Conducting more inclusive solar geoengineering research: A feminist science framework

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Abstract
Solar geoengineering, or deliberate climate modification, has been receiving increased attention in recent years. Given the far-reaching consequences of any potential solar geoengineering deployments, it is prudent to identify inherent biases, blind spots, and other potential issues at all stages of the research process. Here we articulate a feminist science-based framework to concretely describe how solar geoengineering researchers can be more inclusive of different perspectives and potentially contradictory conclusions, in the process illuminating potential implicit bias and enhancing the conclusions that can be gained from their studies. Importantly, this framework is an adoptable method of practice that can be refined, with the aim of conducting better research in solar geoengineering. As an illustration, we retrospectively apply this framework to a well-read solar geoengineering study (also led by the first author of this study), improving transparency by revealing its implicit values, conclusions made from its evidence base, and the methodologies that study pursues. We conclude with a set of recommendations for the geoengineering research community whereby more inclusive research can become a regular part of practice. Throughout this process, we illustrate how feminist science scholars can use this approach to study climate modeling.

Keywords
Solar geoengineering, climate change, Feminist Contextual Empiricism, research transparency, inclusive research

Introduction
Solar geoengineering, or the deliberate modification of the climate by reducing solar energy at Earth’s surface, has received increased attention in recent decades as a means of counteracting...
climate change. These ideas, such as creating a reflective layer of stratospheric aerosols (often sulfate) or brightening low clouds over the ocean, can temporarily offset anthropogenic climate change, allowing for the ramp-up of greenhouse gas emissions mitigation or negative emissions. Scientific research on geoengineering has grown substantially over the past decades (Crutzen, 2006; Oldham et al., 2014), including several national and international assessments of geoengineering (IPCC, 2013; NASEM, 2021; National Research Council, 2015a, 2015b; Shepherd et al., 2009).

Solar geoengineering is controversial, and there have been numerous calls to ban its use (Biermann et al., 2022) or even ban research on the topic (Stephens et al., 2021; Stephens and Surprise, 2020). Given current trends in global warming and the sociopolitical and economic drivers behind those changes, in the absence of solar geoengineering, the planet will exceed 1.5°C of global warming (above the preindustrial era) sometime in the next decade (IPCC, 2018, 2021). While this is not an argument for or against use of solar geoengineering, it does suggest that governments will be taking a critical look at its prospects and consequences in the coming years, and any decisions will be based at least in part on available knowledge about its effects (NASEM, 2021). As such, the position of this study is that, if research on solar geoengineering is to proceed, how can it proceed (more) responsibly?

Most of the research thus far in solar geoengineering has been directed by researchers in rich, industrialized countries in the Global North (Biermann and Möller, 2019). While these studies have been instrumental for advancing scientific understandings of solar geoengineering and its risks, the predominance of certain perspectives in producing knowledge and discourse can lead to blind spots and other serious policy and communication problems (DeLoughrey et al., 2015; Nelson, 2008; Sikka, 2018). In climate engineering and negative emissions technologies, narrow perspectives have led to mistaking modeling feasibility for real-world feasibility (Low and Schäfer, 2020); normalizing particular topics of discourse, which shapes policy (Beck and Mahony, 2018) or de facto governance (Gupta and Möller, 2019); and the enshrinement of particular values that are then imposed more broadly (Oomen, 2019). There have historically been few practical avenues for researchers from the Global South to join the geoengineering research community (Winickoff et al., 2015), leading to numerous debates in solar geoengineering meetings about what the developing world thinks (sometimes even phrased so reductively as to lump the entire Global South into a single entity). Recognition of these issues (Buck et al., 2014; McLaren, 2018) has led to more proactive efforts to include developing country perspectives and build indigenous research capacity in developing countries (Rahman et al., 2018). Nevertheless, it is likely that some perspectives will play a prominent role in solar geoengineering research for the foreseeable future. In a topic like solar geoengineering, which literally involves modifying Earth’s climate, the humility to recognize and address blind spots is of paramount importance. This question of “What are we missing?” is playing an increasingly important role in research that has an end goal of informing decisions, for example in modeling of climate change (Mehta et al., 2021; Scoones and Stirling, 2020).

The importance of facilitating more inclusive, representative, reflexive, and pluralistic scientific practice and outcomes has long been recognized; for example, the European Union’s Responsible Research and Innovation (RRI) framework embodies the idea of incorporating societal decisions into research to better understand consequences and solve societal problems (Owen et al., 2012). We argue that the use of Feminist Contextual Empiricism (Longino, 1990, 2019; Longino and Lennon, 1997; described in more detail in “Feminist Science as a Practice” below) provides a robust research structure that underscores the importance of diversity in research and provides concrete steps that solar geoengineering researchers can take to include diverse perspectives, with tangible positive outcomes for both the science and the researchers. In particular, feminist science approaches are built upon the values of inclusivity and multiple perspectives (i.e. they are directly
focused on showing why diversity matters) and provide space for those perspectives to be equally valued even if they conflict, providing the foundation for a framework whereby scientists can better interpret their results for more policy-relevant conclusions and include broader perspectives that challenge implicit biases and black-boxed assumptions (Sikka, 2018). In addition, through an examination of solar geoengineering, we illustrate an approach whereby feminist science scholars can apply their methods to climate modeling. Through these synergistic approaches, we aim to demonstrate the added value these two different disciplines can provide to each other. Indeed, a ready example is the present work: Kravitz is a climate modeler, and Sikka is a feminist scholar. Both authors have expertise on solar geoengineering but from substantially different perspectives, which engenders a powerful interdisciplinary collaboration that draws on the strengths of both fields.

Feminist science as a practice

A brief introduction to Feminist Contextual Empiricism

A goal of feminist science is to open up new avenues of thinking and analysis while attending to gender and other forms of bias by building on the social study of science (Pickering, 1992). Feminist science focuses specifically on issues of representation and diversity in the sciences, serving as an adoptable method of practice by providing tools to increase inclusivity.

We apply Feminist Contextual Empiricism (FCE) (Longino, 1990, 2019; Longino and Lennon, 1997), which is rooted in the premise that science is value-laden (wherein objectivity and impartiality are established norms) and argues that an important goal of science is to pursue better values. FCE expands upon the values of accuracy, consistency, broad scope, simplicity, and fruitfulness (Kuhn, 1977) to embrace equity and justice wherein truth is achieved through discursive consensus formation. By explicitly including multiple interpretations of the same phenomena, values and underlying assumptions are laid bare, revealing the evidence bases for arguments and theories (Longino, 1990). Although the original iteration of FCE focused on gender differences in experiential knowledge and the unequal power relations in which women are enmeshed, it has since grown (in some cases converging with other avenues of thought) to encompass additional feminist values including heterogeneity and mutuality of interaction in which plurality and complexity of explanation are prioritized. FCE also contends that research must be applicable to human needs, for example, aiming to alleviate misery (Longino, 1996). These norms do not constitute a fundamentally new approach to science, but rather an evolution that is consistent with the idea of scientific revolution (Longino, 1987).

At the root of FCE is the accumulated experiential knowledge of women stemming from their engagements with unequal relations of power (both interpersonal and structural). The biases women face are persistent, pervasive, and in many cases can be overtly hostile (NASEM, 2020). The understanding that emerges out of these experiences can be used as a resource. Similar examples of power disparities that commonly occur in research environments include those of race, nationality, wealth, sexuality, career stage, and geography. In science, it is often the case that the perspectives of the marginalized are repressed in favor of the dominant group, which can stifle creativity, diminish the agency of the workforce and, in some cases, result in the persistence of harmful lines of thought (Lloyd, 2009; Metoyer and Rust, 2011; Young et al., 2019). Rather than enduring the dominance of one kind experience or background or, in extreme cases, the assertion that one set of views or conclusions is “right,” FCE provides a pathway for incorporating pluralism, including multiple sources of hypotheses and analyses into research resulting in a more holistic understanding of the problem at hand (Wylie, 2007). This is what makes feminist empiricism not feminine (thereby eschewing gender essentialism), but
feminist. FCE is fundamentally about examining how scientists practice science, specifically how research is conducted in a way that is consistent with the scientists’ values (Longino, 1987, 1990). In addition to a practice by which science is performed, FCE (and frameworks like it that focus on inclusion of a variety of perspectives) can be used as a tool to reevaluate previous studies or conclusions to obtain stronger or more actionable results. (We note that while FCE is founded in issues of gender, it retains applicability to race and class, providing space for intersectional analysis going forward.)

In addition, feminist science contends that a critical aspect of feminist critique involves the re-examination of biased language (e.g. metaphors and descriptions) that shape scientific practice. Scientific practice is often a reflection of society, including societal gender bias, and in turn science can serve as justification for gender discrimination (Sheets, 2003), including in solar geoengineering (Buck et al., 2014; Sax, 2019).

FCE in particular is a forward-thinking methodology that is distinct among other feminist approaches to science: (1) FCE is built on firm commitment to empirical adequacy or accuracy as it relates to observational data (Haraway, 2004; Harding, 2009), which is particularly important for climate science as it demands “agreement of the observational claims of a theory with data” (Kellert et al., 2006) while retaining the ability to reveal bias. (2) FCE articulates a set of novel, contextual, noncognitive values (like mutuality of interaction) that challenges Kuhn’s framework, a unique feature among feminist approaches. (3) FCE redefines objectivity as a social phenomenon reached through criticism and debate based on a rigorous communicative framework, in contrast to (for example) technofeminism and standpoint theory (Hekman, 1997; Wajcman, 2010). (4) Unlike many other approaches, FCE ascribes normative value to how scientific values should be judged and adjudicated (e.g. through consensus) (Lykke, 2010), which is relevant for the recent discussions in climate science about model democracy (Knutti, 2010; Tebaldi et al., 2011). (5) While a number of feminist frameworks highlight the importance of diversity, pluralism, and heterogeneity (Clough, 2003; Subramaniam, 2009; Wyer et al., 2013), FCE uniquely views difference as ontological, thereby codifying equal standing for different types. This shifts the justifications of heterogeneity from attitudinal to methodological in ways that reject theories of assumed racial, gender, and class inferiority.

In addition to a practice by which science is performed, FCE (and frameworks like it) can be used as a retrospective tool to reevaluate previous studies or conclusions. This is useful not only for revealing how biased viewpoints can result in consequential erroneous conclusions, but also for showing how more inclusive practices can help avoid these pitfalls.

A feminist science-based framework for conducting and evaluating science research

Building on the principles of FCE, we aim to establish a framework whereby solar geoengineering research can adopt feminist science values, asking questions like:

1. For what ends are we practicing science?
2. Whose interests do the phenomena we are studying serve?
3. What are the values that underpin scientific knowledge?
4. Are our chosen models and laboratory practices hierarchical or interactional (and why have we decided to consistently favor hierarchy)?
5. What criteria are we using to justify acceptance of evidence?
6. Are there alternate explanations or hypotheses that can explain the phenomena under investigation?
7. How do we describe science (e.g. by using gendered language)?
The order in which these questions are asked was chosen deliberately. This was in part to align with FCE practices (e.g. Question 1 is most close to the purpose of FCE). But also, this framework is designed as a practice that practitioners (like natural scientists) could follow. By beginning at the top of the list and working down, the overall purpose of the study is interrogated first, thereby shaping the rest of the investigations (and in turn the answers to the rest of the questions) and ensuring that the labor of the study is true to the purpose.

Scientific knowledge is produced by peoples and cultures but retains a claim to objectivity, which has led to politicization and blind spots (Bijker, 2017; Hoppe, 2005). Paralleling movements in other parts of social science, these inquiries aim to interrogate underlying assumptions. In climate science, the dominance of specific tools like Earth System Models, which have their own uncertainties, biases, and assumptions, has led to narrow representations of complexity and partial conclusions (Schneider, 1997; Shackley et al., 1998). In addition, the IPCC process, which aims for consensus, has been criticized for downplaying uncertainty and dissent and producing overconfidence in conclusions (Van Der Sluijs, 2012). There are parallel arguments for pluralism in other sectors, such as energy, energy substitution, and climate research, for similar reasons (Sovacool et al., 2020).

Inclusive solar geoengineering research

Solar geoengineering would not be able to perfectly offset climate change from increased atmospheric carbon dioxide (Moreno-Cruz et al., 2012). It would be effective at offsetting a large portion of the changes in temperature and precipitation (Irvine et al., 2019). A moderate amount of geoengineering (Keith, 2013) in a high CO₂ future would likely result in a climate closer to the present day than a future with high CO₂ alone for a variety of climate variables (Tilmes et al., 2013). We hereafter restrict discussions to solar dimming and stratospheric aerosol geoengineering. While other methods of solar geoengineering, like marine cloud brightening or cirrus thinning, may have applicability to the arguments presented here, we did not give sufficient attention to these proposed technologies to justify making broad conclusions.

Retrospective analysis of a solar geoengineering study

As an illustration of how this feminist science-based framework might improve or reevaluate previous studies, we revisit “A multi-model assessment of regional climate disparities caused by solar geoengineering” by Kravitz et al. (2014). We chose this work because it was led by the first author of the present study, which has the advantage that the authors are intimately familiar with the process of conducting that study. Also, if one is going to throw stones in glass houses, at least this way it’s not someone else’s house.

This study describes analyses of 12 models participating in Geoengineering Model Intercomparison Project (GeoMIP) experiment G1, an idealized solar geoengineering simulation involving an abrupt increase in the CO₂ concentration and an abrupt decrease in solar input (Kravitz et al., 2011). The authors then evaluated changes in temperature and precipitation in 22 “Giorgi regions” (Figure 1) covering the populated continents (Giorgi and Francisco, 2000). They did so by linearly scaling the climate model output from GeoMIP to determine what each model says is the right “amount” of geoengineering to offset temperature change, precipitation change, or any weighted combination of the two for any of the regions, as well as the global average (Figure 1). The optimal amount of solar
geoengineering minimizes a “dis-utility” (damage) function $D_i$ for each Giorgi region $i$, defined as:

$$D_i(w; g) = \sqrt{(1 - w)[\Delta T(g)]^2 + w[\Delta P(g)]^2}$$  

(1)

where $w$ is a weighting function between temperature and precipitation (varies between 0 and 1), and $g$ is the amount of solar geoengineering, where $g = 1$ is defined as the amount that exactly offsets global mean temperature change due to high CO$_2$. $\Delta T$ and $\Delta P$ are the (normalized) amount of temperature and precipitation change, respectively, from the baseline. Positive and negative changes are treated symmetrically.

Their conclusions can be roughly summarized:

- All models show that a sizable amount of solar reduction would bring CO$_2$-caused temperature change closer to the baseline in all 22 regions. Beyond that amount, there is at least one region that is “overcooled”—the amount of temperature change is greater under geoengineering than under climate change.
- In every model, any amount of solar reduction exacerbates the precipitation changes due to climate change in at least one region. That region differs between different models.
- Most combinations of temperature and precipitation (most values of $w$) have the same conclusions as for temperature alone ($w = 0$). This is because all changes were normalized by their respective standard deviations so that temperature and precipitation could be compared directly. Precipitation is highly variable, whereas temperature is comparatively less variable, so even small temperature changes disproportionately affect the metric $D_i$.

**Figure 1.** The 22 Giorgi regions (left) explored in this study and the results of the 12-model mean for temperature (top right; °C) and precipitation (bottom right; mm/day) for each of those regions. x-axis values of 0 indicate temperature or precipitation changes under a high CO$_2$ world with no geoengineering, and values of 1.0 indicate offsetting global mean temperature change from CO$_2$ with solar geoengineering (solar reduction). y-axes indicate a “dis-utility” function, measuring departures from a preindustrial baseline (values closer to 0 are “better”). All panels are reprinted from Kravitz et al. (2014) under a CC BY 3.0 license.
These conclusions are an example of underdetermination (Longino, 1990, 2002), in that the same data can reveal widely varying conclusions and interpretations. FCE has much to contribute to this topic, as is discussed below.

Citations to Kravitz et al. (2014) have been used for statements with a variety of positions about differential regional impacts from solar geoengineering: a moderate amount of solar geoengineering will benefit everyone (Winickoff et al., 2015); solar geoengineering would have a mixed effect on precipitation changes, leading to winners and losers (Keith and Irvine, 2016); and a combination of the two positions (Heutel et al., 2016). Each of these statements is consistent with the current state of knowledge, but with different sociopolitical implications and different influences on discourse.

Revisiting Kravitz et al. through an inclusive framework based on feminist science

Here we address (a) how Kravitz et al. (2014) explicitly or implicitly provided answers to the questions in “A Feminist Science-Based Framework for Conducting and Evaluating Science Research”; (b) how their study exemplified inclusive principles or missed opportunities to incorporate inclusivity (and what that inclusivity could have added to the study); and (c) how feminist practices can be used to improve the way their study might have been conducted.

For what ends are Kravitz et al. practicing science?. No scientific study is purely motivated by curiosity and knowledge production. Scientists have many choices about how they could spend their limited time, and presentation of a completed study implicitly contains choices about what to include (or not).

A winners/losers framing implies assessments of distributional justice and alleviation of misery from climate change. Success in this aim could look like identifying the potential for geopolitical strife (who would be affected and how?) or providing specific, actionable outcomes. The regions being disadvantaged by geoengineering under the chosen metrics in the study differed among models, and because the regions were not based on geopolitical, socioeconomic, or cultural/demographic boundaries, there is little potential for the study to result in anything actionable (which, given the idealized nature of the study, might be seen as a benefit so as to avoid misinterpretation of the results as being policy-relevant).

Kravitz et al. built off earlier work (Ricke et al., 2010) to refine uncertainty bounds around regional differences in outcomes from solar geoengineering and to build confidence in their conclusions. Keeping in mind the caveats related to limited sources of evidence, model intercomparisons are effective in building confidence in conclusions by quantifying structural uncertainty in climate model simulations of solar geoengineering.

Whose interests do the phenomena Kravitz et al. decided to study serve?. Kravitz et al. aimed to resolve uncertainty (see “For what ends are Kravitz et al. practicing science?”), but uncertainty for whom? Scientists want to improve the knowledge base, whereas policy makers want to reduce chances of making political mistakes; miscommunications in the policy making process result from these different conceptions (Enserink et al., 2013). These difficulties are exacerbated when scientists advocate for policy to influence decision making. By evaluating some of the uncertainties addressed by Kravitz et al., we can better understand what interests they are attempting to serve and how successful they were:

• Climate impacts. What are the temperature and precipitation impacts, on a regional basis, of different amounts of solar geoengineering?
Model spread. Do different models agree on the climate impacts of different amounts of solar geoengineering? Do they disagree? Where?

Environmental equity. Would solar geoengineering result in winners and losers?

Environmental justice. Could solar geoengineering alleviate suffering from climate change? For whom? With what consequences?

Climate models are clearly adept at addressing the first two. For the latter two, climate models may be important, but they are missing fundamental pieces that would allow them to address equity or justice, for example impacts assessment, integrated human-societal modeling, and rigorous policy analysis. Inadvertent overreach could be circumvented by consciously evaluating the scope of the study: what questions do we want to answer, and do we have the right tool?

There are three prevalent “cognitive frames” in which climate scenarios sit (Haikola et al., 2019): discussions of possible future scenarios, political prescriptions that attempt to force particular future scenarios/policies, and distortions of science. In which frame(s) are Kravitz et al. operating when they conducted their study, and in which frame(s) are their results being used? This is not simply a thought exercise: by conducting simulations, scientists are telling policy-shaping stories with those models (Beck, 2018); such narrative structures (constrained by the rules encoded into the models) are unavoidable components of modeling (Morgan, 2001). Because of the ubiquity of climate modeling in solar geoengineering, modeling is responsible for how solar geoengineering is understood (Wiertz, 2016).

Kravitz et al. never explicitly decided upon sociopolitical aims or policy questions for their study, and doing so might have shaped the way in which they conducted their analyses or the results they chose to show. It is clear that others have used physical science studies as evidence for arguments about environmental justice issues in solar geoengineering, sometimes to take positions against solar geoengineering deployment (McKinnon, 2020; Surprise, 2020) or research (Stephens and Surprise, 2020). By implicitly framing their study about winners/losers, Kravitz et al. inadvertently entered into a debate about environmental justice issues in solar geoengineering and, in many senses, helped shape that debate through the futures and outcomes they chose to model. We are not arguing that scientists can avoid policy discussions, and indeed science can be an important part of the evidence basis around which policy is made. Rather, we point out that when conducting studies, it is important to critically evaluate what stories the study is telling. Some key questions Kravitz et al. could have asked include:

- What story is this study telling about winners and losers?
- Are winners and losers from solar geoengineering inevitable?
- Is this issue a potential showstopper for solar geoengineering?
- When describing the results, how much attention should be paid to the winners, and how much to the losers?
- Is there actually a binary between winners and losers?

This list is far from comprehensive, but it is aimed at recognizing the power of narrative: models reproduce and reinforce certain discourses and silence others (Ellenbeck and Lilliestam, 2019). By focusing on what a model simulation represents, not just its output, assumptions can be laid bare for scrutiny.

What are the values that underpin the science in Kravitz et al.? There are several implicit or explicit values that guide the analyses of Kravitz et al. Our purpose is not to assess how well those values serve the purposes of Kravitz et al. or how to do better, but instead to name the values and lay bare their implications, which FCE calls for. In doing so, we illustrate where the assumptions or chosen
methodologies could have led to knowledge gaps. Kravitz et al. incorporated (and sometimes simultaneously missed opportunities to incorporate) the following values in their analyses:

- Choice of variables (mean temperature and precipitation), which emphasizes regions for which those variables are relevant and de-prioritizes others
- Standardization, which improves confidence because it enables multi-model intercomparison but necessitates more idealized scenarios
- Participation, in which all available models were included, with varying degrees of accuracy
- Precedent, focusing on Giorgi regions because past geoengineering studies used them
- Quantification, which allows for more precise answers but also introduces assumptions and caveats that may affect accuracy of the results
- Consensus, emphasizing model agreement and spending less effort diagnosing why models may disagree
- Diversity of model response, which lets readers apply their own contexts rather than implicitly making decisions for them as to what is important
- Transparency, in which the findings are reproducible and assumptions embedded in the study are explicitly described.

Several of the values stated above may appear to be incompatible or mutually exclusive, such as consensus and diversity of model response. This is not a flaw of inconsistency, but rather an example of how applying principles of FCE (even if unknowingly at the time) can produce richer conclusions.

We provide more details and description as to the implications of these values.

Choice of variables. It would be impossible for a single study to evaluate all variables relevant to the impacts of climate change and geoengineering, so this study limited its analyses to changes in temperature and precipitation. These two variables are important for characterizing a breadth of climate impacts (IPCC, 2014). Although precipitation is not a perfect proxy for moisture availability, it sufficiently represents hydrological cycle changes under both climate change and solar geoengineering (Cheng et al., 2019). Moreover, solar reduction and stratospheric sulfate aerosol geoengineering cannot simultaneously compensate changes in both temperature and precipitation under solar reduction or stratospheric sulfate aerosol geoengineering (Niemeier et al., 2013; Tilmes et al., 2013), so this choice is illustrative of trade-offs. Nevertheless, choosing temperature and precipitation de-prioritizes regions where other variables might have greater relevance. For example, snow cover in high latitude regions or changes in free tropospheric wind shear (the latter of which is relevant for hurricane formation and intensification) may have tangible impacts on vulnerable populations that are not captured by temperature and precipitation. Importantly, while temperature often serves as a useful proxy for a wide variety of climate impacts under climate change (IPCC, 2014), that relationship no longer holds under scenarios with substantial solar geoengineering, as one can suppress temperature change but still have side effects from the combined forcings of greenhouse gases and solar geoengineering (Irvine et al., 2016).

Standardization. This study was conducted under the auspices of GeoMIP, meaning that all participating models conducted the same idealized solar reduction scenario. As such, researchers can evaluate places where the models agree (building confidence in those conclusions) or disagree (highlighting areas for further research). Nevertheless, standardization necessitates compromise in scenario design: the scenarios are often idealized (and in the case of G1 idealized to the point that its relevance to stratospheric aerosol geoengineering is questionable) (Visioni et al., 2021) to encourage broad participation and to aid in analysis of the results. Less coordinated efforts have more freedom to explore alternate scenarios for specific purposes but without the confidence gained through a multi-model intercomparison. This point reinforces the central FCE notion that
knowledge is contextual: different studies may reach different conclusions depending upon how those studies are conducted. While there is an indication that G1 may be too simple to appropriately represent the climate effects of stratospheric sulfate aerosols (Visioni et al., 2021), in other contexts it may not always be clear whether, among two studies that conflict, one is “right” and one is “wrong.”

Participation. Kravitz et al. used an experiment in which (at the time) 12 models participated. All models were weighted equally, without an attempt to determine whether there should be greater or less confidence in any one model’s results. Moreover, while there are efforts to weight models or eliminate poor-performing models in studies of climate change (Tebaldi et al., 2011), because there are no real-world observations of geoengineering, there is less basis on which GeoMIP studies could perform a similar evidence-based weighting. As such, participating models may vary in the accuracy of their temperature or precipitation responses to forcing. Again, rather than viewing this as a problem for reaching a consensus answer, FCE argues that the diversity of model responses is a strength that provides a more holistic picture of the potential climate response to geoengineering. Every model participating in GeoMIP has fundamental physical underpinnings (what Lloyd (2015) refers to as the causal core), and as such, without other information, we have no evidence basis to conclude that any particular model is so wrong that it should be excluded from analysis.

Precedent. Much of the analysis by Kravitz et al. focuses on Giorgi regions for ease of analysis and to improve robustness of the results, as analyzing each model grid point separately would be cumbersome, and spatially aggregated results are often more trustworthy than results from individual grid boxes. Nevertheless, there are numerous choices for spatial aggregation that could have been pursued, including geopolitical boundaries, Köppen-Geiger climate regions, or even bands of latitudes on different continents. In large part, the Giorgi regions were chosen for this study because they were used by Ricke et al. (2010) in a previous geoengineering study. The Giorgi regions have been used in numerous other geoengineering studies, although it would be difficult to argue that their use has been disproportionate compared to other climate research fields.

Quantification. Kravitz et al. focused on providing quantitative results regarding regional disparities, including a weighting between temperature and precipitation changes. This required several assumptions and methodology choices that affected the results in a variety of ways that have not been thoroughly studied.

- The scenario G1 was compared to a scenario with a quadrupled CO₂ concentration, resulting in a high signal-to-noise ratio but running the risk of exciting climate system nonlinearities, which may result in regional changes that are not representative of moderate climate change or solar geoengineering deployments.
- The “amount” of geoengineering to meet particular outcomes was obtained through linear scaling of the climate effects. This invariably introduced error into the results, although the error is likely greater for extreme scenarios rather than scenarios near the preindustrial baseline.
- To incorporate temperature and precipitation into the same metric, Kravitz et al. normalized changes by the standard deviation of interannual variability, as has been done before (Ricke et al., 2010). This skews the metric toward temperature changes, as the interannual standard deviation of temperature is substantially smaller than that of precipitation.
- They included a quadratic “dis-utility” function (Equation 1), which disproportionally penalizes large departures from the baseline of comparison. This may be appropriate (Nordhaus, 2017) but also places more emphasis on the choice of baseline than a linear metric. Also, it contains the assumption of symmetry, in that “undercooling” by X degrees (as compared to the baseline) is just as damaging as “overcooling” by X degrees.
- They averaged over 22 Giorgi regions, which certainly impacted the results (Figures 2–4).
**Figure 2.** Temperature (°C) change in the high CO$_2$ world (left) and a world with high CO$_2$ and solar reduction (right) in the South Asia Giorgi region. Top row shows annual mean changes over a 40-year average of simulation, middle row shows June-July-August average change, and bottom row shows December-January-February average change.

*Consensus.* Many GeoMIP studies tend to focus on model agreement, evaluating the ensemble average or narrowness of the range of model responses (Kravitz et al., 2013). This reflects the core value of consensus within GeoMIP: evaluating where models agree and where they disagree.
Kravitz et al. (2011) emphasized consensus in the form of a Pareto-improving criterion (Moreno-Cruz et al., 2012): how much can the amount of solar geoengineering be increased before any one of the 22 regions is harmed?

**Diversity of model response.** Although some results were obscured by averaging, the results included presentation of model diversity (e.g. Figures 1 and 4). Other disciplines have similarly heterogeneous approaches to reporting results. For example, health impacts of climate change often
incorporate climate model information on outcomes but rarely include local knowledge or value-driven community data, making it impossible to accurately prioritize information, provide meaning, and decide on courses of action (Donatuto et al., 2020). Allowing for a diversity of model responses lets readers apply their own contexts instead of implicitly deciding for readers by aggregating the results.

Transparency. The value of transparency is simultaneously demonstrated and not demonstrated by Kravitz et al. Descriptions of the methodology and findings are transparent.

Figure 4. The “amount” of geoengineering (solar reduction) required to offset temperature change (left) or precipitation change (right) in South Asia (SAS) or different locations in the South Asia domain (RG#). Amount (y-axis) is defined as a linear scaling where 0 is no solar reduction, and 1 is the amount of solar reduction that will offset global mean temperature change in the annual mean (top), June-July-August mean (middle), or December-January-February mean (bottom). Box and whiskers show the interquartile and range of the 12-model spread, red lines show the median model, and grey bars show the model average. All panels are reprinted from Kravitz et al. (2014) under a CC BY 3.0 license.
and reproducible, and the analysis methods have been used by other studies (Irvine et al., 2019). However, many other value-laden assumptions are embedded in the study but not explicitly described, meaning they cannot be easily examined for inadvertent effects on the results or conclusions. There is potential for some assumptions to have serious ethical implications (Beck and Krueger, 2016). This issue is widespread and certainly not limited to solar geoengineering (Bistline et al., 2021).

Are the chosen models hierarchical or interactional? By hierarchical modeling, we mean approaches in which a single model (or class of models) is run with a set of inputs provided by another model or data source, and the set of outputs is then handed to another set of models or stakeholders (e.g. impacts models). In contrast, interactional modeling involves coupling multiple classes of models to incorporate feedbacks between them, as is common practice in Detailed Process Integrated Assessment Models (Weyant, 2017).

Kravitz et al. exclusively conducted hierarchical modeling without incorporation of climate-society feedbacks (Calvin and Bond-Lamberty, 2018). This is not a criticism, but rather a reflection of their intent: experiment G1 is highly idealized and, while such idealized simulations are essential for gaining critical knowledge about the functioning of the climate system (Kravitz et al., 2013), they are poorly suited to evaluate impacts, policy, or societal feedbacks (Kravitz et al., 2020).

Figures 2 and 3 show annual and seasonal mean temperature and precipitation results for a high CO2 world (abrupt4xCO2) and the high CO2 world with solar reduction (G1). As Kravitz et al. state, the assumption of homogeneity across individual Giorgi regions does not hold. Figure 4 shows what each model says is appropriate “amount” of solar reduction to offset temperature or precipitation changes at different points in the South Asia Giorgi region. These spatially and temporally refined results indicate that aggregation obscures results.

However, one cannot determine whether those more granular differences matter by only using a hierarchical modeling approach (Longino, 1990; Sikka, 2018). It is not obvious whether cooler temperatures or less rain are good or bad for communities in particular regions (Sedova et al., 2020). Moreover, hierarchical modeling can miss important conclusions or factors that would be revealed by interacting directly with communities. As an example, Arctic communities are psychologically impacted by increased winter rainfall and decreased snowfall, leading to increased incidence of depression and suicide (Mettäinen et al., 2022). Common overextensions of hierarchical modeling include (A) physical climate is a good proxy for impacts like food and water security, or (B) less climate change is better. As a counterexample, interactional modeling has revealed that water resource scarcity may be worsened by greenhouse gas emissions mitigation achieved via increased use of biofuels (Hejazi et al., 2015).

How can solar geoengineering research begin to include a more interactional approach? Some obvious low-hanging fruit is to involve more communities who can provide needed perspectives. For example, the field has slowly evolved to include collaborations with experts in various impacts-related fields—agricultural impacts (Fan et al., 2021; Proctor, 2021; Xia et al., 2014), air quality and human health (Eastham et al., 2018; Madronich et al., 2018; Nowack et al., 2016), and ecosystem effects (Trisos et al., 2018; Zarnetske et al., 2021). Another useful step could involve scenario design that incorporates reflexive or participatory modeling (Bistline et al., 2021; McLaren, 2018; Willey, 2016). Involving a variety of stakeholders in the design stage of modeling scenarios, as has been called for in integrated assessment modeling for carbon dioxide removal (Low and Schäfer, 2020; Salter et al., 2010) and solar geoengineering (McLaren, 2018), could address issues of equity in outcomes, in line with the FCE arguments we have presented here. This has the added advantage of increasing transparency of the often poorly documented values and assumptions that go into modeling (Bistline et al., 2021).
Finally, Kravitz et al. found that for temperature, many regions “benefit” from a substantial amount of geoengineering, but for precipitation, at least one region is made worse off by any amount. Presenting either conclusion in isolation would have provided a misleading picture. Instead, Kravitz et al. inadvertently chose an approach more aligned with feminist science by presenting a plurality of outcomes rather than generalizing for the reader and obscuring potentially important conclusions.

What criteria do Kravitz et al. use to justify acceptance of evidence?. Solar geoengineering has not been deployed in the real world, and the use of natural analogues (like volcanoes) has limits, so most results about solar geoengineering are from climate models (Kravitz and MacMartin, 2020). Even though models are inevitably wrong in some capacity, in the absence of other sources, the evidence provided by models is sometimes accepted as an approximation of what might happen in real world deployments of solar geoengineering (Wieding et al., 2020), even in the highly idealized G1 scenario (Flegal and Gupta, 2018).

A multi-model ensemble average tends to be more accurate than individual model results because various forms of random noise/error get averaged out (Knutti et al., 2010). Similarly, time averaging reduces noise from interannual variability. Also, averaging reduces the dimensionality of the results, which makes displaying the results tractable. Nevertheless, averaging also obscures results. Figure 5 shows that the model average of (time-averaged) temperature or precipitation often has a different sign of response from the minimum or maximum over all models. Kravitz et al. to a large degree focus on robustness and multi-model agreement, but a feminist science approach would argue that disagreement or outliers could be just as important, especially since there is no strong justification to believe model consensus over individual model results for the simulations they study.

Based on a history of volcanic eruption simulations before there were sophisticated methods of representing aerosol microphysics (Handler, 1989), it is often assumed that solar dimming is a useful proxy for the climate effects of stratospheric sulfate aerosols. Because solar dimming inaccurately represents the pattern of insolation reduction and stratospheric heating from stratospheric sulfate aerosol geoengineering, there are substantial differences in surface climate response between the two representations, which could lead to erroneous conclusions when evaluating downstream impacts (Visioni et al., 2021).

Comparing simulations of solar geoengineering with the baseline highlights imperfections in how well geoengineering compensates for climate change. Many have argued that a fairer comparison (and one truer to the intended purpose) is to compare solar geoengineering against a world with high CO₂ alone (Govindasamy and Caldeira, 2000; Rasch et al., 2008). Many GeoMIP studies show both to present a more holistic picture of the results (Kravitz et al., 2013). Values near zero can be represented as white to obscure small changes, or one can choose color scales that have warm colors for any positive value and cool colors for any negative value. The latter choice emphasizes differences between geoengineering and the preindustrial baseline, whereas the former downplays differences. Any attempts to quantify results will require a choice that has advantages and disadvantages, but FCE argues that these choices reflect values and interests that should be interrogated (Sikka, 2018).

Moreover, a tenet of FCE is that knowledge is intersubjectively produced; that is, by only focusing on output from models and not including social aspects of knowledge production, vast sources of knowledge are missing from this study. While not a criticism per se of Kravitz et al. (2014), as there is value in modeling studies and no study can do everything all at once, this work would have been made stronger had this point been acknowledged and potential gaps identified.
With these issues in mind, we argue against universal standards of analysis, evaluation of uncertainty, or reporting, as any such standards would inadvertently introduce bias into the emergent conclusions from the field. Instead, in line with feminist approaches, we encourage scientists to adopt practices in which consciously identifying choices and understanding impacts is commonplace (Cancian, 1992). We provide some sample questions that scientists could ask themselves when producing a study:

- Am I averaging my results? Would I obtain different conclusions if I averaged a different way?
- Am I reporting results for some regions or time periods in favor of others? Would I obtain different conclusions if I made different choices?
- How am I choosing to plot my results? Would a reader’s conclusions change if I plotted the results in a different way?

**Figure 5.** Change in temperature (left; °C) and precipitation (right; mm/day) due to solar dimming (GeoMIP experiment G1), as compared to a preindustrial control simulation. Top row shows the 12-model average of the models analyzed by Kravitz et al. (2014). Middle and bottom rows show the maximum and minimum, respectively, over those 12 models on a grid cell basis. Figure combines analyses shown by Kravitz et al. (2013) and Kravitz and MacMartin (2020).
On what sources of evidence am I relying? Are there other sources of evidence? Would I obtain different conclusions if I used different sources of evidence? How am I reporting confidence in my results?

What results am I choosing to report? Would a different scientist, perhaps from a different location or demographic, report different results, or would they report the same results differently?

Are there alternate explanations for phenomena? In simulations that use solar reduction to counteract global warming from CO₂, the tropics are “overcooled,” and the poles are “undercooled” (Govindasamy and Caldeira, 2000; Kravitz et al., 2013) (also see Figure 5). Numerous studies have attributed this feature to the latitude distribution of forcing: CO₂ forcing is ubiquitous, whereas solar reduction has a greater effect in the tropics than the poles. While simple and plausible as an explanation, such statements were effectively unquestioned for a long time. It was recently discovered that meridional energy transport plays an important role in residual polar warming, as well as effects on lapse rate, namely that CO₂ tends to enhance high latitude surface warming more than solar irradiance changes (Henry and Merlis, 2020).

Regardless of the mechanism, overcooling/undercooling appears to be a robust result of climate model simulations of solar reduction (Kravitz et al., 2013, 2020). Simulations of equatorial injection of SO₂, one of the more commonly simulated representations of stratospheric sulfate aerosol geoengineering, also show overcooling of the tropics and undercooling of the poles (Kravitz et al., 2019). However, simulations involving multiple SO₂ injection locations, which are designed to obtain more latitudinally even cooling (Kravitz et al., 2017), are increasingly replacing equatorial injection simulations. A natural question is, even though the wrong explanation persisted throughout the literature for so long, does that matter? Solar dimming poorly represents the climate effects of stratospheric sulfate aerosol geoengineering (Visioni et al., 2021), so correcting erroneous mechanistic understanding of a robust result from a simulation with limited applicability seems moot.

Nevertheless, while this particular error may be of little practical import, failure to consider alternative hypotheses can have important consequences, potentially leading to entire lines of erroneous inquiry. Persistence of incorrect hypotheses can last for a considerable amount of time, which poses serious problems for time-sensitive decisions like how to address climate change and could result in critical decisions being made on false premises. In some cases, this persistence can have important and harmful consequences; as an egregious example, there are numerous instances of declarations that women and minorities are worse at STEMM to justify why they are underrepresented in STEMM fields (NASEM, 2020; Pawley and Hoegh, 2011).

Settling on simple explanations for phenomena is a common form of cognitive bias and was one of the motivations for establishing methods of avoiding these biases, like Analysis of Competing Hypotheses (ACH) (Heuer and Pherson, 2011). While the consequences for settling on this incorrect mechanism may be low, because of the urgency of climate change, as well as the increasing amount of discussion around solar geoengineering, low consequences cannot be expected in all cases. It may be prudent to attempt to identify and articulate multiple possible theories for explanations of phenomena, even if the eventual answer is clearly in favor of a single hypothesis. A core feminist science value of recognizing heterogeneity represents an accurate reflection of the diversity of hard-to-interpret data and rich uncertainty. Maintaining this as a practice improves transparency in the way science is conducted (Sikka, 2018).

How do Kravitz et al. describe science? Choice of language, which results to emphasize or de-emphasize, and interpretation all have some amount of subjectivity that will influence any study’s messages. (This aspect of value-laden language is one of the founding motivations behind FCE.) For example, primarily discussing average results obscures marginalized groups in favor of an “average experience” that may not actually be realized by anyone. Instead, focusing
on disaggregation (Figures 2–4), the local, and the marginalized, as is encouraged by feminist practice, provides a richer picture of the outcomes (Harding, 1991).

Relatedly, the discussion of regional disparities or regional effects also reflects certain choices over others. Alternatives to the Giorgi regions could have included geopolitical boundaries, socioeconomic differences, or cultural/demographic separations. These alternatives could have different approaches to issues of power, for example colonial structures, inequality, and marginalization. Most climate scenarios do not incorporate well-known gender, race, class, and other sociodemographic differences (Kaijser and Kronsell, 2014), and focusing on these instead of more technically oriented boundaries might have produced different assessments of disparities that result from solar geoengineering. Doing so could also improve the degree to which their study evaluates environmental justice.

Kravitz et al. primarily focus on quantitative results, which narrows conclusions, as qualitative results can provide information about material and experiential effects and impacts. Feminist science argues that favoring quantitative results is an effect of gender bias: qualitative methods are often gendered or coded feminine and thus undervalued (Lawson, 1995). However, qualitative descriptions can be overused: for example, at one point Kravitz et al. discuss “small changes” in precipitation, which invariably minimizes certain perspectives: even a “small” change in precipitation might be crucial for subsistence farmers.

**A path toward more inclusive solar geoengineering research**

Through this feminist science framework and its application to a retrospective analysis of Kravitz et al. (2014), we have identified numerous ways in which their findings could be reanalyzed or reinterpreted. We have also identified underlying assumptions which, if challenged, could lead to different conclusions. Our purpose here is not to fault the study or its authors, as the results have invariably improved our understanding of some of the climatic effects of solar geoengineering. Instead, we illustrate the application of practices that could improve the body of knowledge produced by studies and improve transparency of the way studies are conducted using feminist science. By making a study’s values explicit, scientists can assess gaps and opportunities to consider a wider range of values and perspectives. Pluralism, as is encouraged by feminist practice, leads to a more holistic set of scientific conclusions.

Had Kravitz et al. (2014) pursued a feminist approach to their study from the beginning, their focus may have been on deriving multiple, potentially contradictory conclusions from the same underlying data. In doing so, while the conclusions of their study might have been more complex, the study would have enabled more in-depth discussions about the tradeoffs inherent in solar geoengineering, what “winning” or “losing” might actually mean for various stakeholders, and a path toward an informed decision making process among those diverse perspectives.

Important strides to include this plurality of perspectives and conclusions are being pursued. The Carnegie Climate Governance Initiative (C2G) has supported a proposed United Nations resolution on solar geoengineering governance; the International Red Cross/Red Crescent has been involved in rural international public engagement around solar geoengineering for years (Suarez and Van Aalst, 2017); and there has been public engagement around solar geoengineering in the Arctic (Buck et al., 2016). In addition, the Developing Country Impacts Modeling Analysis for SRM (DECIMALS) fund aims at building developing country research capacity in solar geoengineering so that these countries will have their own expertise to address issues specific to their perspectives and will be empowered at international discussions (Rahman et al., 2018); several DECIMALS studies focused on country-level and regional climate and climate extremes have already been produced, with more on the way (Da-Allada et al., 2020; Pinto et al., 2020). While not sufficient, these
steps will result in substantially more plurality in solar geoengineering research and tangible benefits for participatory governance.

We note that a focus on a specific study is not entirely aligned with FCE, which is more focused on the practices, assumptions, and values of communities. By choosing this focus, we have not alleviated the difficulty discussed in “Introduction”; a Global North researcher conducting an analysis of his own study (even informed by the critical elements of FCE) cannot address the lack of inclusivity in this community of practitioners and will thus not fully shed light on the perspectives that are missing. While there have been some investigations into the broader research community and its conclusions (e.g. McLaren, 2018), there is currently no basis on which FCE could make conclusions about solar geoengineering research as a field. The discussions here are hopefully a first step toward a more thorough and rigorous application of this feminist science-based framework to solar geoengineering.

The questions raised here are a good start but incomplete. Moreover, not all of the questions or suggestions may be applicable to every study. Further retrospective analyses, as well as applications to future studies, could help refine these lists into a set of best scientific practices. Ultimately, the purpose is to consciously evaluate the values being encapsulated by a study to understand how they (or the absence of other values) might shape conclusions. Regardless of the outcome of this evaluation process (for example, the implicit values might have a neutral or positive effect on the study), we argue that the answer is important to know.

**Highlights**

- Solar geoengineering research would benefit from more widespread use of inclusive practices.
- A feminist science-based framework can reveal implicit biases and blind spots in research.
- This framework is an adoptable method of practice.

**Acknowledgements**

The authors thank Miranda Böttcher for invaluable comments on the manuscript.

**Author contributions**

Both authors contributed to designing the study and writing the paper.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: Support was provided in part by the National Science Foundation through agreement CBET-1931641, the Indiana University Environmental Resilience Institute, and the Prepared for Environmental Change Grand Challenge initiative. The Pacific Northwest National Laboratory is operated for the US Department of Energy by Battelle Memorial Institute under contract DE-AC05-76RL01830.

**Data accessibility statement**

Data are available via the Earth System Grid Federation; see instructions at http://www.geomip.org.
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