Expertise at the Limits of Quantified Risk:
Social Constructions of Ignorance in the Scientific Controversy on Solar Geoengineering

J. Daniel Andersson

The Department of Thematic Studies – Environmental Change & Centre for Climate Science and Policy Research (CSPR), Linköping University, Sweden/ daniel.j.andersson@liu.se

Anders Hansson

The Department of Thematic Studies – Environmental Change & Centre for Climate Science and Policy Research (CSPR), Linköping University, Sweden

Mathias Fridahl

The Department of Thematic Studies – Environmental Change & Centre for Climate Science and Policy Research (CSPR), Linköping University, Sweden

Abstract

Quantitative risk analysis has long underpinned public trust in experts who interpret and address environmental disputes. However, in the uncertain and complex context of responding to a changing climate, it has been argued that trust in scientific expertise must be warranted on norms other than experts' competence in quantifying risk. Nowhere is this more evident than in the case of solar geoengineering. Much like abrupt climate change, solar geoengineering involves potential nonlinear or threshold responses, where both the triggering points and the system's reactions are poorly understood, leaving risks inadequately characterized. In this paper, we examine climate model experiments with solar geoengineering to understand how expertise is justified in the absence of reliable risk assessments. We argue that these experts enact a specific norm of competence, which holds that trust should be warranted not on their ability to quantify risk, but to render unknown unknowns into known unknowns.

Keywords: Anticipatory Governance, Computer Simulation, Ignorance, Public Trust, Scientific Expertise, Solar Geoengineering.

Solar geoengineering as an object of expertise

As the goal of limiting global warming to 1.5°C under the Paris Agreement becomes increasingly unlikely, some experts – albeit reluctantly – argue for increased investment in solar geoengineering research. Their rationale is to better understand its potential efficacy and risks (MacMartin et al., 2018), and to keep it on the table as a possible option, should it prove feasible (Keith, 2013; Wagner, 2021). In 2015, the United States National Research Council (2015) recommended studying solar geoengineering as a strategic complement to reducing greenhouse gas emissions. Less than a year later, Harvard University launched the Solar Geoengineering Research Program, one of the first dedicated research centers in the field, followed by similar initiatives at institutions such as Cornell and Stanford. In 2019, the United States Congress allocated $4 million to the National Oceanic and Atmospheric Administration for solar geoengineering research. Since then, the National Academies of Sciences (2021) has recommended that the United States invest $100 to 200 million over five years in a coordinated federal research program to evaluate its feasibility as a stopgap measure, with calls for a special report from the Intergovernmental Panel on Climate Change dedicated to its potential impacts (Reynolds, 2021). Most recently, the United Kingdom's Advanced Research and Invention Agency (2024) announced a £56.8 million initiative to fund research addressing the mechanisms and effects of various short-term methods to cool the earth. Once a fringe idea dismissed as too risky to even warrant serious attention, empirical evidence suggests that expert opinion on solar geoengineering is changing, and with it, the perception of its status as a legitimate domain of scientific expertise (Dai et al., 2021).

Solar geoengineering – sometimes also referred to as 'solar radiation management' (e.g., Intergovernmental Panel on Climate Change, 2018: 70, 73 et passim) – refers to a set of hypothetical or at most pilot-scale technologies designed to reduce net radiative forcing by either reflecting sunlight back into space or releasing the earth's re-radiated heat. The most prominent and widely studied proposal involves injecting highly reflective sub-micron particles into the lower stratosphere to reduce incoming solar energy. This method, known as stratospheric aerosol injection (SAI), would likely involve aircraft releasing particles at altitudes of 20–25 kilometers above sea level. Popularized by the 1995 Nobel Laureate Paul Crutzen (2006), it aims to create a cooling effect through global dimming and increased albedo.[1] Although a fifteen-year development phase has been deemed feasible for a scenario to inject large quantities of aerosols into the stratosphere that would effectively halve the increase in anthropogenic radiative forcing (Smith and Wagner, 2018), experts widely agree that large-scale deployment could generate unanticipated negative impacts (Keith, 2013: 43; Hulme, 2014: 47–53). As a planetary-scale intervention, SAI lacks direct historical precedents, with volcanic eruptions serving as its only natural analog (Robock et al., 2013). Observations of global cooling following major volcanic eruptions suggest that injecting reflective particles into the stratosphere could rapidly lower global temperatures, but the extent to which SAI could mitigate climate hazards, alleviate ecological damage, or reduce human suffering remains poorly understood. Although it has been an issue of some controversy, its environmental and social impacts are uncertain and likely to vary across regions (e.g., Heyen et al., 2015; MacMartin et al., 2016; Lawrence et al., 2018; Kravitz and MacMartin, 2020). Artificial cooling could disproportionately benefit some areas while exacerbating challenges in others (Irvine et al., 2010). For instance, changes in precipitation patterns could affect biodiversity, agriculture, and access to food and water (Bala et al., 2008; Tilmes et al., 2013; Proctor et al., 2018). SAI would also alter stratospheric chemistry, potentially depleting the ozone layer (Tilmes et al., 2022). So, whilst it might reduce global climate risks overall, SAI could simultaneously increase risks for certain regions in unpredictable and potentially severe ways.

The science underlying issue-driven assessments of large-scale environmental interventions, such as solar geoengineering, thus differs from curiosity-driven laboratory research (Van Der Sluijs, 2006: 64–65; 2012: 174–177). Some experts believe that unlike laboratory research, a statistically robust series of experiments to explore the impacts of SAI is impossible without full-scale deployment (Robock et al., 2010; cf. MacMynowski et al., 2011). Furthermore, earth – the only system available for such experiments – is poorly monitored, and numerous factors influencing the climate remain beyond human control. Since large-scale practical experience with any solar geoengineering method is nonexistent and field experiments are highly controversial, computer simulation has become essential for exploring potential earth system responses and assessing the risks associated with various deployment scenarios (Hansson, 2014). By facilitating a virtual world in which to evaluate these hypothetical technologies, computer-based modeling plays a central role in framing solar geoengineering as a viable policy option, with disagreements about model structures and assumptions being key points of contention (Shackley and Wynne, 1996). In this paper, we thus proceed from the assumption that solar geoengineering is not merely a scientific research agenda focused on proposed technologies to alleviate climate hazards. Equally, it is an object of expertise, subject to anticipatory governance (Foley et al., 2018; Gupta et al., 2020). It involves linking expert judgments about potential impacts to prevailing norms of rational decision-making under deep uncertainty.

Framing, then, does not occur solely at the end of the technological or scientific development process, nor only at the point of implementation, when governance issues typically become public. Instead, social choices can become embedded in practices and tools of scientific research long before they materialize as field experiments (Wilsdon and Willis, 2004). As solar geoengineering gains traction through models as part of broader efforts to manage climate risks, some have warned that its institutionalization as a distinct field of research – with its own experts and specialized practices (Schubert, 2021) – could have profound political implications (e.g., Horton, 2015; Frumhoff and Stephens, 2018; Schäfer and Low, 2018; MacLaren and Corry, 2021). Indeed, experts do not simply compile a repository of knowledge for others to use; they actively shape political discourse and influence how issues are framed and understood (Haas, 1992). As Schubert (2021: 17) puts it:

> In the emerging debate over climate engineering, science does not merely figure as a neutral base for politics; it does not simply prepare a difficult position with positive facts. Instead, science and politics are coupled "upstream." That is, they are linked in the very formulation of climate engineering as a potential measure to counteract climate change.

It is surprising therefore that, with the exception of Wiertz (2016a, 2016b), little attention has been paid to the role of model studies in transforming solar geoengineering into an object of expertise. We aim to address this gap. In the next section, we develop upon the analytical concept of an object of expertise, focusing on the challenge that deep uncertainty poses to trust in claims to expertise when that trust is warranted on experts' competence in quantifying risk. After briefly outlining our empirical case in section three, we then go on in section four to contextualize the scientific controversy on solar geoengineering research within broader concerns about the trustworthiness of model studies, particularly when models are used for assessment purposes. There, we examine how computer simulations have contributed to constructing ignorance in ways that enact a specific norm upon which trust in models ought to be warranted. Finally, in the fifth section, we conclude that this controversy centers on norms of competence rather than empirical truth claims. We argue that claims to expertise on solar geoengineering revive the age-old virtue of learned ignorance.

Claims to expertise in the face of deep uncertainty

In the social sciences, one approach to studying environmental expertise has been to conceptualize it as enacted by collectives of knowledge-based specialists (Lidskog and Sundqvist, 2018). Often, the role of such specialists is to analyze cause-and-effect relationships in complex environmental problems, frame political issues for public debate, assist stakeholders in articulating their interests, and identify key points for negotiation. Integrated environmental assessments have been examined as processes for appraising the knowledge base of multi-scale environmental issues and advising governments in maintaining multilateral environmental agreements (Oppenheimer et al., 2019). Scholars have also studied how expert organizations, such as the Intergovernmental Panel on Climate Change and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, contribute to environmental governance by shaping the global environment into an administrative domain, making it amenable to government regulation and market mechanisms (e.g., Lövbrand and Stripple, 2011; Borie et al., 2021). To study expertise as something that is enacted thus means treating issues like solar geoengineering not as pre-existing problems but as objects brought into being through specialized – often technical and opaque – practices and tools (Aykut, 2019; Esguerra, 2019, 2024). We draw upon this strand of research to focus on how, in the constitution of such objects of expertise, norms around good scientific practice interact with norms around good governance.

Without downplaying the central role of uncertainty in expert assessment, the authority granted to expertise is nevertheless fundamental to how values like knowledge, truth, and evidence have come to underpin policymaking in postwar democracies. Policymakers rely on knowledge-based specialists to define complex issues and formulate strategies for addressing them. Due to a growing public awareness of the inherent complexities of our globalized world, however, the authoritative status of expertise has become increasingly contested (Straßheim, 2015; Weingart, 2023), particularly regarding its trustworthiness (Resch et al., 2024).[2] Not only is the advice often subject to criticism, but the underlying assumptions, concepts, and model structures of expert assessment are also disputed (e.g., Biddle and Winsberg, 2009; Scheinke et al., 2011; Winsberg, 2012; Frisch, 2013; Talberg et al., 2018; Hollnaicher, 2022). Disputes like these highlight what sets science-for-policy apart from conventional science. Political decisions on complex issues often need to be made before definitive scientific evidence is available, and so when high-stakes political decisions rely on expert advice that is tentative or provisional, assessment processes tend to become politicized, and the interpretation of scientific evidence can spark controversy (Jasanoff, 2005). As Fischer (2005: 56) emphasizes:

> Uncertainty opens the door for competing interests to emphasize different interpretations of the findings. […] The question of how to define a situation is as problematic as the question of what to do about it. Competing definitions emerge from multiple, often conflicting, perspectives. […] Empirically, each side engages in the politics of expertise, employing the same or similar data to suit their own purposes.

Sometimes, stakeholders intentionally manipulate the assessment process for political purposes (Proctor, 1995; Oreskes and Conway, 2010). Such tactics may include misrepresenting arguments, omitting inconvenient findings, making unwarranted generalizations, misleadingly appealing to authority, or manufacturing doubt. But more commonly, stakeholders do not purposefully set out to undermine research that could help ameliorate social problems. Instead, disagreements about the norms that should guide the assessment process arise because the available knowledge base is characterized by imperfect understanding (Funtowicz and Ravetz, 1993).

The framing of contentious areas in science and technology through the lens of risk has long underpinned public trust in experts who interpret and address environmental disputes. As an approach, risk management standardizes the characteristics of the phenomena being assessed and directs practical reasoning based on norms grounded in quantifiable measures, such as those formalized in rational choice theory (Irwin and Wynne, 1996; Jasanoff, 1999; Wynne, 2002, 2005). Power (2007) suggests that risk management is simultaneously epistemological and forensic in character. It operates as a 'moral technology' (Power, 2007: 38) that combines instrumental and normative elements, defining a decision space in which responsibility can be assigned, accountability exercised, and trust produced. The expansion of quantified risk analyses across public and private sectors therefore reflects not only a growing preoccupation with uncertainty but also the pursuit of good governance – the aspiration to demonstrate rational, disciplined, and accountable management. However, in the notoriously uncertain and complex context of responding to a changing climate, it has been argued that trust in scientific expertise must be warranted on norms other than experts' competence in quantifying risk (Ravetz, 2005; Fischbacher-Smith, 2023). Nowhere is this more evident than in the case of solar geoengineering. Much like abrupt climate change, solar geoengineering involves potential nonlinear or threshold responses, where both the triggering points and the system's reactions are poorly understood, leaving risks inadequately characterized. "The consequence is that limiting risk analysis for policy purposes to quantified risk," as Kadvany (1996: 2–3) puts it:

> confuses the role of science in policy, and at worst effectively eliminates valuable scientific research from decision-making by agencies or the public. Not that probabilistic quantification of uncertainty should be "given up," whatever that might mean. […] The point is that the role of uncertainty in science and our understanding of dangers can go significantly beyond the standard methodological assumptions of risk analysis.

Since scientific uncertainty is exactly about the definition or characterization of hazards, experts may know just enough to be concerned about them, yet not enough to quantify that uncertainty via probability. Uncertainties may thus undermine the predictive validity required for accurate risk determinations, complicating both prediction and early intervention.

As unquantifiable risk disrupts the ability to reliably ground expert advice on statistical probabilities and cost-benefit analyses, it poses a challenge for trust in scientific expertise when that trust is warranted on proof of experts' performance in quantifying risk. As Gross and MacGoey (2022: 6) observe, "[t]he question of what might furnish such proof is a social and political one – not simply a cognitive one." It is a question that extends beyond technical calculations to involve how expertise at the science-policy interface is socially constituted (Douglas and Wildavsky, 1982) – not only to assess what is known, but also to address what remains poorly known or recognized as unknown (Wynne, 1992). Such expertise is not confined to the courtroom. One of the primary tasks of integrated assessments of climate change has been to report on the limits of the existing knowledge base and to design robust strategies to achieve 'climate proofing' under deep uncertainty (Van Der Sluijs, 2010). According to the standard definition by Lempert et al. (2003: 3–4), situations characterized by deep uncertainty are those in which experts do not know or policymakers cannot agree on: "(1) the appropriate models to describe the interactions among a system's variables, (2) the probability distributions to represent uncertainty about key variables and parameters in the models, and/or (3) how to value the desirability of alternative outcomes." This is particularly true in relation to emerging technologies, since they are not yet sufficiently well-understood to be tied to specific situations with predictable consequences for definite stakeholders (Vallor, 2016). Decisions about them must often be made under conditions where "facts are uncertain, values in dispute, stakes high, and decisions urgent." (Funtowicz and Ravetz, 1993: 744). Such conditions expose not only the limits of calculability but also the structured ways in which uncertainty is organized – what is deemed sufficiently known, what is prioritized as needing to be better known, what is provisionally left unknown, and what is considered unknowable.

Rather than drawing on the sociology of knowledge, this paper therefore adopts a different lens: that of agnotology, examining the social structures and processes for the production of ignorance. Following in the vein of scholars like Smithson (1985), Proctor (2008), and MacGoey (2012), we approach ignorance not as an epistemic state but as a social construct. As opposed to a mere lack of knowledge, we treat ignorance as "[…] a productive force in itself" (MacGoey, 2012: 3) and a strategic resource to be mobilized – not simply denied – in claims to expertise (Rayner, 2015). By emphasizing the generative and strategic role of ignorance, we aim to illuminate its centrality in the scientific controversy on solar geoengineering. However, as Frickel and Edwards (2014: 216) note, agnotology has tended to pursue "a conspiratorial logic that ties the production of ignorance to the specific political, economic, or professional interests of powerful organizations and individuals' intent on keeping certain research results private." In contrast, we contribute to the literature that examines ignorance in a non-pejorative sense (Paul et al., 2022). Rather than viewing ignorance solely as a tool for sowing distrust, and thus as inherently problematic for trust in expertise, we examine its role as a contested resource that experts use to reconfigure authority.

A case in point – the Geoengineering Model Intercomparison Project

In the absence of observational data and given the controversial nature of field experiments, expert assessments of solar geoengineering rely to an overwhelming degree on computer simulation. A systematic approach to organizing data during virtual experiments is through model intercomparison projects (MIPs). Comparing simulations across different climate models is essential for assessing model biases, evaluating the robustness of climate responses to external forcings, and partitioning uncertainties in climate projections (Lehner et al., 2020). Climate models are computer codes that simulate digital analogues of the earth's climate system. While they serve as important tools for exploring how human activities might influence the climate and how different extremes could evolve, many climate processes occur at spatial and temporal scales too comprehensive to be explicitly represented in models, necessitating simplifications. As each model implements these simplifications differently, variability is introduced into the results. By establishing standardized experiments, MIPs help experts distinguish between actual climate responses due to human activity and the idiosyncrasies of individual models.

One such initiative is the Coupled Model Intercomparison Project (CMIP), a global infrastructure for climate modeling that has expanded significantly since its inception in the mid-1990s. Now in its sixth phase, CMIP coordinates more than fifty modeling centers worldwide and includes twenty-four endorsed MIPs. Although participating modeling centers contribute based on their own scientific interests and priorities, all must adhere to CMIP's standardized experimental protocols and data-sharing requirements. These standards ensure continuity, facilitate documentation of model characteristics over time, and make MIPs key sites for negotiating and designing climate model experiments. The Geoengineering Model Intercomparison Project (GeoMIP), founded in 2010, is one such CMIP-endorsed project. GeoMIP was initiated specifically to address inconsistencies in model studies of solar geoengineering, which produced widely varying results, with difficulties to distinguish the sources of these differences (Kravitz et al., 2011). Building on the experimental frameworks established by CMIP's fifth and sixth phases, GeoMIP follows the protocols, historical simulations, and data distribution mechanisms organized by the Working Group on Coupled Modeling of the World Climate Research Programme (Eyring et al., 2016: 1946). As a branch of CMIP, it coordinates a series of standardized experiments specifically designed to study the physical processes and assess the potential impacts of different strategies to modify the planetary radiation budget – from SAI to MCB, CCT, surface albedo modification, and even space-based sun shading. Over the years, GeoMIP has produced the largest body of scientific research literature and come to constitute an important network of expertise on solar geoengineering.

Building on previous work by Sundberg (2011), our approach is based on a qualitative research design that combines document analysis, ethnographic fieldwork, and semi-structured interviews. We draw on an extensive source of grey literature produced as part of GeoMIP, including workshop report drafts, meeting minutes, experiment protocols, vision statements, and workshop and conference posters and presentations. These documents capture early stages of expert deliberation, including justifications for experimental choices, reflections on protocol limitations, and discussions about the broader implications of research findings, thus offering a window into the processes through which expert judgement comes to bear on assessments of solar geoengineering. This rich documentation is a testament to GeoMIP's careful record-keeping, exemplified by the collaborative preparation and subsequent publication of finalized workshop reports in the *Bulletin of the American Meteorological Society*, such as those by Visioni and Robock (2022) and Visioni et al. (2023). In parallel, the ethnographic component of the study was conducted over a two-year period and involved participant observation at three annual, multi-day GeoMIP workshops, as well as other coordinating activities taking place in and around an international conference on climate engineering in general and an international forum on solar geoengineering in particular. Fieldwork included attending working group sessions, panel discussions, plenary talks, poster sessions, and informal networking events to observe negotiations around experimental protocols and methodological assumptions. In addition to field notes, the study also incorporates insights from semi-structured interviews conducted with active participants in GeoMIP. A total of ten interviews were conducted, with an average duration of forty-five minutes. Interviewees were recruited based on their involvement in experimental design and scenario development and followed a flexible guide designed to explore the same kind of negotiations as the fieldwork.

As opposed to treating analysis as a separate phase, we approached it as a continuous engagement with the GeoMIP constellation in which data collection and interpretation iteratively informed one another. This reflexive design allowed us to adjust field objectives and interview guides as our understanding developed, while insights from fieldwork and interviews in turn shaped our interpretation of documents and reports. Our aim was not to reach saturation but to remain attentive to the social construction of ignorance across different sites and stages of model intercomparison cycles – through the shared vocabularies, work routines, data standards, and experiment protocols and design choices that shape GeoMIP's organization of uncertainty. Rather than moments of in-group disagreement or tension, the analysis was geared toward identifying the accomplishment of consensus around the organization of uncertainty – an emphasis well suited to the empirical characteristics of MIPs. Since our analytical focus is on the constitution of solar geoengineering as an object of expertise, the study was guided by the controversies that surround this process. In particular, we treated the arguments advanced by opponents of continued investment in solar geoengineering research as a critical reference point in shaping both our empirical questions and analytical lens. These arguments suggest that even model experiments may unintentionally normalize specific framings of feasibility, safety, and risk, while ignoring others. They therefore helped us remain attentive to how expert practices render certain uncertainties salient and others invisible, and to how such dynamics shape the boundaries of legitimate expertise. Reflecting this orientation, we begin the next section by reconstructing the main lines of critique against solar geoengineering research, as we understand them, in order to situate our subsequent examination of how GeoMIP-affiliated experts organize uncertainty in practice.

Salience in controversial science – competing expert practices for reconfiguring authority

In highly polarized controversies, it is common for stakeholders on both sides to call for more research to clarify disputed or poorly understood issues. When it comes to solar geoengineering, however, that is decidedly not the case. Opponents argue that research should be approached with caution, as it could unintentionally normalize deployment, reduce the urgency of mitigation, and create misleading expectations about its feasibility and safety, all while potentially diverting attention from more equitable, long-term solutions to climate change. In the literature on the ethics of geoengineering, for instance, scholars have debated whether the mere pursuit of research could under certain circumstances delay emissions reductions, either by distracting or discouraging stakeholders from pursuing more effective decarbonization pathways, or by lending scientific legitimacy to the interests of those advocating for geoengineering to protect their fossil fuel assets from becoming stranded (e.g., Hale, 2012; Lin, 2013; Morrow, 2014; MacLaren, 2016). This reflects a broader point made by opponents of research: scientific findings, especially when preliminary or incomplete, can inadvertently lead to harmful outcomes. While scientific analysis and assessment can support policymaking, it can also cause harm, even when experts act with the best intentions (Tang, 2023a). Because experts operate within infrastructures that shape their work in ways they may not fully recognize, those infrastructures, if not carefully designed, can fail to make critical moral and security considerations salient to experts throughout the research process (Reynolds, 2019; MacLaren and Corry, 2021).

For this reason, some opponents of research even argue that model studies alone could generate institutional momentum, creating a slippery slope toward full-scale deployment (Hulme, 2014: 68–69; Callies, 2019; Tang, 2023b). As model studies of solar geoengineering are normalized, opponents are concerned that the demand for pilot studies to validate these results and calibrate the models with in-situ experiments will increase. Many in fact agree – proponents of research too (e.g., Keith, 2017), it should be noted – that the political consequences of how solar geoengineering is framed are critical to address, particularly in the early stages of research and development, as this initial phase represents a window of opportunity to avoid technological and institutional lock-in (Carr et al., 2013; Cairns, 2014; Stilgoe, 2015: 13; MacKinnon, 2019). In their proposal for a non-use agreement, Biermann et al. (2022) note that because solar geoengineering research relies on sophisticated knowledge infrastructures, it remains concentrated within a few institutions in North America and Europe. Due to these infrastructures being highly resource-intensive, the expert community is disproportionately shaped by a handful of industrialized countries, leaving less economically powerful nations with little to no ability to speak with authority in formal assessment processes (Biermann and Möller, 2019). This is especially troubling given that the global poor, who are most vulnerable to the negative impacts of solar geoengineering, would bear the greatest risks from unintended consequences of large-scale deployment (Preston, 2012). As an example of a lock-in effect then, opponents are concerned that this inequity in model studies may extend into field experiments and eventual deployment, since, as they argue, it is unlikely that industrialized countries would later relinquish control over sensitive know-how and geopolitically significant technologies to stakeholders with potentially competing interests.

In any case, the suggestion that solar geoengineering "research be considered separately from implementation" and that "we should proceed as we would for any other scientific problem, at least for theoretical and modeling studies" (Cicerone, 2006: 221, 223) is hotly contested. Opponents emphasize that the mere reliance of expert-led assessments on model studies establishes de facto governance mechanisms (Gupta and Möller, 2019) – ones that make certain risks salient while ignoring others. Indeed, aside from occasional concerns about the potential weaponization of stratospheric aerosols, most objections to research stem less from fears of deliberate misuse and more from the inherent limitations of model studies. Of course, most risks associated with novel technologies cannot be fully captured through full-scale experiments, making confident extrapolation difficult. But solar geoengineering, opponents argue, amplifies this challenge: it targets systems that cannot be easily isolated for study, yet its full complexity remains well beyond the reach of models (Bunzl, 2009). Moreover, opponents argue that model studies fail to account for crucial risks related to the security and governance of deployment (Sovacool et al., 2023: 4; Low and Honegger, 2022: 1970–1971), which may create misleading impressions of the feasibility and safety of solar geoengineering. Some of the risks that are most difficult to quantify, such as the geopolitical consequences of unilateral research and deployment (Low et al., 2022: 255–259, 261), are precisely those that should be central to policy discussions (Stephens et al., 2021: 1161). "An implication of this idea," Smith (2018: 342, 344) explains:

> is that various taxonomies of geoengineering strategies – those based on risk or on mechanism – will fail to capture all of the governance issues related to these strategies. […] [R]esearch and deployment of reflective aerosol particles are currently justified – if they are justified – on maximizing, consequentialist grounds in ways that ignore other considerations.

When opponents object to research then, they do so on the grounds that it institutionalizes ignorance by failing to make some of the most relevant impacts salient to risk assessment. As Low et al. (2022: 263) observe, opponents contend that "ESMs [earth system models] and IAMs [integrated assessment models] are mediums that are mediums that shape the message: solar geoengineering and carbon removal are made feasible through constrained modes of assessment based around modeling radiative forcing or techno-economic criteria." Because of its reliance on computer-based modeling, their concern is that limited conceptions of risk have gained disproportionate prominence within the solar geoengineering expert community (Low and Schäfer, 2019: 960).

In order to illuminate this concern, let us take GeoMIP's G1 experiment as an example. Like other model intercomparison projects, GeoMIP is structured around standardized experimental protocols designed to ensure comparability across models. These protocols organize experiments into hierarchical tiers: tier-1 experiments are prioritized for their broad scientific relevance and feasibility, while tier-2 and lower-tier experiments address more specialized research questions. This tiered system facilitates coordination by guiding modeling centers toward collectively recognized priorities. Among GeoMIP's core experiments, G1 is the simplest and most easily replicated across different climate models, as it offsets the radiative forcing from increased CO_2 by uniformly reducing the model's solar constant, trading on the fact that solar dimming broadly approximates the radiative effects of SAI. But while G1 offers clear methodological advantages for model intercomparison purposes, such as ease of implementation and a high signal-to-noise ratio, its idealized nature makes it insufficient for reliably assessing many of the risks of solar geoengineering. First, this insufficiency is particularly pronounced for variables such as regional precipitation, where solar dimming is a poor proxy for aerosol injections or other strategies. Secondly, G1's uniform solar reduction disproportionately cools the tropics, complicating comparisons between tropical and high-latitude effects. And thirdly, because solar dimming inaccurately represents the pattern of insolation reduction and stratospheric heating from SAI, there are substantial differences in surface climate response between the two representations, which could lead to erroneous conclusions when evaluating downstream impacts. Evidently, these shortcomings support concerns raised by opponents of research: some of the most policy-relevant variables are also those for which scenarios like G1 serve as poor proxies. Any uncertainties embedded in the earth system models inevitably then propagate through impact models, compounding uncertainties rather than resolving them – especially when considered alongside the variability introduced by different emissions pathways and solar geoengineering deployment scenarios.

Designing for known unknowns – transforming ignorance into a structured space of inquiry

One might thus expect proponents of research to counter criticisms of model studies by emphasizing what they know with relative certainty. While they have done so to some extent, this has not been their primary strategy. On the contrary, as Rayner (2015: 310) has noted, "one factor emerges strongly on both sides of the argument and is invoked both to justify and to oppose research into stratospheric aerosols. That factor is ignorance." In fact, proponents of research often justify their position by invoking ignorance too, arguing that model studies are essential for transforming so-called unknown unknowns into known unknowns (Keith, 2013: 39; Wagner, 2021: 66). GeoMIP-affiliated experts emphasize that the value of their model studies lies not exclusively in the ability to narrow down possible contingencies and outcomes, but at least as much in the ability to widen awareness of them. Rather than measuring success by a reduction in uncertainty – as if uncertainty was simply an obstacle to be eliminated – these studies serve to partition and attribute it, clarifying which processes contribute most to variability in model outcomes. Uncertainties surrounding stratospheric sulfate aerosols have not so much been resolved through GeoMIP experiments as their sources have been systematically dissected, with distinct roles attributed to aerosol microphysical growth, spatial distribution, and stratospheric circulation. Similarly, experiments on MCB, such as G4cdnc and G4sea-salt, have revealed critical insights into the role of cloud microphysics and the direct radiative forcing of sea salt aerosols – factors that experts now agree must be considered in any serious evaluation of MCB's feasibility, even though their exact impacts remain uncertain. The significance of illuminating key processes that shape uncertainties is further underscored by GeoMIP's decision to compare solar dimming and sulfate aerosols within identical experimental protocols – a methodological choice that became a tier-1 experiment in CMIP6. By running two distinct experiments targeting similar climate responses, it allowed experts to isolate the contributions of stratospheric uncertainties to the overall uncertainty in climate responses to solar geoengineering. Rather than treating experiments as isolated exercises in prediction, these intercomparison exercises highlight the indispensable role of experimental design in institutionalizing a form of expert advice that may support the recognition of limited awareness and how it might change over time, so as to inform decision-making on solar geoengineering by making the anticipation of a change in awareness play an active role in deliberations (Steele and Stefánsson, 2021: 87–89).

Another illustrative example is the modeling of SAI, where most simulations have relied on the precedent of volcanic analogs. Relying on analogs has practical advantages, as volcanic eruptions provide observational data that can be used to calibrate models. However, model studies indicate that sulfur dioxide injections would lead to the formation of larger aerosol particles than those from volcanoes, and that these particles, in turn, would reduce scattering efficiency, increase fall speed, and amplify unwanted side-effects. In response, the GeoMIP community designed a test-bed experiment to observe how a subset of models with interactive aerosol microphysics would react to different precursors, and by comparing sulfur dioxide injections it demonstrated that even when fixed amounts of material were injected, models exhibited significant differences in aerosol formation, radiative forcing efficiency, and cascading impacts on stratospheric dynamics. Here, the use of three models with different aerosol treatments allowed for more in-depth analyses of models' differences in terms of simulated size distribution, thereby highlighting the need for more detailed aerosol microphysics in climate models. In other words, multi-model experiments are often designed to probe for potential blind-spots, and the surprising outcomes they generate then serve as catalysts for further exploration of uncertainties. These surprises play a critical role in helping experts recognize previously unnoticed gaps in their understanding. Proponents of research thus argue that the key challenge lies not in the inherent incompleteness of risk assessments derived from models, but in our limited awareness of the boundaries of this incompleteness. In this sense, ignorance should not merely be understood "as unawareness or as the mere absence of knowledge, but rather as a specific kind of knowledge about what is not known." (Gross, 2016: 388). By experimenting with varying aerosol treatments, the model study revealed new contingencies that would otherwise have remained overlooked, in effect expanding awareness of what is yet to be fully understood.

A similar process can be seen in experiments on polar injections. While GeoMIP's early experiments primarily tested equatorial sulfur dioxide injections, the community also explored the effects of injecting aerosols into the polar stratosphere. Initial results suggested that polar injection was inefficient at reducing global mean surface temperatures and had adverse effects on global precipitation patterns. However, more recent experiments with seasonal injections during spring revealed that such a strategy could minimize disruptions while effectively restoring sea ice, with the added advantage of requiring injection at lower altitudes due to the lower height of the tropopause in polar regions. This illustrates that, as a GeoMIP-affiliated expert put it, "geoengineering may have important tradeoffs that need to be uncovered and discussed to inform future decisions around whether and how [it] might be deployed." Because "calls for 'more experiments' or 'more research,'" the expert complains, "often lack detail, which is a barrier to action." The notion of uncovering is key here. Instead of quantifying risks, what these model studies afford is a growth in awareness of the contingencies that affect a decision, such as by making entirely new contingencies salient – which, if they also prove relevant, may reframe the problems that experts need to assess, qualify the questions that policymakers will want answered, and make explicit the tradeoffs that the public needs to consider. As Keith (2013: 29), another GeoMIP-affiliate, puts it:

> Political conflict too often morphs into proxy battles about what constitutes objective fact. Nowhere is this more evident than in the battle over climate policy, where legitimate differences about the role of government and hard trade-offs between the welfare of present and future generations are played out as shrill debates about the "hockey stick" temperature record. This is similar to the debate about geoengineering, where proponents minimize risks and opponents exaggerate them.

Central to his observation, here, is not that opponents exaggerate risks – though he does seem to think they do – but that their focus on quantifying risk elides the proper role of computer-based models in expert assessments of solar geoengineering. He accepts that the low-probability, high-consequence tails of the probability distribution curve account for too much of the overall climate risk for models to fulfill that role. Moreover, "we cannot estimate the uncertainty very well," Keith (2013: 25) concedes, because "we do not know how much we do not know." His points is, however, that if expert assessments of solar geoengineering become entangled in disputes over risk, it obscures the broader value of model studies in contributing to a growing awareness of what we do not know.

Proponents often emphasize that many of the uncertainties associated with solar geoengineering – including those cited by opponents – have been identified through model studies in the first place. Some acknowledge, therefore, that while research may not illuminate all the risks that we would like, it could ultimately help settle the case against deployment, removing the issue from political consideration once and for all. However, most proponents do not share this view. Just as no amount of research can generate absolute certainty in favor of deployment, no amount of research can definitively rule it out. Decisions about solar geoengineering will never follow automatically from scientific findings because knowledge does not dictate action; rather, it is always mediated by values, priorities, and concerns. Science can clarify possible consequences, but it cannot resolve the normative and governance dilemmas that shape policy choices. Or, as yet another expert from the GeoMIP community puts it:

> We will obviously not know everything we need to know in the next year, or even in the next fifty years. That is not how decisions work anyway. […] Decisions are a continuous process. There is not just one magical risk-register that we put together and then that dictates how the field works. That is not what we are doing. What we are doing is talking about how we prioritize in the near term.

By foregrounding the ability of model studies to widen awareness of possible contingencies and outcomes, proponents challenge what Heyward and Rayner (2015) call the linear model of technology development, namely, the assumption that the possible outcomes of various deployment strategies can be directly extrapolated from early forms of research. They argue that such a linear conception implies an overly deterministic progression from research to deployment that in fact underestimates uncertainty and contingency. Put differently, more information does not always reduce the range of contingencies and possible outcomes. Instead, at any time throughout the research process, experts might suspect that there is some unknown contingency inconsistent with any contingency they are currently aware of, or that there are contingencies they recognize but cannot yet describe in sufficient detail, any of which could make solar geoengineering either significantly more beneficial or more hazardous than presently understood.

From the point of view of proponents then, modeling practices reveal a dialectical interplay between knowing and designing that is much more nonlinear, sometimes even overturning conventional assumptions about their relationship (see also Wiertz, 2016a: 446, 451). In the context of solar geoengineering, the standard view holds that knowledge must precede design, with the accumulation of knowledge guiding the development of implementation strategies. From this point of view, design is seen as a secondary phase, initiated only once sufficient understanding has been established. According to proponents, however, model studies illustrate that, in this case, design in many ways precede knowledge. For instance, the GeoMIP-affiliated experts treat variability and divergence between models as valuable sources of insight, which is made possible only through the coordinated and concerted effort of multiple modeling teams and experimental frameworks working in tandem. "The results demonstrate that it is possible to flip the research question that has been guiding geoengineering studies," one of the experts argues, "and not just explore what geoengineering does but see it as a design problem." This shift reframes solar geoengineering not as a phenomenon to be predicted but as an emergent object of design – one that is recursively shaped by the experimental frameworks used to explore it (Wiertz, 2016a: 452). Rather than treating uncertainty as a temporary deficit awaiting resolution, this perspective emphasizes the constructive role of experimental design in making ignorance operational. While it may seem intuitive to argue that designing for something about which these experts know little is premature or even futile, they insist that this intuition is wrong. Precisely because knowledge in this domain is severely limited and the problem ill-structured, careful infrastructural design is essential to structure experts' awareness of the limits of their knowledge. In this sense, model intercomparison exercises do not merely assist in widening our knowledge base, but more importantly, in widening our awareness of its limits. By making the blind-spots of models explicit through the act of coordinated experimentation, these experts actively transform ignorance into a structured space of inquiry.

Model studies and the epistemic virtue of learned ignorance

As an object of expertise, solar geoengineering has coalesced around a network of experts with technical competence in probing the limits of the existing knowledge base by jointly exploring the relevance of limited awareness. As we have seen, the stakes in these experiments extend well beyond testing the validity of scientific propositions against the behavior of a target system. Like Van Der Sluijs (2006: 56) argues is often the case for environmental assessments, it comprises bits and pieces of knowledge that vary in certainty and credibility, covering the entire spectrum from well-established facts to educated guesses, tentative assumptions, and crude speculations. This is not to suggest that quantitative risk plays an unimportant role in constituting solar geoengineering into an object of expertise (see, e.g., Felgenhauer et al. 2025). On the contrary, model intercomparisons are effective in building confidence in results by quantifying structural uncertainty in simulations of solar geoengineering. It should not come as a surprise, because scholars have long argued that risk discourse serves as a meeting point for different practices of risk management that should not be regarded as mutually exclusive. Most settings will involve a combination of such practices, not always involving probabilistically motivated calculation. Power (2014: 386), for instance, distinguishes between what he calls 'anticipationism' and 'resilience': the former is driven by a commitment to prediction and control, seeking to know and calculate the future through the extrapolation of past regularities; the latter arises from the recognition that such prediction is often impossible, emphasizing instead the capacity to withstand and adapt to unforeseeable events. While the anticipationist orientation aspires to manage risk through data-rich artefacts such as risk registers and warning systems, the resilient orientation redirects attention toward organizational design, redundancy, and recovery. In practice, these orientations frequently overlap. Even where prediction fails, the anticipationist impulse persists in the continuous production of analytical devices that mimic scientific control, while resilience strategies borrow from calculative practices to demonstrate preparedness.

Yet, neither anticipationism nor resilience fully captures the kind of practice that we observe among GeoMIP-affiliated experts. Their work does not primarily aim to predict or to prepare, but to probe – to expose the boundaries of what is known and to systematically expand awareness of its implications. Whereas anticipationism treats uncertainty as a deficit to be reduced and resilience treats it as a force to be absorbed, the GeoMIP-affiliated experts treat it as a constraint to be groped for orientation – something to be mapped and partitioned. Through model intercomparison as a form coordinated experimentation, they cultivate a distinctive norm of competence grounded not in calculative mastery or institutional preparedness, but in the sustained analytic capacity to make ignorance operational. To value awareness of the unknown as a foundational element of prudent action is nothing new. On the contrary, it has a particularly long and rich history. Ever since Socrates recognized that a person is only as wise as their recognition of their own ignorance, philosophers have reflected on the virtue of making the unknown salient. With his 1440 treatise *De Docta Ignorantia*, the renaissance man Nicholas of Cusa gave this virtue a fitting name – 'learned ignorance' (Franke, 2015). Revived most famously in the terminology of second-order cybernetics (Luhmann, 1993: 219–231), cultivating learned ignorance is to construct internal distinctions that allow a system to relate to the form of its own unknowing. This does not produce knowledge in the conventional sense, for the unknown cannot be directly represented. Rather, it results in second-order representations – representations of what is not represented – which make the distinctions constituting observation available to observation. In modeling practices, this approach is evident in the design of experiments that expose divergence, anomaly, and surprise – not to eliminate them, but to observe the sequence of operations as the modeling of a recursive blind-spot. Indeed, such reflexivity must be sociotechnically facilitated. It must be sustained by infrastructures that support observation of the system's own operations: protocols that highlight model disagreement, experimental tiers that isolate structural assumptions, and deliberative formats that make methodological decisions contestable. These do not resolve ignorance into knowledge; they organize ignorance into a space of inquiry. Within this space, what counts as a salient variable, a legitimate scenario, or a relevant trade-off becomes not just a matter of technical input, but of ongoing redefinition. Thus, the system orients not only toward the world it seeks to represent, but toward its own process of representation. It is in this recursive relation, where the system both observes and observes itself observing, that learned ignorance becomes actionable.

How proponents of solar geoengineering research justify their position, we claim, is through a revival of this ancient virtue, or at least a form of it. To call learned ignorance an epistemic virtue is to follow in the general vein of scholars such as Daston and Galison (2007) in providing thick descriptions of how norms that shape experts into honest, reliable, and competent advisors at the science-policy interface are enacted in practice. As Daston and Galison (2007: 41) put it, "epistemic virtues earn their right to be called virtues by molding the self, and the ways they do so parallel and overlap with the ways epistemology is translated into science" – or, we might add, the ways in which science is translated into policy-relevant assessment. And as in the case of moral virtues, epistemic virtues can not only coexist with or even support one another but also come into tension. In fact, we find that the scientific controversy on solar geoengineering research centers on disputes over norms of competence rather than over empirical truth claims. In making this distinction, we borrow from O'Neill (2018: 294), who has highlighted the difference between placing trust in the truthfulness of others' claims and trusting their commitments and competence – a distinction which aligns with the philosophical concept of two directions of fit. As O'Neill (2018: 294–295) explains:

> In trusting or mistrusting others' truth claims we aim to judge whether those claims fit or do not fit the world as it is. In trusting or mistrusting others' commitments or their competence we aim to judge whether their action will live up to their commitments and whether it will achieve the relevant standards of competence. The first direction of fit is empirical, and the second normative. The first aims to report on the world and the second to judge whether action meets or will meet relevant norms – inter alia norms of honesty, norms of reliability, and norms of competence.

In the first case, practice may fail because expertise itself fails, which can result in either inadequate explanations, flawed outcomes, or both. But the situation is different for the case of action-guiding norms in that they are intended to shape rather than fit the world: they are not applied in a straightforward manner but are instead enacted, as experts rely on the very norms they are in the process of enacting to guide their actions. Without an external point of reference, these norms function as both the basis and the benchmark for the work of experts (O'Neill, 2007). In our case, what the GeoMIP-affiliated experts enact is similar to what in decision theory has been called 'awareness growth.' Even in the absence of stable risk assessments then, these experts can maintain authority by appealing to their competence in helping policy audiences anticipate a growth in awareness. Since risk-averse agents – those particularly concerned about the unknown – should reasonably place a higher value on increasing their awareness than those who are less risk-averse (Steele and Stefánsson, 2021: 89), proponents of research turn the very concerns of the opponents into a strength. In this way, proponents argue that it is precisely the risk-averse that should embrace a commitment to expanding awareness, thus framing the particular expertise that they possess as not only necessary but also aligned with the caution that opponents advocate.

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Notes

1 Other methods are particularly amenable to regional application. So-called marine cloud brightening (MCB), for instance, seeks to enhance the reflectivity of low marine clouds by introducing sea salt aerosols that stimulate the formation of small cloud droplets, thereby brightening the clouds and increasing their albedo. Some deployments, like targeted MCB-interventions or land and ocean-based albedo modifications, are explicitly intended to produce localized effects, such as protecting vulnerable ecosystems or mitigating extreme weather impacts. Another, slightly less explored method is cirrus cloud thinning (CCT), which aims to reduce the warming effect of high-altitude cirrus clouds that trap outgoing infrared radiation. At the speculative end of the spectrum, proposals such as deploying orbital sunshades have also been suggested, though their long development timelines and prohibitive costs make them far less feasible.

2 This development aligns with Anthony Giddens' (1991) account of reflexive modernization, wherein modernity itself becomes the object of reflection and critique. Rather than resulting from ignorance, public skepticism toward expert institutions emerges from a heightened awareness of the risks that modern systems themselves generate. According to Giddens, this reflexivity does not undermine the role of science and expertise per se, but it does destabilize the taken-for-granted trust in institutional authority, as individuals and societies become more attuned to the limits of prediction and control in conditions of manufactured uncertainty.