes denouncing completely. Also, no distinction between CDR and SRM was made by groups.	?	Weather, Climate, and Society
Pidgeon (2012)				
Borick (2012)	US / n=887	Effectiveness: only 30% are confident that scientists can alter climate in ways that limits problems; Framing matters; SRM will lead to more harm than good (∼70%); Climate change deniers are more negative about geoengineering than those who see climate change as happening	11-Dec	Issues in Governance Studies
Kahan et al. (2015)	US, UK / n=3,000	General ambivalence; Experimental had small effect: concern about climate change risks was higher in geo than control condition; However, ECs were more concerned about risks than HI, with polarization higher in US population than UK	July-August 2011	Annals of the American Academy of Political and Social Science

Table 4.3: Existing survey research on public perceptions of geoengineering (Part 3)

Authors	Sample (geography/n)	Key findings	Date conducted	Journal
Corner & Pidgeon (2014)	UK / n=610	People convinced by moral hazard argument (vs. no moral hazard); People who are skeptical and self-enhancing values were more likely to admit to moral hazard	Summer 2013	RSTA
Wright et al. (2014)	Australia (n=1,006); New Zealand (n=1,022)	Publics most frequently choose 5 negative attributes, and least frequently choose 5 positive attributes; Two associations: unknown effects and risky account for 40% of associations; Highest positive association for CDR, lowest for SRM	?	Nature Climate Change
Corner & Pidgeon (2015)	UK / n=412	Framing geoengineering as natural increased likeliness to support geoengineering; Views about relationship between geoengineering and nature predicted support	Summer 2013	Climatic Change
Merk et al. (2015)	Germany / n=1,040	Broad approval for lab research, field research trickier; Acceptance is associated with belief that climate change is serious problem & belief in human control of nature; Strong objections include hands off nature	12-Dec	Climatic Change
Merk (2016)	Germany/n=658	People don't reduce mitigation when told that SAI might partially address climate change; instead, information about SAI = more mitigation than those who haven't heard of it	?	Environmental Research Letters
Gregory (2016)	US /n=910	More concern about climate change = more support for climate engineering & investment in Res, as long as they don't overly manipulate nature. This support is offered even when they view risks as more likely than benefits; Those least concerns about climate change will still support some geoengineering, are distrustful of government, support Res, favor infrastructure investment	2013	PNAS
Mahajan (forthcoming)				

Characteristic	Options	%	#	Characteristic	Options	%	#
Gender	Female	29.4	79	Education	Post-graduate degree	97.8	262
	Male	70.1	188		College	1.9	5
	Declined response	*	1		High-school or less	*	1
Age	18-29	5.6	15	Sector	University	67.9	182
	30-49	53.3	143		Government	13.1	35
	50-64	31.0	83		Non-profit	9.3	25
	65+	10.0	27		Private sector	4.5	12
					Other	5.2	14
Ethnic background	White/Caucasian	75.0	201				
	Asian	9.0	24	Discipline	Ecology	13.8	37
	Hispanic/Latino	3.7	10		Engineering	12.7	34
	African American	1.1	3		Interdisciplinary	11.9	32
	Native American	*	1		Economics	11.2	30
	Other	10.4	28		Geography	7.5	20
	Declined response	*	1		Biology	4.9	13
					Atmospheric sciences	4.9	13
Geography	Within US	31.3	84		Forestry	4.5	12
	Outside US	68.7	184		Policy	3.7	10
					Hydrology	1.9	5
Household income	Less than $30,000	12.7	34		Mathematics	1.9	5
	$30,000 - $49,999	12.3	33		Physics	1.5	4
	$50,000 - $99,999	25.0	67		Oceanography	1.1	3
	$100,000 - $249,999	39.2	105		Chemistry	*	1
	More than $250,000	7.8	21		Other social sciences	6.3	17
	Declined response	3.0	8		Other physical sciences	2.2	6
					Other	9.3	25
Political ideology	Very liberal	21.3	57		Declined Response	*	1
	Liberal	46.3	124				
	Moderate	26.9	72	Experience	0-2 years	3.4	9
	Conservative	3.7	10		3-7 years	25.0	67
	Very conservative	*	1		8-12 years	31.7	85
	Declined response	1.5	4		13-17 years	14.2	38
					18-22 years	10.1	27
Religious affiliation	Atheist	19.8	53		23-27 years	6.7	18
	Agnostic	19.0	51		28-32 years	4.1	11
	Christian	34.3	92		33-42 years	3.0	8
	Buddhist	5.2	14		More than 42 years	1.5	4
	Muslim	4.1	11		Declined response	*	1
	Jewish	3.0	8				
	Declined response	3.0	8	Cultural worldview	EC	29.5	79
					EI	20.5	55
Religion	Not at all important	47.4	127		HC	20.5	55
	Slightly important	23.1	62		HI	29.5	79
	Moderately important	14.9	40				
	Very important	10.1	27				
	Extremely important	4.5	12				

Table 4.4: Summary table of respondents (n=268)

Table 4.5: Cultural worldview short-form scale questions

Individualism scale	• The government interferes too much in our everyday lives. • Sometimes government needs to make laws that keep people from hurting themselves. • It's not the government's business to try to protect people from themselves. • The government should stop telling people how to live their lives. • The government should do more to advance society's goals, even if that means limiting the freedom and choices of individuals. • Government should put limits on the choices individuals can make so they don't get in the way of what's good for society.
Hierarchy scale	• We have gone too far in pushing equal rights in this country. • Our society would be better off if the distribution of wealth was more equal. • We need to dramatically reduce inequalities between the rich and the poor, whites and people of color, and men and women. • Discrimination against minorities is still a very serious problem in our society. • It seems like blacks, women, homosexuals, and other groups don't want equal rights, they want special rights just for them. • Society as a whole has become too soft and feminine.

4.5 Supplementary Materials

Response Variable Derivation

To derive the set of five predictor variables, a series of factor analyses were performed on the 18 question geoengineering battery (Table 4.6). Three-, four-, and five-factor analyses were conducted, and the latter was ultimately selected as the most explanatory and the most interpretable (Table 4.7). To derive the continuous variables associated with each of the factors, all of the questions with loading values equal to or greater than 0.3 were used, and their values (ranging from 1 to 6 on the Likert scale) were multiplied by the associated loading. The final response variables represent the sums of the sets of values that loaded onto each factor. For example, in the case of the moral hazard factor, only questions 1 and 2 were loaded with weights > 0.3. Thus, the Likert responses to these two questions were multiplied by the associated loading values and summed to give the final moral hazard response value for each individual.

Predictor Variable Derivation

The following sections outline the methods used to derive the candidate variables that were used in the regression models presented above. In each case, a simple group means comparison (i.e., t-test) was conducted to determine the strength of the predictor with regard to each geoengineering-related question. These group means tables are illuminating, but they must be viewed as independent considerations of each predictor. As such, potential correlations between these candidate predictors are not directly incorporated. Thus, the results in one group means table might reflect variation that is described more effectively by another of the predictor variables, but this dynamic is not accounted for explicitly.

Gender

Gender was treated as a simple binary measure (male or female). The results of a group means analysis are presented in Table 4.8.

Geography

Geography was treated as a simple binary based on the self-expressed country of origin and country of residence of each respondent. In many cases, multiple countries would be expressed as responses to either of these questions, but individuals were categorized as 'Within U.S.' if the United States appeared at any point in the list of countries. All others were treated as 'Outside U.S.' in the regression analysis. The results of a simple group means comparison are presented in Table 4.9.

Familiarity

A binomial measure of familiarity was derived based on responses to the question "How much have you heard about geoengineering" (Figure 4.4). Those responding with 'some' or 'a lot' were considered to be familiar, whereas those responding with 'nothing' or 'just a little' were treated as unfamiliar in subsequent analyses. See Table 4.10 for an independent evaluation of the role of familiarity in the responses to the 18 geoengineering-related questions.

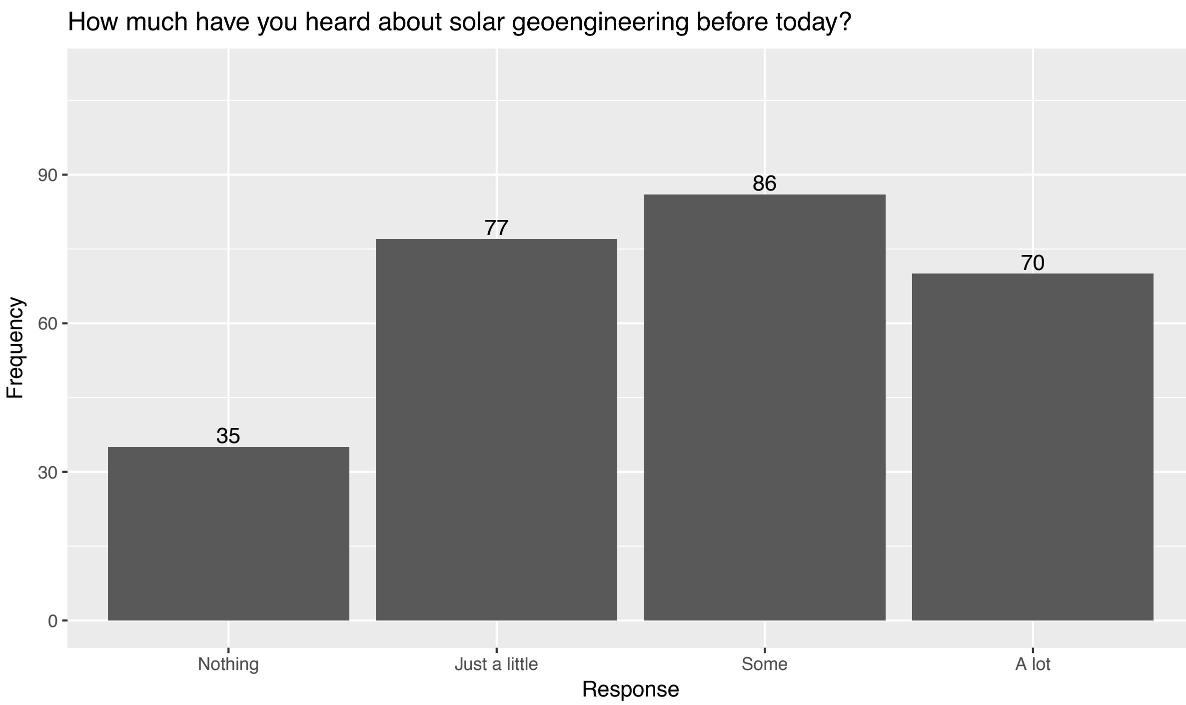

Figure 4.4: **Familiarity with geoengineering**

Cultural worldviews

Cultural worldview measures aim to measure latent or unobservable dispositions, for which the scales used here are observable indicators. We measured respondents' cultural values with items used in previous studies of cultural cognition [124, 123, 120]. The items characterize worldviews along two cross-cutting dimensions: hierarchy-egalitarianism (hierarchy) and individualism-communitarianism (individualism). Hierarchy items reflect "attitudes toward social order that connect authority to stratified social roles based on highly conspicuous and largely fixed characteristics such as gender, race, and class" [120]. Individualism items "indicate attitudes toward social orderings that expect individuals to secure their own well-being without assistance toward social orderings that expect individuals to secure their own well-being without assistance or interference from society versus those that assign society the obligation to secure collective welfare and the power to override competing individual interests" (*ibid*).

Respondents indicated agreement or disagreement on a six-point scale to the short-form versions of both the Hierarchy and Individualism scales (Table **??**). These two dimensions formed reliable scales according to Cronbach's alpha (α), which is a measure of scale reliability that ranges from 0.0 to 1.0; a score of 0.70 signifies that a set of indicators display the degree of intercorrelation necessary to measure some underlying latent variable [125]. In our case, both Hierarchy and Individualism met this threshold ($\alpha = 0.79$ and $\alpha = 0.74$, respectively). Though a two-factor analysis revealed that the 12 questions did not load as cleanly onto two separate axes as in the case of the U.S. public, we split the questions according to [125] and simply used the loading values associated with our factor analysis (Table 4.12). Unlike in the case of the response variables, all of the weights were maintained in deriving the two worldview scores, even if they did not meet the 0.3 threshold. In this way, we obtained analogous hierarchy (ranging from hierarchical to egalitarian) and individualism (ranging from individualist to communitarian) scales, but certain questions in the battery played relatively small roles in deriving the final Hierarchy and Individualism scores. Just as in the case of climate catastrophism, these two variables were transformed into simple binary predictors using the median values along each axis. The group means tables for both Hierarchism (Table 4.13) and Individualism (Table 4.14) are presented below.

ISRPM and climate catastrophism

Scholars in cultural cognition argue that members of the general public have a general affective orientation toward risks (including climate change) that shapes all of their more particular beliefs about it. One way to measure this affective orientation is via the industrial strength risk perception measure, or ISRPM (Table 4.15). The claim is that ISRPM will correlate strongly with more specific questions about putative risk sources, and can then be appropriately probed for sources of variance that can help explain who believes what and why about the putative risk source. ISRPM is also a useful validator of measures we suspect are reflecting the same latent state. In our case, α of the ISRPM battery was 0.80.

We developed 16 items aimed to evaluate general attitudes about climate risk and attribution. Five of those were used to generate a measure of relative climate catastrophism (Table 4.16). We might expect that it is measuring the same latent attitude as ISRPM, although perhaps more precisely, given the α of 0.78. A single-factor analysis was used to determine the appropriate loading values for each question and a single continuous metric was derived (Table 4.17). Using the median of this metric, the entire sample was divided into catastrophists (above the median) and non-catastrophists (below the median) for subsequent analyses. This procedure resulted in 13 individuals whose scores could not be accurately calculated due to a failure to respond to one of more of the questions in the catastrophism battery. See Table 4.18 for a comparison of the two groups in terms of their responses to the

18 geoengineering-related questions.

Partisanship & political ideology

99 of our respondents were from the US (in that either the US is their country of origin or they are currently residing in the US). 78 identified as liberal or very liberal (50 were liberal, and 28 were very liberal), 18 identified as moderate, and 2 identified as conservative (0 were very conservatives). 28 self-identified as strong democrats, 28 democrats, 31 independent leaning democrat, 6 independent leaning republican, no republicans, and no strong republicans. If we are to include respondents from outside of the US as well, (which may raise challenges given the US-specific nature of the political categories), 181 respondents identified as very liberal or liberal, 72 self-identified as moderate, and 11 identified as conservative or very conservative. Using both domestic and international respondents in the regression models, we created a variable with three levels and treated the moderates as the baseline for comparison.

Table 4.6: Responses to battery of 18 questions on Geoengineering (n=268)

Question	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly Agree
Individual moral hazard	9	60	57	73	54	15
Politicians moral hazard	5	40	33	83	64	43
Deployment unpredictable	1	14	12	59	101	81
Favors indoor research	10	17	27	86	93	35
Favors outdoor research	25	32	56	78	55	22
No new oversight unless large-scale	51	58	46	61	41	11
No new oversight for all research	2	16	21	72	85	72
Self-regulation sufficient	67	75	69	35	17	5
Research results in lock-in	6	46	74	83	48	11
Experts decide	78	78	49	39	18	6
Representation in science important	2	16	20	66	89	75
Representation in science unimportant	4	13	30	81	83	57
Uncertainty means never deploy	7	41	40	62	76	42
Solar geo requires technocracy	35	60	72	56	34	11
Rule by experts undesirable	14	35	66	70	56	27
Fossil fuel interests benefit	3	17	40	97	77	34
Deployment risks outweigh benefits	5	16	38	75	82	52
Research benefits outweigh risks	19	43	64	79	46	17

Table 4.7: Factor loading across 18 geoengineering-related questions

Question	Factor1	Factor2	Factor3	Factor4	Factor5
Individual moral hazard		0.87			
Politicians moral hazard		0.82			
Deployment unpredictable			0.42		
Favors indoor research	0.88				
Favors outdoor research	0.76		-0.37		
No new oversight unless large-scale	0.52				
No new oversight for all research				0.83	
Self-regulation sufficient				-0.35	0.52
Research results in lock-in	-0.32			0.33	
Experts decide					0.46
Representation in science important				0.32	
Representation in science unimportant					
Uncertainty means never deploy			0.7		
Solar geo requires technocracy					0.61
Rule by experts undesirable					-0.38
Fossil fuel interests benefit					
Deployments risks outweigh benefits			0.48		
Research benefits outweigh risks	0.43				

Table 4.8: Gender-based group means across 18 geoengineering questions (n=268); p values are based on a two-sample t-test and significance below the $\alpha = 0.05$ threshold is indicated by an asterisk. The minimum value for each question was 1 (indicating strong disagreement) and the maximum possible value was 6 (indicating strong agreement).

Question	Female	Male	p	sig
Individual moral hazard	3.61	3.53	0.66	0
Politicians moral hazard	4.23	4.02	0.25	0
Deployment unpredictable	5.05	4.73	0.03	*
Favors indoor research	4.06	4.35	0.08	0
Favors outdoor research	3.03	3.9	0	*
No new oversight unless large-scale	2.68	3.23	0	*
No new oversight for all research	4.95	4.5	0	*
Self-regulation sufficient	2.25	2.64	0.02	*
Research results in lock-in	3.76	3.51	0.09	0
Experts decide	2.32	2.53	0.23	0
Representation in science important	5.03	4.53	0	*
Representation in science unimportant	4.28	4.57	0.08	0
Uncertainty means never deploy	4.52	3.88	0	*
Solar geo requires technocracy	3.24	3.04	0.3	0
Rule by experts undesirable	3.7	3.77	0.68	0
Fossil fuel interests benefit	4.46	4.14	0.03	*
Deployment risks outweigh benefits	4.57	4.3	0.1	0
Research benefits outweigh risks	3.35	3.6	0.18	0

Table 4.9: Geography-based group means across 18 geoengineering questions (n=268); p values are based on a two-sample t-test and significance below the $\alpha = 0.05$ threshold is indicated by an asterisk. The minimum value for each question was 1 (indicating strong disagreement) and the maximum possible value was 6 (indicating strong agreement). Respondents who indicated that they were currently residing in the United States or that it was their country of origin were considered "Within US".

Question	Outside.US	Within.US	p	sig
Individual moral hazard	3.55	3.55	0.97	0
Politicians moral hazard	4.09	4.06	0.85	0
Deployment unpredictable	4.77	4.93	0.28	0
Favors indoor research	4.16	4.5	0.03	*
Favors outdoor research	3.59	3.76	0.33	0
No new oversight unless large-scale	2.99	3.2	0.28	0
No new oversight for all research	4.77	4.33	0.01	*
Self-regulation sufficient	2.58	2.43	0.34	0
Research results in lock-in	3.78	3.13	0	*
Experts decide	2.46	2.51	0.74	0
Representation in science important	4.74	4.52	0.15	0
Representation in science unimportant	4.54	4.36	0.21	0
Uncertainty means never deploy	4.14	3.89	0.19	0
Solar geo requires technocracy	3.29	2.69	0	*
Rule by experts undesirable	3.63	4	0.03	*
Fossil fuel interests benefit	4.26	4.17	0.51	0
Deployment risks outweigh benefits	4.39	4.36	0.86	0
Research benefits outweigh risks	3.39	3.83	0.01	*

Table 4.10: Familiarity-based group means across 18 geoengineering questions (n=268); p values are based on a two-sample t-test and significance below the $\alpha = 0.05$ threshold is indicated by an asterisk. The minimum value for each question was 1 (indicating strong disagreement) and the maximum possible value was 6 (indicating strong agreement). Respondents who claimed to have heard either "Some" or "A lot" about solar geoengineering were considered "Familiar" whereas those who claimed to have heard "Nothing" or "Just a little" were considered "Unfamiliar".

Question	Familiar	Unfamiliar	p	sig
Individual moral hazard	3.44	3.71	0.08	0
Politicians moral hazard	3.96	4.25	0.08	0
Deployment unpredictable	4.87	4.75	0.37	0
Favors indoor research	4.33	4.19	0.36	0
Favors outdoor research	3.56	3.76	0.24	0
No new oversight unless large-scale	3.03	3.11	0.65	0
No new oversight for all research	4.62	4.65	0.83	0
Self-regulation sufficient	2.42	2.69	0.1	0
Research results in lock-in	3.56	3.59	0.86	0
Experts decide	2.35	2.65	0.07	0
Representation in science important	4.55	4.85	0.04	*
Representation in science unimportant	4.38	4.62	0.09	0
Uncertainty means never deploy	4.15	3.95	0.23	0
Solar geo requires technocracy	2.89	3.39	0	*
Rule by experts undesirable	3.99	3.41	0	*
Fossil fuel interests benefit	4.19	4.29	0.42	0
Deployment risks outweigh benefits	4.51	4.19	0.03	*
Research benefits outweigh risks	3.53	3.53	0.99	0

Table 4.11: Responses to battery of twelve questions to evaluate Cultural Worldview (n=268)

Question	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly Agree
IINTRSTS	44	79	64	53	24	4
CHARM	4	6	7	85	108	58
IPROTECT	50	103	69	32	11	3
IPRIVACY	29	76	88	49	20	6
CPROTECT	14	21	44	104	61	24
CLIMCHOI	12	21	53	108	50	24
HEQUAL	116	89	21	21	19	2
EWEALTH	5	4	6	26	101	126
ERADEQ	2	6	7	41	79	133
EDISCRIM	3	4	11	45	89	116
HREVDIS2	127	74	26	17	15	9
HFEMININ	140	68	24	18	13	5

Table 4.12: Factor loading across 12 worldview questions

Question	Factor1	Factor2
IINTRSTS	0.61	-0.27
CHARM	-0.15	0.58
IPROTECT	0.21	-0.39
IPRIVACY	0.39	-0.3
CPROTECT	0.01	0.78
CLIMCHOI	-0.01	0.7
HEQUAL	0.75	-0.06
EWEALTH	-0.36	0.42
ERADEQ	-0.38	0.42
EDISCRIM	-0.42	0.27
HREVDIS2	0.7	-0.01
HFEMININ	0.74	-0.06

Table 4.13: Hierarchism-based group means across 18 geoengineering questions (n=268); p values are based on a two-sample t-test and significance below the $\alpha = 0.05$ threshold is indicated by an asterisk. The minimum value for each question was 1 (indicating strong disagreement) and the maximum possible value was 6 (indicating strong agreement). Respondents were assigned to "Hierarchist" or "Egalitarian" based on their responses to a six-question battery within the worldview section.

Question	Egalitarian	Hierarchist	p	sig
Individual moral hazard	3.57	3.53	0.78	0
Politicians moral hazard	4.11	4.05	0.71	0
Deployment unpredictable	5.07	4.57	0	*
Favors indoor research	4.19	4.35	0.27	0
Favors outdoor research	3.45	3.84	0.02	*
No new oversight unless large-scale	2.84	3.28	0.01	*
No new oversight for all research	4.71	4.56	0.3	0
Self-regulation sufficient	2.34	2.72	0.01	*
Research results in lock-in	3.49	3.66	0.2	0
Experts decide	2.31	2.64	0.04	*
Representation in science important	4.75	4.6	0.28	0
Representation in science unimportant	4.28	4.68	0.01	*
Uncertainty means never deploy	4.15	3.98	0.31	0
Solar geo requires technocracy	2.88	3.32	0.01	*
Rule by experts undesirable	3.83	3.66	0.32	0
Fossil fuel interests benefit	4.27	4.19	0.59	0
Deployment risks outweigh benefits	4.39	4.37	0.88	0
Research benefits outweigh risks	3.41	3.64	0.15	0

Table 4.14: Individualism-based group means across 18 geoengineering questions (n=268); p values are based on a two-sample t-test and significance below the $\alpha = 0.05$ threshold is indicated by an asterisk. The minimum value for each question was 1 (indicating strong disagreement) and the maximum possible value was 6 (indicating strong agreement). Respondents were assigned to "Communitarian" or "Individualist" based on their responses to a six-question battery within the worldview section.

Question	Communitarian	Individualist	p	sig
Individual moral hazard	3.6	3.5	0.51	0
Politicians moral hazard	4.15	4.01	0.41	0
Deployment unpredictable	4.9	4.74	0.22	0
Favors indoor research	4.31	4.22	0.55	0
Favors outdoor research	3.66	3.62	0.79	0
No new oversight unless large-scale	2.91	3.21	0.1	0
No new oversight for all research	4.79	4.48	0.03	*
Self-regulation sufficient	2.39	2.68	0.06	0
Research results in lock-in	3.54	3.61	0.6	0
Experts decide	2.34	2.61	0.09	0
Representation in science important	4.8	4.55	0.09	0
Representation in science unimportant	4.45	4.51	0.64	0
Uncertainty means never deploy	4.25	3.87	0.02	*
Solar geo requires technocracy	3	3.2	0.22	0
Rule by experts undesirable	3.87	3.62	0.12	0
Fossil fuel interests benefit	4.34	4.13	0.13	0
Deployment risks outweigh benefits	4.37	4.38	0.96	0
Research benefits outweigh risks	3.5	3.55	0.75	0

Table 4.15: Responses to battery of 18 questions on ISRPM (n=268)

Question	No risk at all	Very low risk	Between low and moderate risk	Moderate Risk	Between moderate and high risk	High Risk	Very high risk
Private gun	2	11	32	45	60	60	58
Global warming	1	3	3	18	41	64	138
Nuclear power	1	36	49	60	47	40	35
GM food	15	70	64	43	43	25	8
Air pollution	0	3	9	33	66	110	47
Hazardous waste	0	7	40	56	70	71	24
Medical X-rays	13	125	62	43	16	9	0
Domestic terror	0	98	60	41	24	29	16
Fluoridation	69	95	38	27	11	19	6
Second-hand smoke	1	27	65	80	44	41	10
Illegal immigration	50	122	39	31	16	7	3
Marijuana legalization	71	99	39	27	14	12	6
Prostitution legalization	80	103	36	22	10	11	4
Fracking	1	21	50	66	61	49	20
Excessive taxes	40	75	66	46	19	20	1
Environmental regulations	103	110	32	16	5	1	1
Birth control	184	64	8	7	5	0	0
Radiation	23	105	48	37	15	20	11

Table 4.16: Responses to battery of five questions on Climate Catastrophism (n=268)

Question	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly Agree
Estimate of climate sensitivity above 4.5 degrees	6	52	51	72	60	17
Likely sea level rise due to melting icecaps	4	7	22	57	105	72
Likely greenhouse gas release from Arctic	4	20	38	75	93	33
Likely permanent loss of Arctic sea ice	2	16	29	74	102	41
Likely climate change will disrupt food supply	4	15	22	71	89	66

Table 4.17: Factor loading across 5 climate catastrophism questions

Question	Factor1
Estimate of climate sensitivity above 4.5°	0.54
Likely sea level rise due to melting icecaps	0.59
Likely greenhouse gas release from Arctic	0.72
Likely permanent loss of Arctic sea ice	0.68
Likely climate change will disrupt food supply	0.71

Table 4.18: Climate-catastrophism-based group means across 18 geoengineering questions (n=268); p values are based on a two-sample t-test and significance below the $\alpha = 0.05$ threshold is indicated by an asterisk. The minimum value for each question was 1 (indicating strong disagreement) and the maximum possible value was 6 (indicating strong agreement). Catastrophism was determined based on a median split following a single-factor analysis of the five associated questions. Those above the median value were treated as "Catastrophists" whereas those below the median were considered "Non-catastrophists". Note that this median value is entirely unrelated to the values displayed below, as responses to the climate questions were multiplied by the loadings that emerged from the factor analysis.

ID	Non-catastrophist	Catastrophist	p	sig
Individual moral hazard	3.37	3.76	0.02	*
Politicians moral hazard	3.8	4.35	0	*
Deployment unpredictable	4.72	4.92	0.14	0
Favors indoor research	4.41	4.11	0.05	*
Favors outdoor research	3.8	3.51	0.09	0
No new oversight unless large-scale	3.26	2.87	0.04	*
No new oversight for all research	4.41	4.83	0	*
Self-regulation sufficient	2.72	2.37	0.03	*
Research results in lock-in	3.33	3.83	0	*
Experts decide	2.61	2.35	0.12	0
Representation in science important	4.54	4.79	0.09	0
Representation in science unimportant	4.47	4.5	0.85	0
Uncertainty means never deploy	3.8	4.32	0	*
Solar geo requires technocracy	3.15	3.02	0.46	0
Rule by experts undesirable	3.7	3.83	0.41	0
Fossil fuel interests benefit	3.99	4.46	0	*
Deployment risks outweigh benefits	4.14	4.61	0	*
Research benefits outweigh risks	3.62	3.43	0.24	0

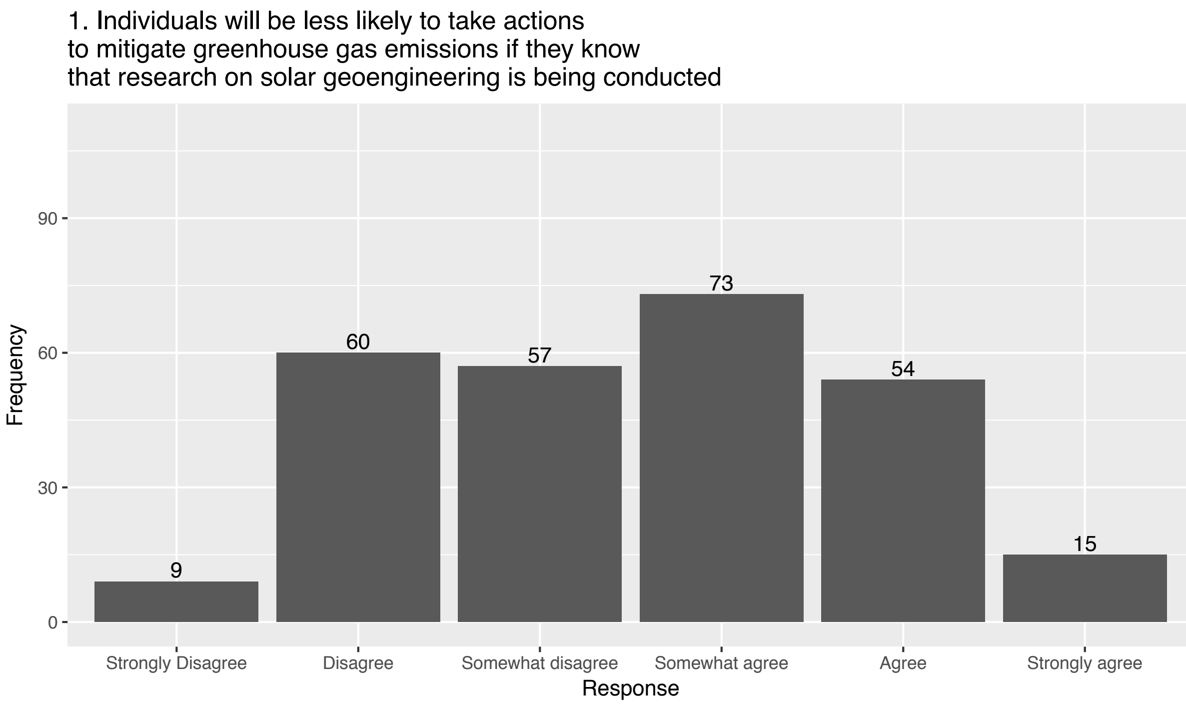

Figure 4.5: **Individual Moral hazard**

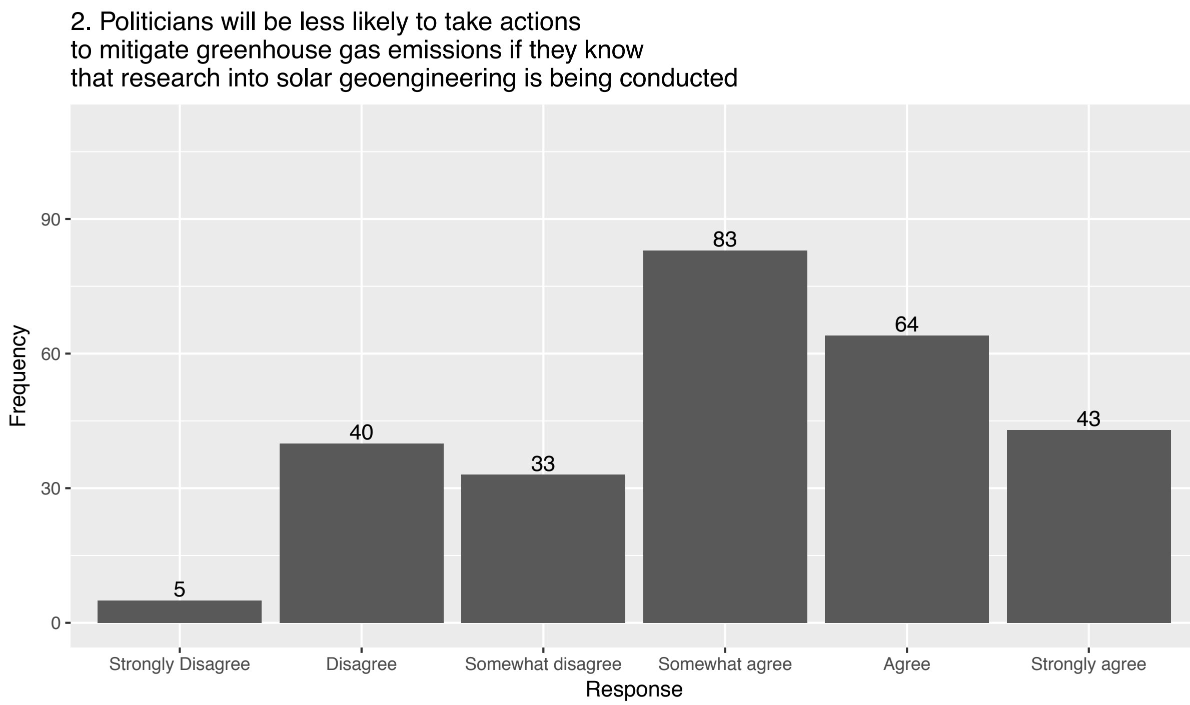

Figure 4.6: **Politician Moral hazard**

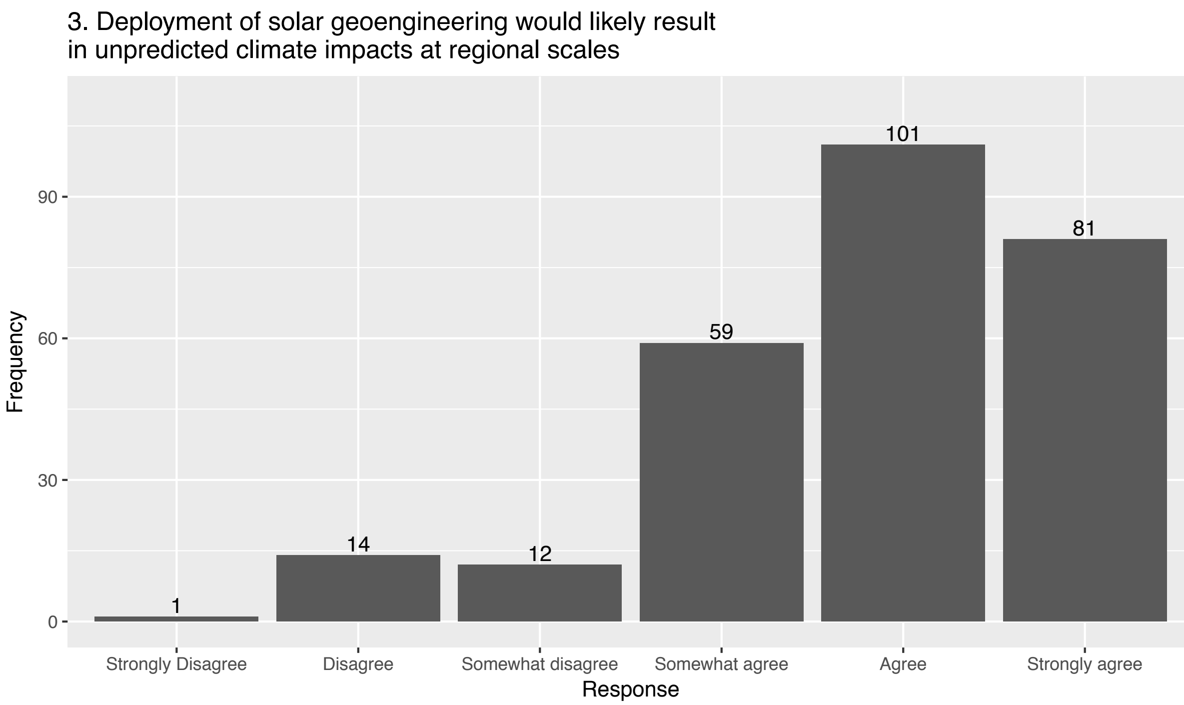

Figure 4.7: **Unpredictable impacts**

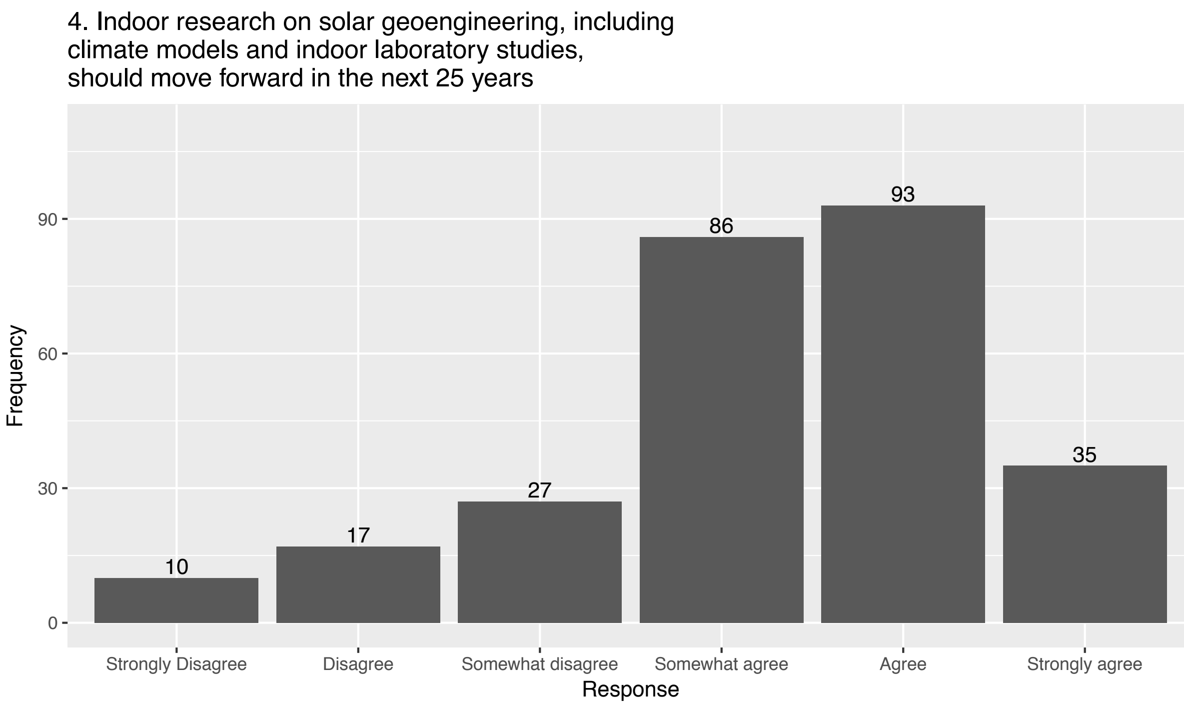

Figure 4.8: **Indoor research**

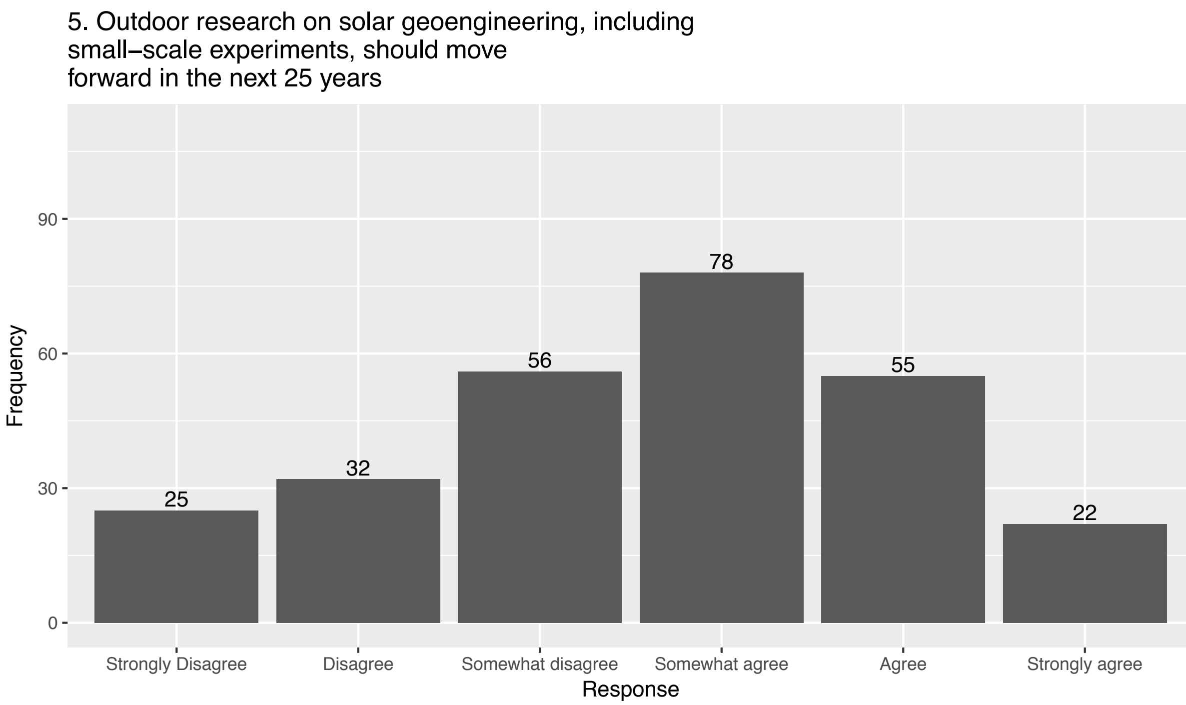

Figure 4.9: **Outdoor research**

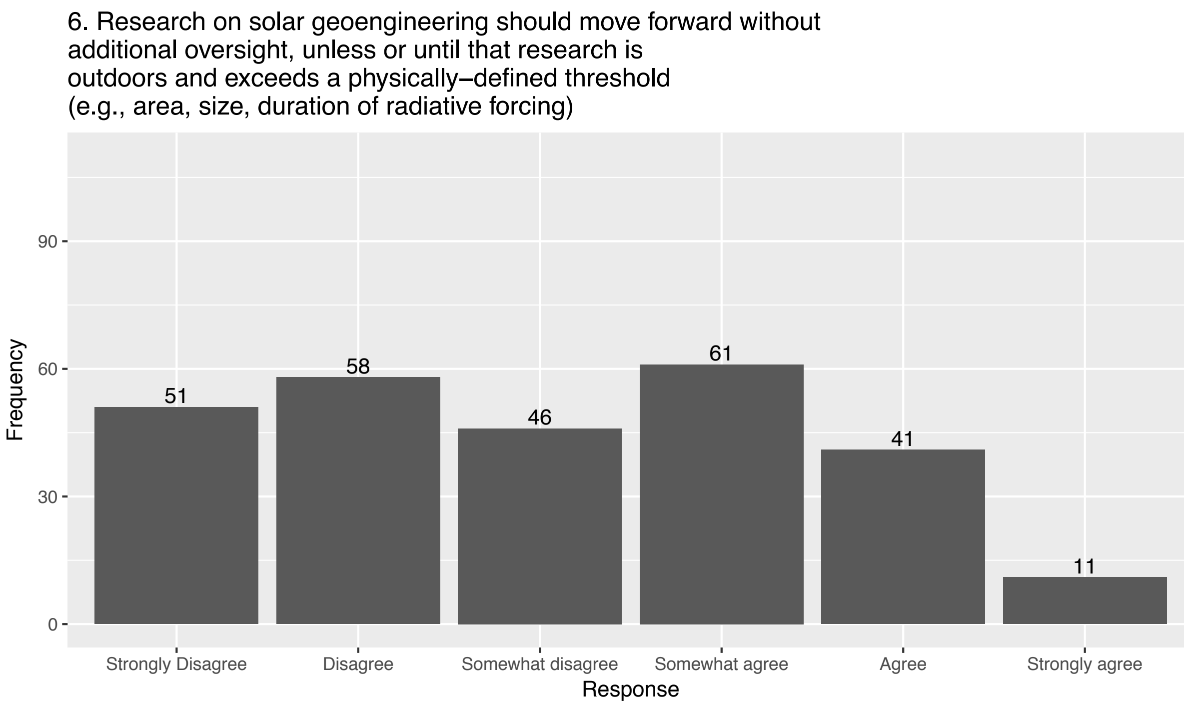

Figure 4.10: **Physical thresholds**

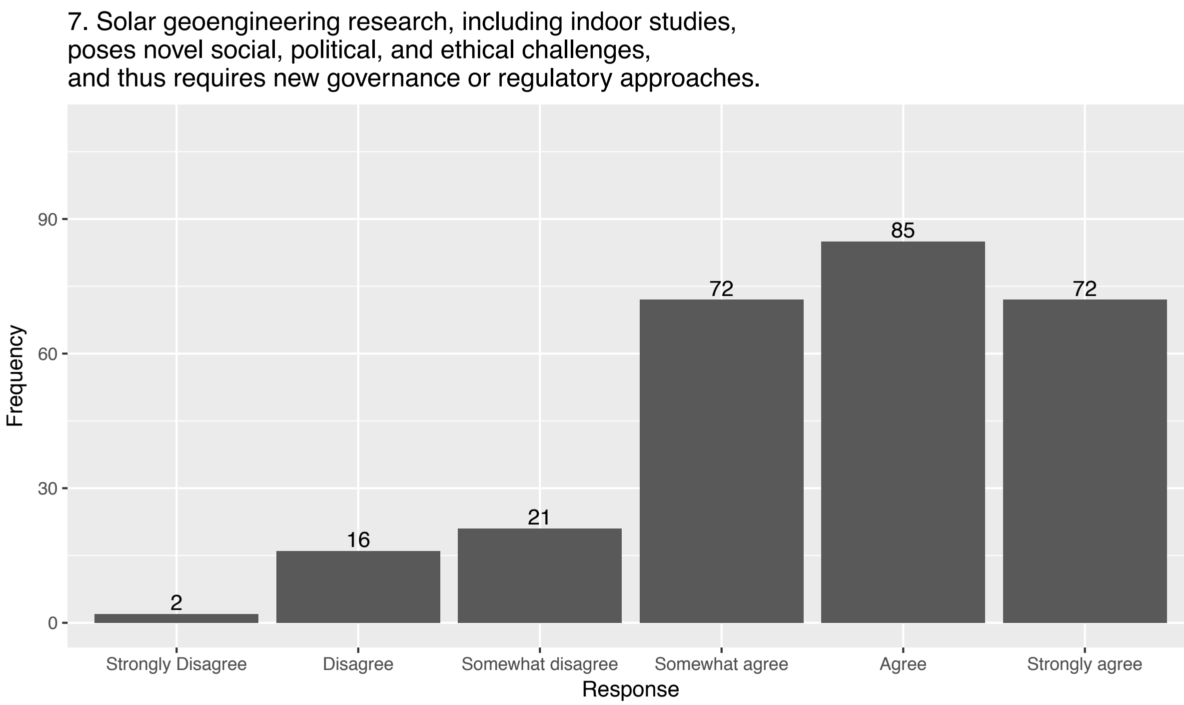

Figure 4.11: **New governance for all research**

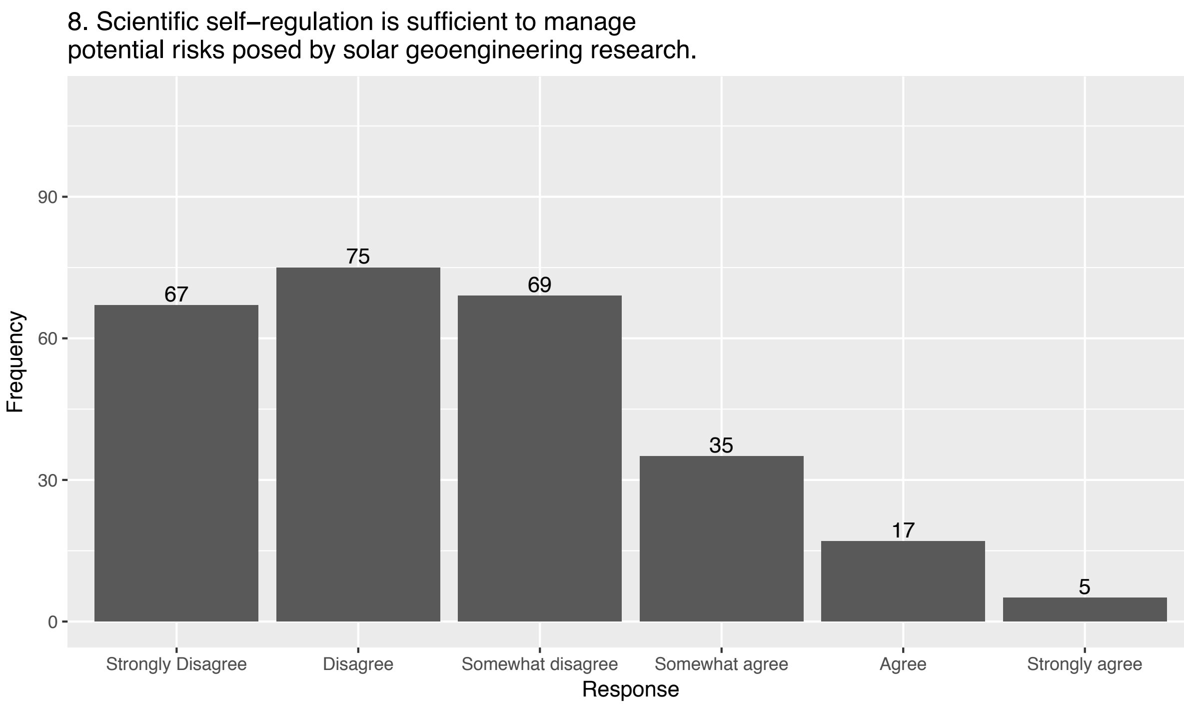

Figure 4.12: **Scientific self-governance is sufficient**

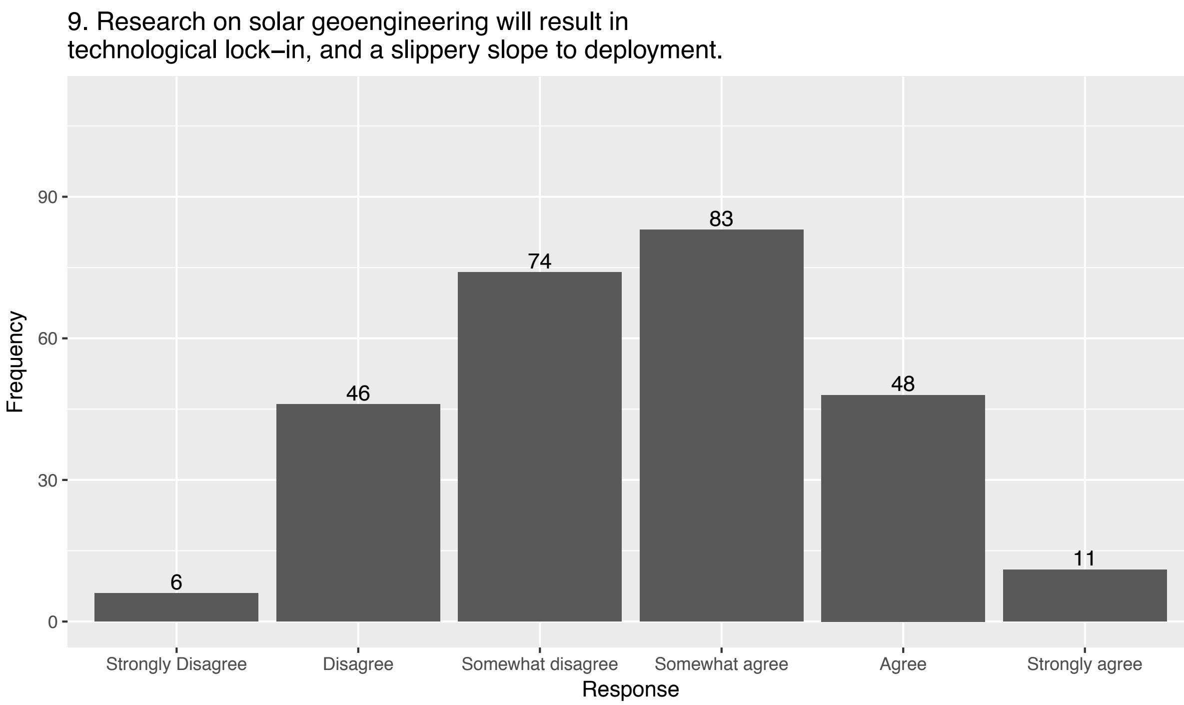

Figure 4.13: **Lock-in & Slippery Slope**

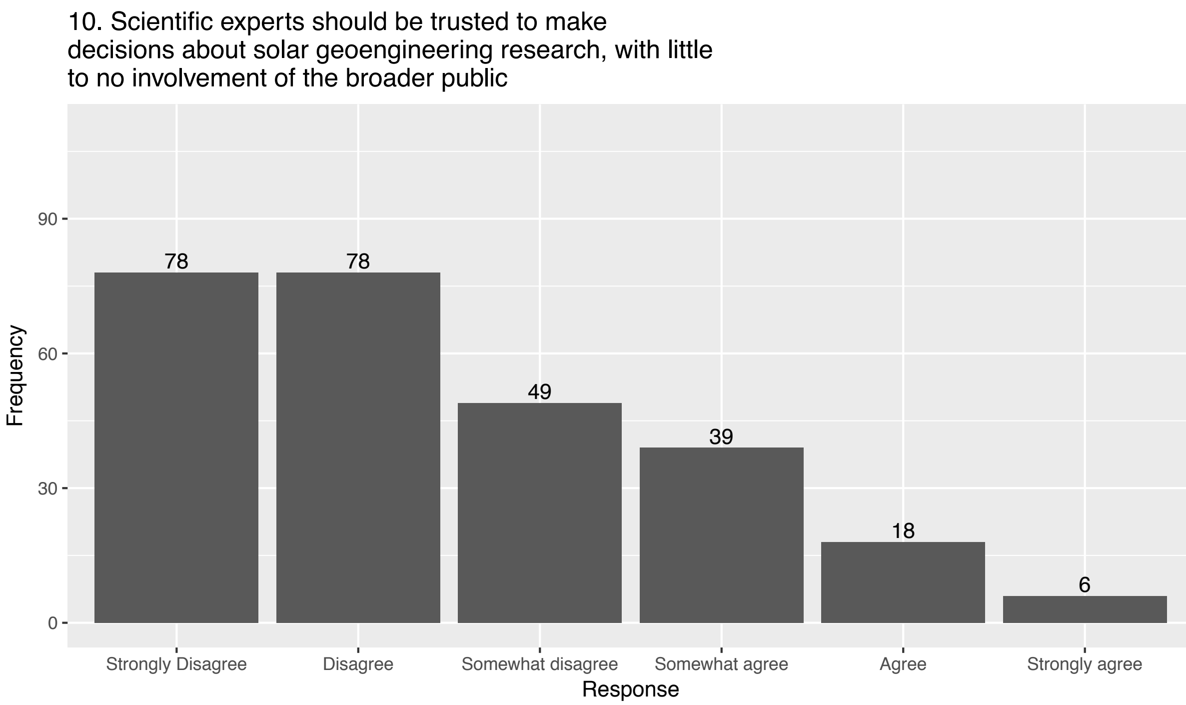

Figure 4.14: **No public involvement in decisions**

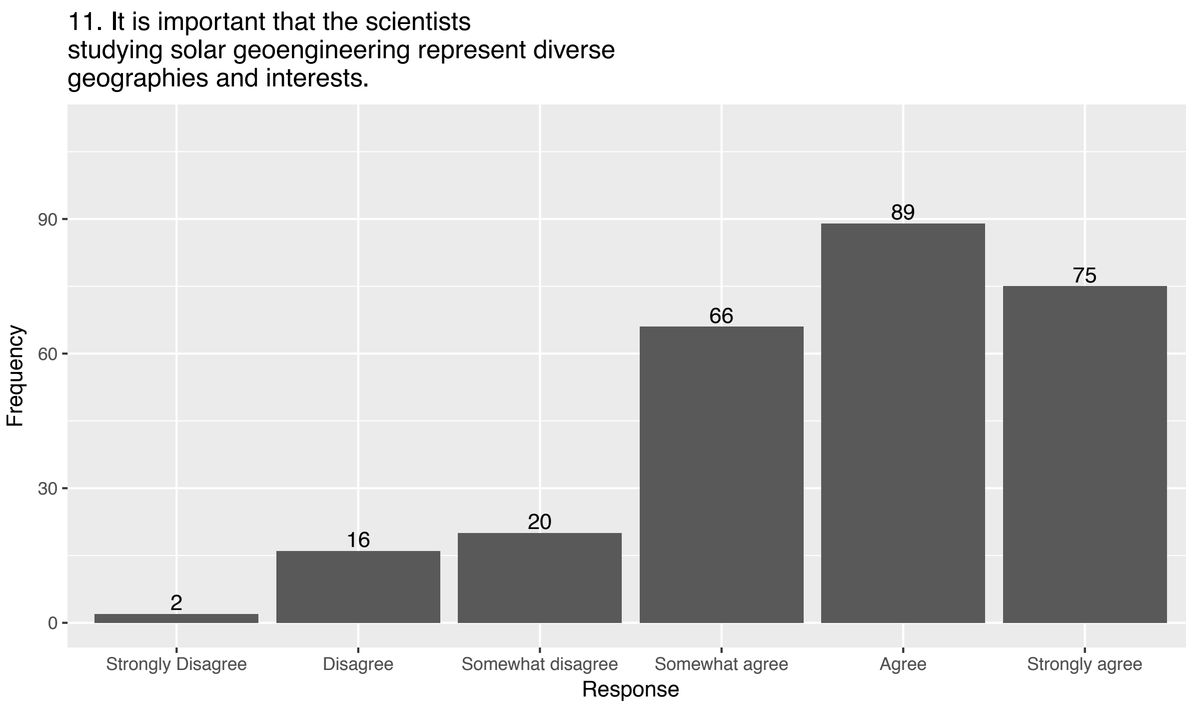

Figure 4.15: **Diverse knowledge production**

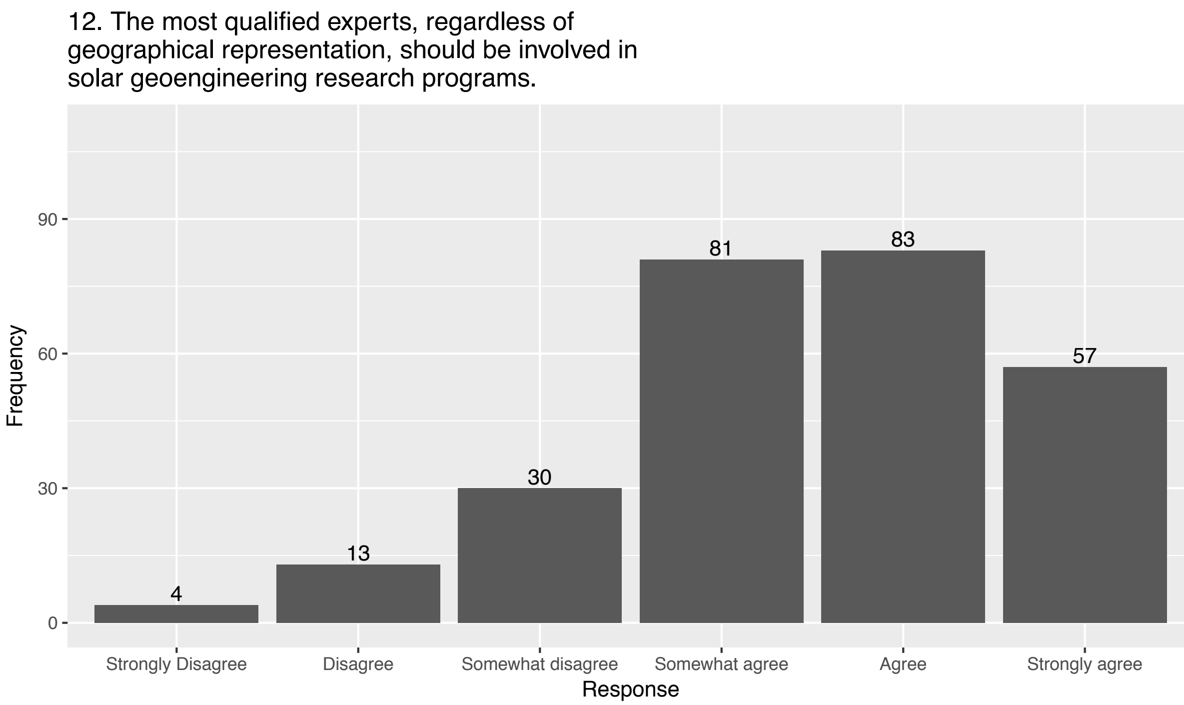

Figure 4.16: **Meritocracy**

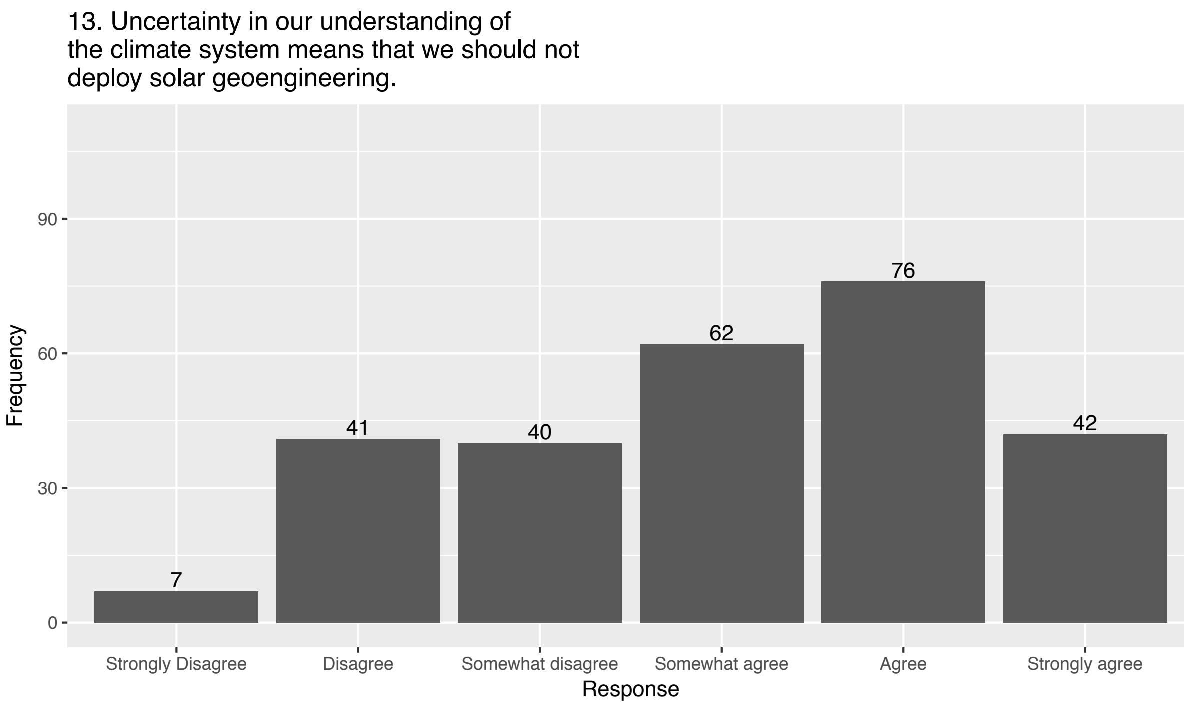

Figure 4.17: **Uncertainty no deployment**

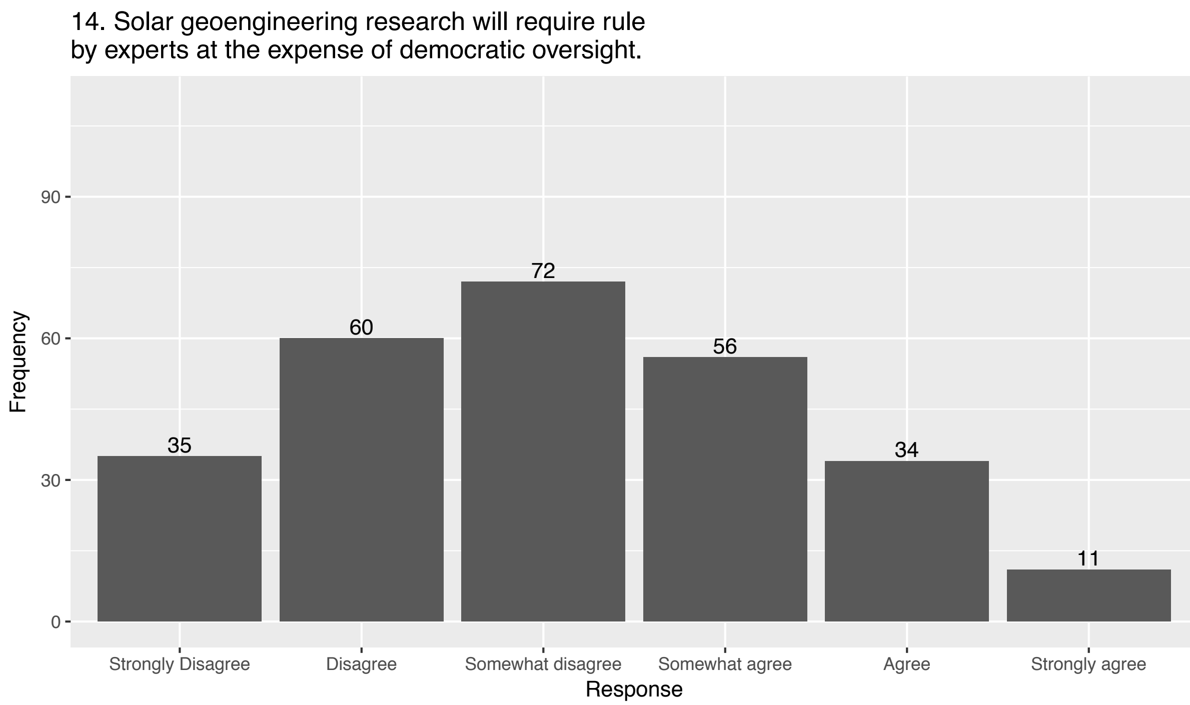

Figure 4.18: **Technocracy**

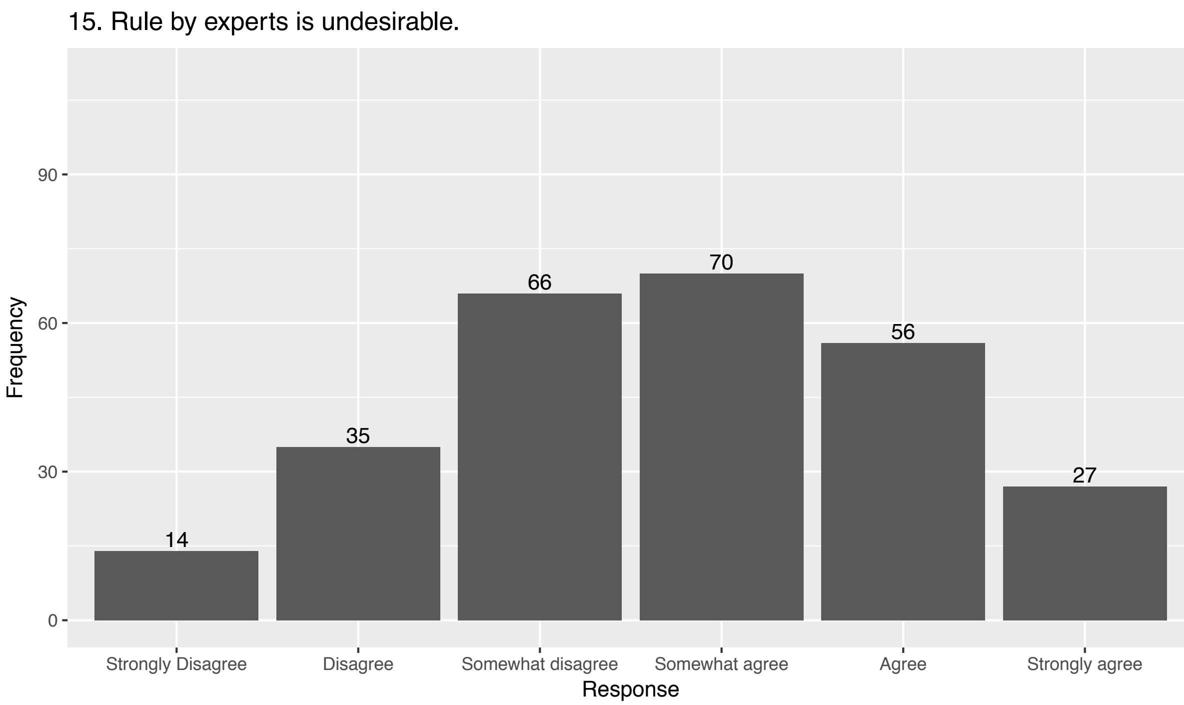

Figure 4.19: **Technocracy undesirable**

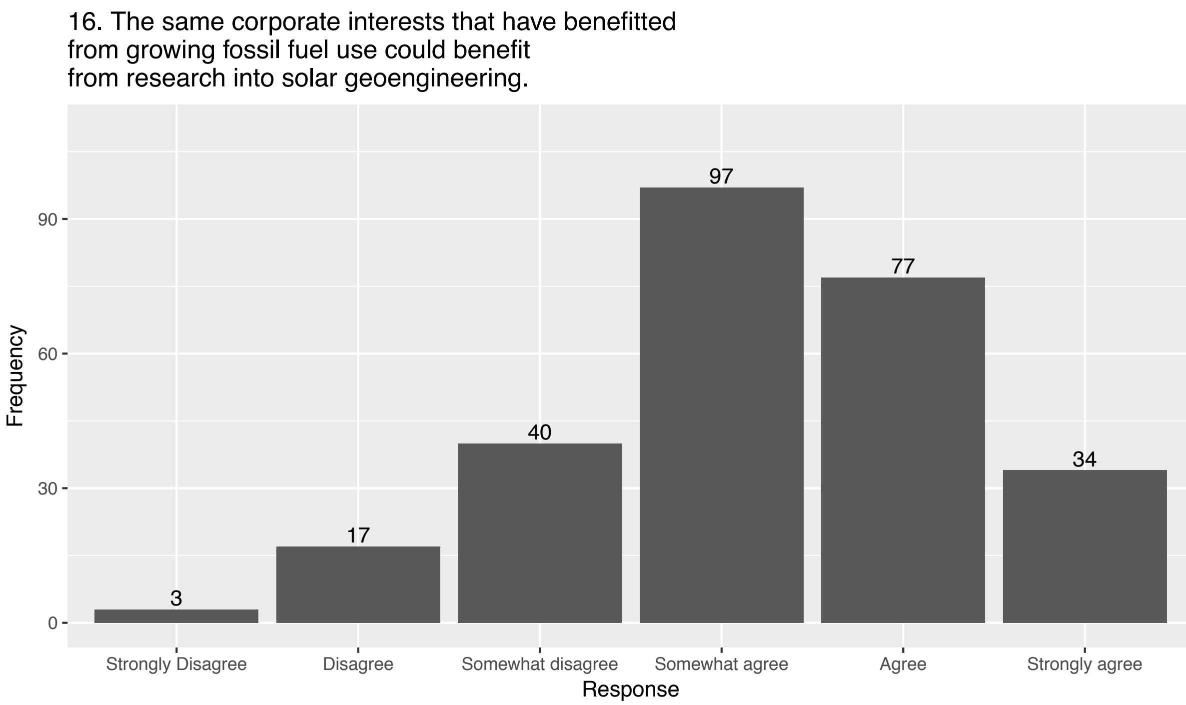

Figure 4.20: **Corporate benefit**

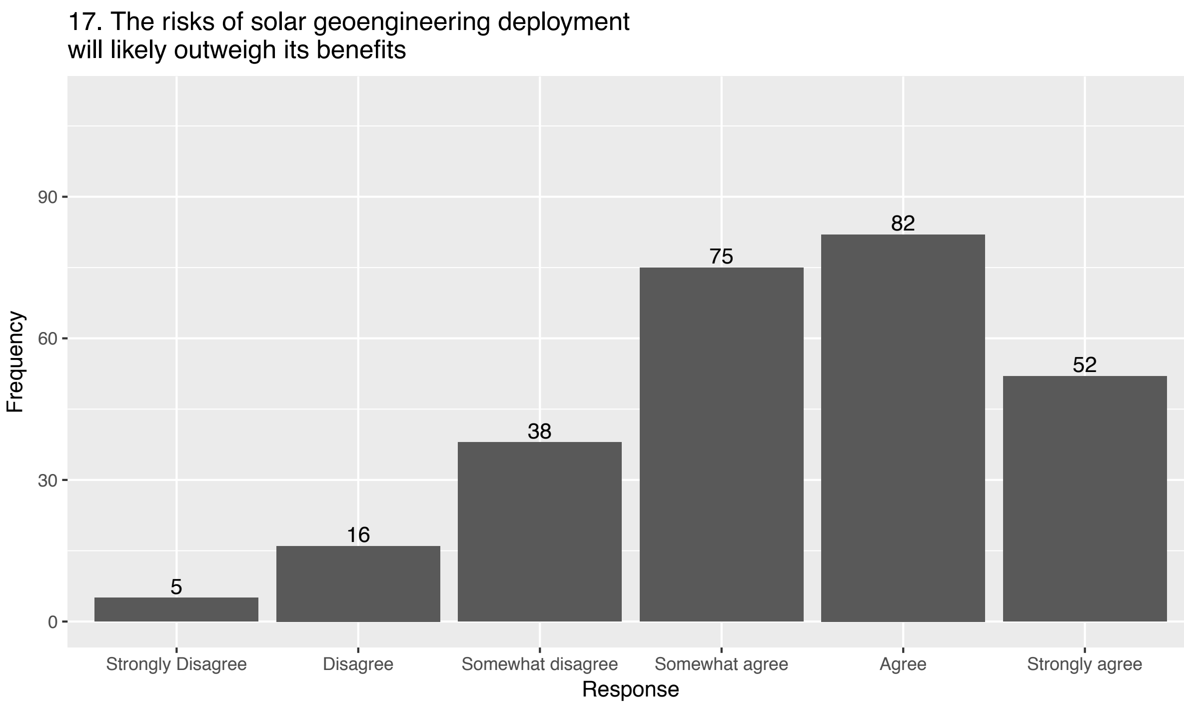

Figure 4.21: **Risks of deployment**

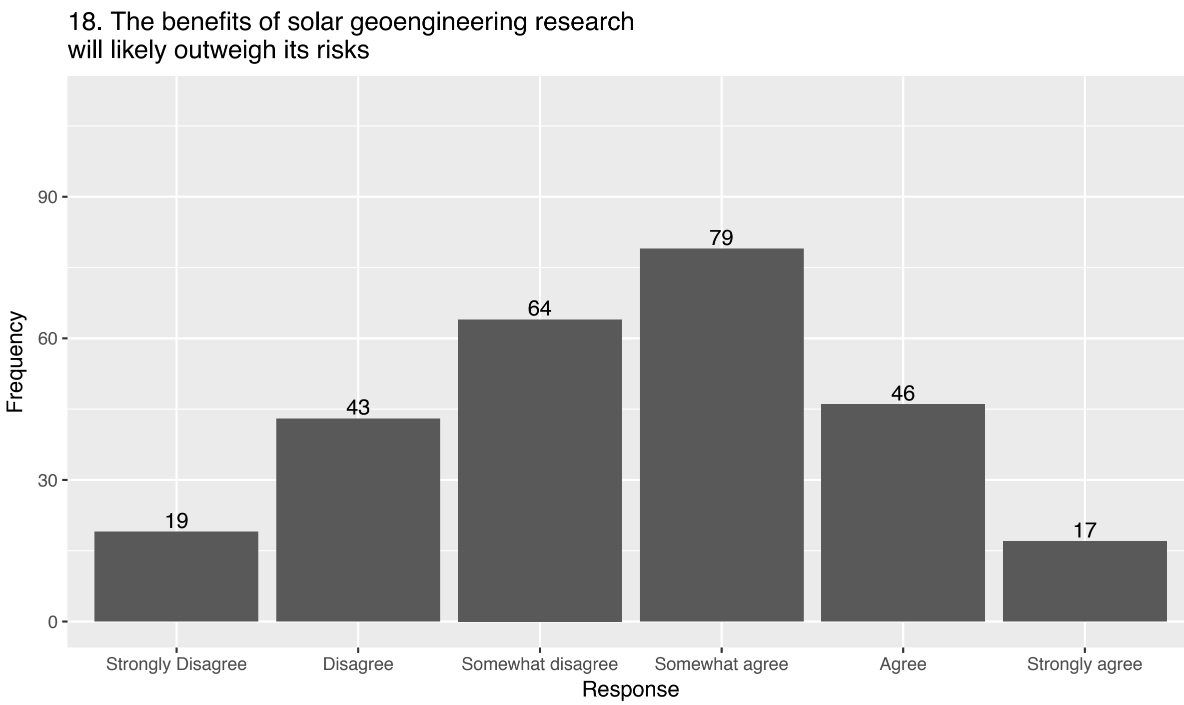

Figure 4.22: **Risks of research**

Chapter 5

Conclusion

The question at the heart of this dissertation is not whether solar geoengineering will succeed, or even whether it should, but rather what makes it — and its governance — imaginable. The bulk of this dissertation aimed to analyze the co-production of the evidence — and governance assumptions — for a sociotechnical system that does not yet exist. This necessarily meant looking to those actors — sociotechnical vanguards, experts, advocates, and activists — working to articulate and advance their visions for the future. There are advantages afforded by studying an emerging technology in this way: one has the opportunity to witness how things develop over time, and values often hidden behind claims of scientific objectivity are often more explicit, as there is little science to hide behind.

As Buck (2018) notes, given low awareness of technologies like solar geoengineering, participation by a narrow set of actors — including scientists, but also those who claim to represent the views of civil society — tend to close down discussion rather than open it up, meaning that "global public views are authoritatively authored and mapped out before the vast majority of people have even heard of these techniques." (p. 135) It remains to be seen whether and how early visions of solar geoengineering will cohere or acquire collective stability over time, or whether they will be radically disrupted. My hope is that the data and analysis in this dissertation may prove useful in tracing the evolution of solar geonegineering and its governance over time.

Research has shown that once public officials grant formal agenda status to new topics, stakeholders (including those who may disagree with early imaginaries) are more likely to engage in debate about the definition of the problem and potential solutions[133]. At a hearing on solar geonengineering in November of 2017 titled "Geoengineering: Innovation, Research, and Technology," Republican Congressman Andy Biggs offered a new definition of solar geoengineering — one that is at odds with early, 'responsible' scientific framings: "Geoengineering is the concept of using scientific understanding to alter the atmosphere in a way that produces positive outcomes and results." It is notable that the primary definition of solar geoengineering put forward by scientific advocates of research (the techniques may be tools to better manage the risks of anthropogenic climate change) may be upended, for better or worse, if and when geoengineering receives more formal policymaking attention.

The kinds of evidence underpinning imaginaries of solar geoengineering matter, not least because they have the potential to shape governance regimes. For example, Bellamy & Healey [10] and Rayner [192] suggest that early visions of solar geoengineering as cheap, easy, and being amenable to slippery slopes to deployment, path dependencies, and lock-in have resulted in assumptions that the role for governance is to restrict research, rather than enable it. Given the dearth of public funding of research on solar geoengineering, early assumptions about geoengineering – and its governance – may need to be revisited. In addition, evidence in this dissertation suggests that assumptions that climatic preferences are scientifically knowable or quantifiable, and therefore amenable to optimization, should be scrutinized.

5.1 Scientizing equity

How do future visions of 'sociotechnical vanguards' — of responsibility and agency, in particular — inform solar geoengineering debates and/or policy? Who are the key actors? How is the 'public good' defined, and by whom?

I identify three sets of equity-related arguments advanced by sociotechnical vanguards advocating for more solar geoengineering research. The first is a call for more solar geoengineering research as a means to shed light on the distributional outcomes of envisioned futures with and without solar geoengineering. This includes a call to reduce uncertainties inherent in scientific models examining distributional outcomes of potential deployment of solar geoengineering. Accompanying such calls is a discernible shift in the content of science itself, from more extreme to more 'realistic' modeled scenarios of deployment, and from consideration of global to regional effects. The second equity-related rationale for more research is a call for comparative risk-risk assessment, underpinned by the claim that equity demands that potential risks and benefits of solar geoengineering be compared to the risks of climate change itself, especially for vulnerable populations. The third equity-related rationale for more solar geoengineering research is the evocation of the 1.5°C aspirational goal of the Paris Agreement as requiring research on solar geoengineering, out of concern for the global poor and those most vulnerable to the consequences of climate change.

My research suggests that the expert-driven, outcome-oriented, and risk-based understanding of equity has a number of implications. First, it may suggest that more research on solar geoengineering is the only rational choice since many of the relevant equity concerns are empirical matters, amenable to resolution through the provision of more science. Second, it sidesteps the question of whether and how diverse non-experts should have a say in whether and how such research moves forward — even if it is to occur on their behalf.

Third, the focus on predicting or projecting the outcomes of any future deployment at this stage may represent an exercise in speculative ethics, and risks ignoring alternative ways of thinking about equity and responsibility in the context of technological innovation. Finally, I suggest that further analysis should be directed toward whether the vanguard visions we explore reflect a broader shift in operationalizing equity within multilateral climate politics, with those bearing the greatest responsibility now recast as risk managers on behalf of the global poor and the vulnerable.

Following Sheila Jasanoff, I have argued that those characterized as 'the vulnerable' in expert discourses need to "regain their status as active subjects, rather than remain undifferentiated objects in yet another expert discourse" ([113], p. 241). Empirical research suggests that publics have a set of concerns not captured in the approach to equity we analyze in this paper, including issues around moral responsibility, historical global injustices, the ability to be included in, and benefit from, technological development, and concerns around lack of agency and self-determination in shaping innovation pathways.

5.2 The politics of climate models of future technology deployment

What kinds of evidentiary thresholds are constructed and contested, and by whom, in the early stages of policy development?

Evidence in this dissertation suggests that there is an oft-neglected politics of evidence around attempts to put emerging topics on the formal public agenda, which has the potential to shape the interface of science and policy in future policy regimes. With regard to solar geoengineering, there are at least two issues around uncertainty and representation in the use of climate models for knowledge about solar geoengineering, which raise questions at the intersection of modeling and politics (particularly around regulatory science and responsible innovation). The first is that models are being used to represent technologies which don't yet exist. As one interviewee stated, "In the model, you can just *make geoengineering work*. You can just assume that the oceans have a higher albedo because of ocean bubbles, whether it's possible or not." This elides important near-term considerations about geoengineering, including the complexities of technology development and the structure of responsible research programs. Secondly, there is significant debate about whether these models can usefully predict outcomes; uncertainties that may be less relevant to models of and for climate science may become 'matters of concern' when it comes to the effects of geoengineering.

I argue that imaginaries of solar geoengineering technologies — despite not serving current regulatory demands, and despite the non-existence of the technologies themselves (perhaps because of it) — are engaging directly with policy needs (both current and predicted). With regard to current needs, the focus on *models* as proxies for actual *deployment* of these imagined technologies has the effect of making it seem as though societies ‘know’ more about whether and how to develop these techniques than they do, which is resulting in debates about the management of the *representation* of a technology which does not yet exist. This has contributed to the current research impasse, in which “technologists await a green light from social scientists before proceeding with research, while social scientists are limited to commenting on highly speculative ideas about how geoengineering might turn out in practice.”[192] In this context, policymakers are avoiding decisions regarding the advisability of a responsibly-structured research program aimed at answering societally-relevant research questions in a pluralistic manner. Alternatively, one might argue that the existing settlement, at least in the US, between governments, NGOs, and scientists, in which governments seem willing to fund indoor modeling studies but accept an informal moratorium on everything else, may itself be a kind of clumsy solution, the stability of which depends on its non-articulation [256].

5.3 Researchers’ views of solar geoengineering

What paradigms of risk assessment and management are invoked/co-produced in debates about whether and how to move forward with research? How do climate researchers view the benefits, risks, and appropriate governance architectures for solar geoengineering research? What are potential sources of variation?

I present the results of the first survey of climate change researchers’ views of solar geoengineering research and its appropriate oversight. I argue that definitions of ‘expert’ in emerging domains is itself a contested political category, and far from straightforward, particularly when the technologies under consideration do not yet exist. Respondents in this survey, much like surveys of general publics, report concern about the moral hazard operating at the level of political decision-making. Nevertheless, respondents generally support research on solar geoengineering, including small-scale outdoor studies — despite both a general concern that research may result in lock-in and slippery slopes to deployment, and skepticism about the advisability of ever deploying these techniques. I find strong support for some form of novel or supplementary governance arrangement(s) for research, and a belief that scientific self-regulation is insufficient to manage risks. There seems to be less agreement, however, on particular governance approaches; I find mixed responses regarding the desirability of a ‘physical thresholds’ approach to governing geoengineering experiments, for example.

Despite the fact that most respondents express skepticism about the desirability of future deployment, respondents tend to support more research into these techniques, both indoor and, to a lesser extent, outdoors. This might be explained by a view that research will reveal reasons not to move forward, or because of a belief that concerns about slippery slopes are overstated (although this seems less likely, given that most respondents report concern that research may result in lock-in and slippery slopes to deployment). Alternatively, a substantial number of researchers surveyed here may have an interest in scientific research moving forward in general, irrespective of its strategic aims. Respondents express skepticism about prediction and controllability when it comes to solar geoengineering deployment. It remains an open question whether a desirable future world with solar geoengineering would depend upon predicting such outcomes, although most respondents also report a belief that uncertainty in our understanding of the climate system means we should never deploy solar geoengineering.

Cultural worldview was only a significant predictor for one of the five factors used as response variables in the regression models (delegation to experts). There are several possible explanations for this finding. First, my sample was very international. While some work in cultural cognition suggests that the worldview scales transfer across geopolitical boundaries [125, 126], this research — on 'cross-cultural cultural cognition' — is nascent. Second, my sample was highly skewed relative to surveys of the general public (Figure 4.3); relative Hierarchical-Individualists (HIs) in my sample might actually be absolute Egalitarian-Communitarians (ECs) in a sample of the general public (including climate researchers). HIs and ECs in my study, therefore, might be more similar to one another than my division suggests. This finding also raises some question about cultural and political diversity in the academy — in climate research, and potentially beyond [274].

Gender emerged as a significant predictor for three of the five factors in this study (research, deployment, and governance). While one study of risk perception of scientists regarding nuclear power did find gender differences [5], a more recent meta-analysis of gender and risk by Julie Nelson raised some doubts about such finidngs. She concluded that women are not more 'risk averse,' or only marginally so, and only in certain contexts. Even then, the differences between men and women are small. Nelson finds that, in general, there are more differences within men or within women than across genders [166]. Importantly, the analysis conducted by Nelson implies that simple group means comparisons (e.g., t-tests) or conclusions drawn from differences *on average* will obscure the true degree of difference between these groups [167]. Instead, she advocates for the application of measures of substantive difference (Cohen's d) and substantive overlap (e.g., Index of Similarity) to determine the true nature of the differences between males and females. The multiple linear regressions conducted here do not account for this shortcoming directly, which could indicate that the statistically significant differences between the genders with regard to these three factors may be somewhat misleading. To situate these results, Cohen's d was calculated for the research, deployment, and governance values associated with males and females, and the results indicate that the all three imply differences in means separated by approximately 0.5 of the whole-sample standard deviation (0.49, 0.59, and 0.54, respectively).

To the extent that women researchers do, on average, tend to view solar geoengineering research and its governance differently than their male counterparts, this finding does not explain the *sources* of these differences. Research suggests that these differences, where they exist, are likely to be due to social facts and/or norms [68, 175] or to particular contexts (e.g., risks to identity and/or concerns about stereotypes have been found to amplify differences across genders in some instances).

Irrespective of the source of the variation, the analysis here suggests that it may be important to consider gender explicitly, both in the conduct of future empirical social science on solar geoengineering and in the design and conduct of solar geoengineering research programs and governance institutions. One early study of gender and geoengineering finds very low representation in scientific publications on geoengineering, at expert meetings on the topic, and in media accounts [24]. In terms of the impacts of this under-representation, as Buck *et al.* point out, an important concern relates less to women missing out on careers in geoengineering, but rather "in the framing and decision-making powers that participation in geoengineering research implies." This is not just a normative concern (women are vulnerable to climate change and also geoenginering, so should have a say) but also a substantive one: when confronting 'wicked problems' [204] like geoengineering, the deliberate design of pluralistic institutions which seek to include multiple rationalities and perspectives can help facilitate the development of 'clumsy solutions' [256].

Arguments for inclusion also apply to geographical differences. My study used binary categories (inside/outside of US), and thus cannot address important country-specific differences. However, comparative work in STS on the role of political culture in shaping sociotechnical choices supports the view that this may be an important variable when it comes to considerations of risk and regulation [22, 112]. Other potentially interesting geographic divisions could have been used, but the relatively small sample size limited the statistical power of alternative breakdowns. One that may warrant additional investigation is a Global North vs. Global South comparison. Given the findings presented in Winickoff *et al.* (2015) [264], it would not be surprising to see an even more stark difference among these broad geographic regions.

Climate catastrophism (or 'perceived climate risk') was a significant predictor for moral hazard (where those who see the risks of climate change as greatest also see the risks of moral hazard as highest), deployment (where catastrophists were associated were more negative perceptions of deployment), and governance (where catastrophists tended to favor novel governance arrangements). Despite its appearance in these regression models, one might expect catastrophism to play an even greater role, particularly with respect to the topic of geoengineering research. Its non-significance there could be driven by a skew in the sample surveyed here, which consisted exclusively of climate scientists, where the variance in feelings of catastrophism is likely reduced relative to a sample of the general public (i.e., most climate researchers are *absolute* catastrophists). Even so, the set of questions that give rise to this particular predictor variable could be valuable when considering experts with broader disciplinary emphases or when surveying the public.

Moving forward, studies should include variables not accounted for in this analysis, including discipline, religiosity, sector, etc. Assumptions that 'expertise' is straightforward in an emergent domain need to be questioned, as do assumptions that more science will yield agreement about the benefits and risks of research and its appropriate oversight.

Given low awareness of solar geoengineering, participation by a narrow set of actors — including scientists, but also those who claim to represent the views of civil society — can close down discussion rather than open it up, meaning that the views of relevant but disempowered publics are assumed before most people have even heard of these techniques. It remains to be seen whether and how early visions of solar geoengineering will cohere or acquire collective stability, or whether they will be radically disrupted. My hope is that the data and analysis in this dissertation may prove useful in tracing the evolution of solar geongineering and its governance over time.

Appendix A

Interview Guide: Politics of Models for Solar Geoengineering

1. Can you tell me a bit about how and why you got involved in climate modeling?
    - Why geoengineering?
2. What knowledge derived from climate models do you see as most important in geoengineering?
    - For science?
    - For policy/decision-making?
    - Do these things conflict/align?
    - Which purposes should receive preference?
3. If you think of GCMs as a kind of policy-relevant evidence, what is the role of GCMs in making decisions about moving forward with research on SRM?
    - On potential deployment?
4. How would you describe the relationship between model results and the real world (i.e., deployment of SRM)?
5. Are there significant debates about what SRM will/wont be, based on GCMs?
    - What are these big debates?
    - What do you think the major drivers of differences are with respect to these debates?
6. Do you have explicit guidance from decision-makers re: what is / is not useful? In absence of this, how do you make decisions about scenario choice?

7. Do you think there are differences between GCMs for climate change policy generally, and for technology development specifically? If so, what are they?

8. What is the future of modeling broadly for SRM (IAMs?)

9. Any questions for me?

Appendix B

Interview Consent Form (CPHS Protocol ID # 2016-06-8918)

The following is a reproduction of the content of the CPHS Consent Form permitting the research activities that form the basis of one of the chapters included in this dissertation.

Study Title:
Governing Geoengineering: Expert Assessment & the Politics of Evidence for Climate Policy Principal Investigator: Jonas Meckling
Protocol ID #: 2016-06-8918

Introduction and Purpose

My name is Jane Flegal. I am a graduate student at the University of California, Berkeley in the Department of Environmental Science, Policy and Management. I would like to invite you to take part in my research study, which investigates the role of science and technical expertise in debates about the governance of climate engineering.

Procedures

If you agree to participate in my research, I or one of my co-researchers will conduct an interview with you at a time and location of your choice. The interview will involve questions about the governance of climate engineering. It should last about 40 minutes. With your permission, I will audiotape and take notes during the interview. The recording is to accurately record the information you provide, and will be used for transcription purposes only. If you choose not to be audiotaped, I will take notes instead. If you agree to being audiotaped but feel uncomfortable at any time during the interview, I can turn off the recorder at your request. Or if you don't wish to continue, you can stop the interview at any time.

I expect to conduct only one interview; however, one follow-up to answer similar questions may be needed for added clarification. If so, I will contact you by mail/phone to request this.

Benefits

There is no direct benefit to you from taking part in this study.

Risks/Discomforts

As with all research, there is a chance that confidentiality could be compromised; however, we are taking precautions to minimize this risk.

Confidentiality

Your study data will be handled as confidentially as possible. If results of this study are published or presented, individual names and other personally identifiable information will not be used.

To minimize the risks to confidentiality, interview data will be transferred to an encrypted and password protected hard drive. When the research is completed, I may save the tapes and notes for use in future research done by myself or others.

Compensation

You will not be paid for taking part in this study.

Rights

Participation in research is completely voluntary. You are free to decline to take part in the project. You can decline to answer any questions and are free to stop taking part in the project at any time.

Questions

If you have any questions about this research, please feel free to contact me. I can be reached at 603- 674-6097 or at jflegal@berkeley.edu.

If you have any questions about your rights or treatment as a research participant in this study, please contact the University of California at Berkeleys Committee for Protection of Human Subjects at 510-642-7461, or e-mail subjects@berkeley.edu.

Consent

You will be given a copy of this consent form to keep for your own records. If you wish to participate in this study, please sign and date below.

Appendix C

Survey Questions: Cultural Cognition, Climate Change, and Technological Risk

1. As individuals and as a society, we face a number of possible hazards. Some threaten peoples health, safety, or financial well-being directly. Others threaten health, safety, or financial well-being indirectly through the damage they can impose on the environment or the economy. How much risk do you believe each of the following poses to human health, safety, or prosperity?

   (Possible responses: No risk at all, Very low risk, Between low and moderate risk, Moderate risk. Between moderate and high risk, High risk, Very high risk)

   - Private gun ownership
   - Global warming
   - Nuclear power
   - Genetically modified food
   - Air pollution
   - Disposal of hazardous wastes in landfill sites
   - Medical X-rays
   - Domestic terrorist attacks
   - Fluoridation of drinking water
   - Exposure to sand-hand cigarette smoke
   - Illegal immigration
   - Legalization of marijuana

- Legalization of prostitution
- 'Fracking' (extraction of natural gas by hydraulic fracturing)
- Excessive government taxes on businesses
- Environmental regulations
- Teaching high school students about birth control
- Airborne radiation

2. Assessment of the risks posed by climate change has been central to the development of policy responses. How much do you agree or disagree with the following statements about climate change science?

   (Possible responses: Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree)

   - To develop effective climate change mitigation strategies, it is necessary to accurately predict the impacts of climate change.
   - Differences in simulated versus observed trends over the period from 1998-2012 (the 'reduced warming period') call into question the predictive ability of climate models.
   - My best estimate of climate sensitivity (i.e. the temperature response to a doubling of carbon dioxide) is likely above 3.5 degrees Celsius.
   - It is difficult for climate models to simulate precipitation at regional scales.
   - Decision-makers can effectively adapt to climate risks without precise predictions of the future impacts of anthropogenic climate change.
   - Climate change is already the greatest contributor to increased economic losses associated with extreme weather events.
   - Rising sea level is likely by 2050 due to melting of the Greenland and West Antarctic Icecaps.
   - Massive releases of greenhouse gases from the Arctic region (Alaska and Siberia) are likely by 2050.
   - Permanent loss of Arctic floating ice is likely by 2050.
   - Over the past several decades, observed climate trends have adversely affected total global production of wheat and maize.
   - Climate change is likely to disrupt global food supplies by 2050.
   - Climate change is already having an impact on interstate conflict.
   - Future climate change will likely increase interstate conflict by 2050.
   - Climate change is responsible for the intensification of hydrological drought in Southeast Australia

- Climate change is already adversely affecting human health
- Climate change has already had a detectable impact on Atlantic tropical cyclone activity
- Climate change has already increased the intensity and/or duration of droughts.

Currently there is increasing discussion about 'solar geoengineering,' a measure for manipulating Earths surface temperature directly. When sulfate particles are released into higher regions of the atmosphere, they reflect some of the sunlight back out into space before it warms the Earth. This measure could slow down global warming much faster than cutting back greenhouse gas emissions. To achieve that goal, the particle layer would have to be renewed constantly until the share of greenhouse gases in the atmosphere dropped again. Ocean acidification cannot be prevented by this measure. Little research has been done on the effects and side effects of this measure. Injecting sulfate particles could have negative effects on various ecosystems, the ozone layer and the health of animals and people. Furthermore, political conflicts might arise over deployment itself and the extent of deployment. It is unclear whether additional negative effects would occur during deployment. Research can provide new information about effects and side effects, without necessarily coming to any definite conclusions.

3. How much have you heard about solar geoengineering before today?

   (Possible responses: Nothing, Just a little, Some, A lot)

4. The risks of solar geoengineering research will likely outweigh its benefits

   (Possible responses: Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree)

5. The benefits of solar geoengineering research will likely outweigh its risks

   (Possible responses: Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree)

6. Solar geoengineering deployment is likely to be

   (Possible responses: Not effective, Largely ineffective, Effective, Very effective)

7. The idea of sulfate particles being released into higher regions of the atmosphere to counter climate change affects my feelings about climate change. I now find it:

   (Possible responses: A lot more threatening, More threatening, It doesn't affect my feelings about climate change, Less threatening, No longer threatening)

8. How much do you agree or disagree with the following statements

   (Possible responses: Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree)

- Individuals will be less likely to take actions to mitigate greenhouse gas emissions if they know that research on solar geoengineering is being conducted.
- Politicians will be less likely to take actions to mitigate greenhouse gas emissions if they know that research into solar geoengineering is being conducted.
- Deployment of solar geoengineering would likely result in unpredicted climate impacts at regional scales.
- Indoor research on solar geoengineering – including climate models and indoor laboratory studies – should move forward in the next 25 years.
- Outdoor research on solar geoengineering – including small-scale experiments – should move forward in the next 25 years.
- Research on solar geoengineering should move forward without additional oversight, unless or until that research is outdoors and exceeds a physically-defined threshold (e.g., area, size, duration of radiative forcing).
- Solar geoengineering research, including indoor studies, poses novel social, political, and ethical challenges, and thus requires new governance or regulatory approaches.
- Scientific self-regulation is sufficient to manage potential risks posed by solar geoengineering research.
- Research on solar geoengineering will result in technological lock-in, and a slippery slope to deployment.
- Scientific experts should be trusted to make decisions about solar geoengineering research, with little to no involvement of the broader public.
- It is important that the scientists studying solar geoengineering represent diverse geographies and interests.
- The most qualified experts, regardless of geographical representation, should be involved in solar geoengineering research programs.
- Uncertainty in our understanding of the climate system means that we should not deploy solar geoengineering.
- Solar geoengineering research will require technocracy.
- Technocracy is undesirable
- In general, allowing scientists to pursue their own intellectual interests will result in benefits to society.
- In general, I have benefitted from innovation in science and technology over the last 50 years.
- In general, innovation in science and technology has benefitted the wealthy, and hurt the poor.

- Solar geoengineering will be appealing to individuals who deny anthropogenic climate change.
- Solar geoengineering will be appealing to politicians who deny anthropogenic climate change.
- The same corporate interests that have benefitted from growing fossil fuel use will benefit from research into solar geoengineering.
- There is no evidence that chemtrails, or the belief that the persistent contrails left by airplanes provide evidence that a secret program of large-scale weather and climate modification is on-going, is correct.

9. Business-as-usual projections see global carbon dioxide emissions reaching 57 Gigatons (Gt)/year by 2050. Please choose which global carbon dioxide target you think is necessary to address climate risks by 2050.

   (Possible responses: 0 Gt in 2050, 4.3 Gt in 2050 (80% below 1990 levels), 14 Gt in 2050 (50% below 2005 levels), 16 Gt in 2050 (450 ppm target), Other)

10. How likely do you think it is that global emissions will hit this target by 2050?

    (Possible responses: Extremely likely, Moderately likely, Slightly likely, Slightly unlikely, Moderately unlikely, Extremely unlikely)

11. Total global primary energy demand was 16.4 Terawatts (TW) per year in 2010. Business-as-usual scenarios project primary energy demand roughly doubling over the next 40 years, with an annual growth of 1.4%. Please choose which scenario for global primary energy demand projections for 2050 you think is most likely:

    (Possible responses: Greater than 1.4% annually, 1.4% annually, 1.2% annually, Remaining roughly flat annually, Absolute declines in global energy demand through 2050)

12. How important do you think reductions in global energy consumption should be by 2050 for addressing climate change risks?

    (Possible responses: Extremely important, Moderately important, Slightly important, Slightly important, Moderately important, Extremely important)

13. How likely do you think reduced global energy consumption will be by 2050?

    (Possible responses: Extremely likely, Moderately likely, Slightly likely, Slightly unlikely, Moderately unlikely, Extremely unlikely)

14. Sub-Saharan Africas electric power will mostly come from non-hydro renewable sources by 2050.

    (Possible responses: Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree)

15. How strongly do you disagree or agree that each of the following should play a part in addressing climate change risks in the developed world by 2050

    (Possible responses: Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree)

    - Greater utilization of wind and solar
    - Greater utilization of hydropower
    - Greater utilization of nuclear power
    - Greater utilization of carbon capture and storage for coal-fired energy sources
    - Greater utilization of carbon capture and storage for natural gas
    - Greater utilization of natural gas
    - Greater use of bioenergy
    - Greater use of bioenergy with carbon capture and storage
    - Increased research on solar geoengineering
    - Deployment of solar geoengineering
    - Increased research on carbon dioxide removal technologies
    - Deployment of carbon dioxide removal technologies
    - Other

16. How strongly do you disagree or agree that each of the following will play a part in addressing climate change risks in the developed world by 2050

    (Possible responses: Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree)

    - Greater utilization of wind and solar
    - Greater utilization of hydropower
    - Greater utilization of nuclear power
    - Greater utilization of carbon capture and storage for coal-fired energy sources
    - Greater utilization of carbon capture and storage for natural gas
    - Greater utilization of natural gas
    - Greater use of bioenergy
    - Greater use of bioenergy with carbon capture and storage
    - Increased research on solar geoengineering
    - Deployment of solar geoengineering
    - Increased research on carbon dioxide removal technologies

- Deployment of carbon dioxide removal technologies
- Other

17. How strongly do you disagree or agree that each of the following should play a part in addressing climate change risks in the developing world by 2050

    (Possible responses: Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree)

    - Greater utilization of wind and solar
    - Greater utilization of hydropower
    - Greater utilization of nuclear power
    - Greater utilization of carbon capture and storage for coal-fired energy sources
    - Greater utilization of carbon capture and storage for natural gas
    - Greater utilization of natural gas
    - Greater use of bioenergy
    - Greater use of bioenergy with carbon capture and storage
    - Increased research on solar geoengineering
    - Deployment of solar geoengineering
    - Increased research on carbon dioxide removal technologies
    - Deployment of carbon dioxide removal technologies
    - Other

18. How strongly do you disagree or agree that each of the following will play a part in addressing climate change risks in the developing world by 2050

    (Possible responses: Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree)

    - Greater utilization of wind and solar
    - Greater utilization of hydropower
    - Greater utilization of nuclear power
    - Greater utilization of carbon capture and storage for coal-fired energy sources
    - Greater utilization of carbon capture and storage for natural gas
    - Greater utilization of natural gas
    - Greater use of bioenergy
    - Greater use of bioenergy with carbon capture and storage

- Increased research on solar geoengineering
- Deployment of solar geoengineering
- Increased research on carbon dioxide removal technologies
- Deployment of carbon dioxide removal technologies
- Other

19. People in our society often disagree about how far to let individuals go in making decisions for themselves. How strongly do you agree or disagree with each of these statements?

    (Possible responses: Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree)

    - The government interferes too much in our everyday lives.
    - Sometimes government needs to make laws that keep people from hurting themselves.
    - It's not the government's business to try to protect people from themselves.
    - The government should stop telling people how to live their lives.
    - The government should do more to advance society's goals, even if that means limiting the freedom and choices of individuals.
    - Government should put limits on the choices individuals can make so they don't get in the way of what's good for society.
    - We have gone too far in pushing equal rights in this country.
    - Our society would be better off if the distribution of wealth was more equal.
    - We need to dramatically reduce inequalities between the rich and the poor, whites and people of color, and men and women.
    - Discrimination against minorities is still a very serious problem in our society.
    - It seems like blacks, women, homosexuals, and other groups don't want equal rights, they want special rights just for them.
    - Society as a whole has become too soft and feminine.

20. How important is religion in your life?

    (Possible responses: Extremely important, Moderately important, Slightly important, Slightly important, Moderately important, Extremely important)

21. Aside from weddings and funerals, how often do you attend religious services?

    (Possible responses: More than once a week, Once a week, Once or twice a month, A few times a year, Seldom, Never)

22. Outside of attending religious services, do you pray

    (Possible responses: Several times a day, Once a day, A few times a week, Once a week, A few times a month, Seldom, Never)

23. What is your religious preference?

    (Possible Responses: Muslim, Mormon, Seventh-Day Adventist, an Orthodox church such as the Greek or Russian Orthodox Church, Roman Catholic, Protestant, Christian Scientist, Jewish, Something else [write in])

24. Would you describe yourself as:

    (Possible Responses: American Indian/Native American, Asian, Black/African American, Hispanic/Latino, White/Caucasian, Pacific Islander, Other [write in])

25. In which country do you currently reside?

26. In which country are you a citizen? List all that apply

27. What is your identified gender?

    (Possible responses: Male, Female, Other)

28. What is your age?

    (Possible responses: 18-29, 30-49, 50-64, 65+)

29. What is the highest level of education you have completed?

    (Possible responses: High school or less, Some college, College, Post-graduate degree)

30. What is your total household income?

    (Possible responses: Less than $30,000, $30,000-$49,999, $50,000-$99,999, $100,000 or more)

31. In politics, do you consider yourself a:

    (Possible responses: Strong Republican, Republican, Independent leaning Republican, Independent leaning Democrat, Democrat, Strong Democrat)

32. In general, would you describe your political views as:

    (Possible responses: Very conservative, Conservative, Moderate, Liberal, Very liberal)

33. Do you donate to a professional environmental advocacy organization?

    (Possible Responses: Yes, No)

34. Are you employed by a professional environmental advocacy organization?

    (Possible Responses: Yes, No)

35. Do you advise a professional environmental advocacy organization in a formal capacity? (Possible Responses: Yes, No)

Appendix D

Survey Consent Form (CPHS Protocol ID # 2016-06-8918)

The following is a reproduction of the content of the Consent Form (also under CPHS Protocol ID # 2016-06-8918) permitting the research activities that form the basis of one of the chapters included in this dissertation.

University of California at Berkeley
Consent to Participate in Research
Climate Change & Technological Choice

Introduction and Purpose

My name is Jane Flegal. I am a graduate student at the University of California, Berkeley, working with my faculty advisor Professor Jonas Meckling in the Department of Environmental Science, Policy and Management. I would like to invite you to take part in my research study, which concerns expert views regarding climate change science, policy, and technology. While many studies have surveyed the general public about both climate change and technological responses, very little research has been done to understand expert perceptions of these issues. The link to participate in the survey is at the bottom of this email.

Procedures

If you agree to participate in my research, I will ask you to complete the attached online survey. The survey will involve questions about climate change science, policy, and potential responses to climate change risk, and should take about 15 minutes to complete.

Benefits

There is no direct benefit to you from taking part in this study. It is hoped that the research will generate important insights into expert understandings of climate change risk and potential responses to those risks.

Risks/Discomforts

Some of the research questions may make you uncomfortable or upset. You are free to decline to answer any questions, or to stop participating at any time. As with all research, there is a chance that confidentiality could be compromised; however, we are taking precautions to minimize this risk.

Confidentiality

Your study data will be handled as confidentially as possible. If results of this study are published or presented, individual names and other personally identifiable information will not be used.

To minimize the risks to confidentiality, we will store anonymous data on secure servers, and accessed only by the principal investigators.

When the research is completed, I may save the data for use in future research done by myself or others. I will destroy this data at the end of the study period. The same measures described above will be taken to protect confidentiality of this study data.

When the research is completed, I may save the tapes and notes for use in future research done by myself or others. I will retain these records for up to three years after the study is over. The same measures described above will be taken to protect confidentiality of this study data.

Compensation

You will not be paid for taking part in this study.

Rights

Participation in research is completely voluntary. You are free to decline to take part in the project. You can decline to answer any questions and are free to stop taking part in the project at any time. Whether or not you choose to participate, to answer any particular question, or continue participating in the project, there will be no penalty to you or loss of benefits to which you are otherwise entitled.

Questions

If you have any questions about this research, please feel free to contact me. I can be reached at jflegal@berkeley.edu.

If you have any questions about your rights or treatment as a research participant in this study, please contact the University of California at Berkeleys Committee for Protection of Human Subjects at 510-642-7461, or e-mail subjects@berkeley.edu.

If you agree to take part in the research, please click on the link below.

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