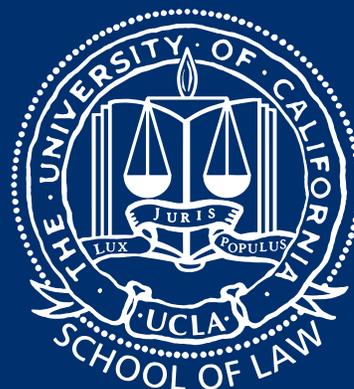
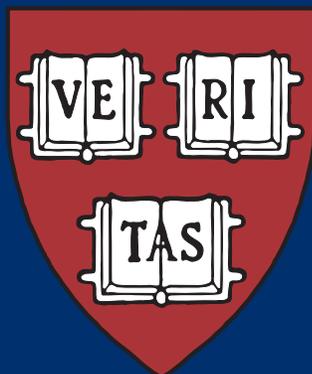


Report

Forum on U.S. Solar Geoengineering Research

March 24, 2017

The Conference Center at the
Carnegie Endowment for International Peace
1779 Massachusetts Ave NW, Washington, DC 20036



This document was originally prepared as background for participants at the Forum on U.S. Solar Geoengineering Research. It now also includes reflections written after the Forum. Moving forward, we hope it proves useful for anyone seeking to gain background information on solar geoengineering.

For a full video of the event, see:
geoengineering.environment.harvard.edu

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Forum Agenda

March 24, 2017

8:45 – 9:00 a.m.

Setting the Stage

- Lizzie Burns — Fellow, Harvard John A. Paulson School of Engineering and Applied Sciences
- Edward A. (Ted) Parson — Dan and Rae Emmett Professor of Environmental Law; Faculty Co-Director, Emmett Center on Climate Change and the Environment, UCLA School of Law
- Gernot Wagner — Research Associate, Harvard John A. Paulson School of Engineering and Applied Sciences; Lecturer, Environmental Science and Public Policy; Associate, Harvard University Center for the Environment

Part I: The Science

9:00 – 10:15 a.m

Social Science: What we know, and what we ought to know

- Edward A. (Ted) Parson [Moderator] — Dan and Rae Emmett Professor of Environmental Law; Faculty Co-Director, Emmett Center on Climate Change and the Environment, UCLA School of Law
- Scott Barrett — Lenfest-Earth Institute Professor of Natural Resource Economics, Columbia University
- Holly Buck — Doctoral Candidate, Development Sociology, Cornell University; Faculty Fellow, Forum for Climate Engineering Assessment, American University
- Rose Cairns — Research Fellow, SPRU – Science Policy Research Unit, University of Sussex
- Kate Ricke — Assistant Professor, Scripps Institution of Oceanography and the School of Global Policy and Strategy at University of California San Diego

10:30 a.m. – 11:45 a.m.

Natural Science: What we know, and what we ought to know

- Doug MacMartin [Moderator] — Senior Research Associate, Cornell University
- Thomas Ackerman — Professor of Atmospheric Sciences and Director of the Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington
- David Keith — Gordon McKay Professor of Applied Physics, Harvard John A. Paulson School of Engineering and Applied Sciences; Professor of Public Policy, Harvard Kennedy School
- Joyce Penner — Ralph J. Cicerone Distinguished University Professor of Atmospheric Science, University of Michigan
- Alan Robock — Distinguished Professor, Department of Environmental Sciences, Rutgers University

- Daniel Schrag — Sturgis Hooper Professor of Geology, Professor of Environmental Science and Engineering, Harvard University; Director, Harvard University Center for the Environment; Director, Harvard Kennedy School Program on Science, Technology, and Public Policy

11:45 a.m. – 12:45 p.m. Lunch

Part II: Policy and Politics

12:45 – 2:00 p.m.

State of Play

- Jesse Reynolds [Moderator] — Postdoctoral Researcher, Faculty of Law, Economics and Governance, Utrecht University, The Netherlands
- Peter C. Frumhoff — Director of Science and Policy, Union of Concerned Scientists
- Steven P. Hamburg — Chief Scientist, Environmental Defense Fund
- Joseph Majkut — Director of Climate Science, Niskanen Center
- Janos Pasztor — Senior Fellow, Carnegie Council for Ethics in International Affairs; Executive Director, Carnegie Climate Geoengineering Governance Initiative (C2G2)
- Janie Wise Thompson — Vice President, Cassidy & Associates

2:15 – 3:30 p.m.

The Path Forward

- Oliver Morton [Moderator] — Senior Editor, Essays and Briefings, The Economist
- Anna-Maria Hubert — Assistant Professor, Faculty of Law, University of Calgary; Associate Fellow, Institute for Science, Innovation and Society (InSIS), University of Oxford
- Peter Kareiva — Director, Institute of the Environment and Sustainability, UCLA; Former Chief Scientist and Vice President, The Nature Conservancy
- Andrew Light — Distinguished Senior Fellow in the Climate Program, World Resources Institute; University Professor, George Mason University
- Jane C. S. Long — Lawrence Livermore National Lab (ret)
- Kelly Wanser — Principal Director, Marine Cloud Brightening Project

3:30 – 3:45 p.m.

Conclusion & Next Steps

- Gernot Wagner — Research Associate, Harvard John A. Paulson School of Engineering and Applied Sciences; Lecturer, Environmental Science and Public Policy; Associate, Harvard University Center for the Environment

Background Paper

Forum on U.S. Solar Geoengineering Research

Edward A. Parsonⁱ, Lizzie Burnsⁱⁱ, John Dykemaⁱⁱ,
Peter Irvineⁱⁱ, David Keithⁱⁱ, and Gernot Wagnerⁱⁱ

This paper was prepared as background for the Forum on U.S. Solar Geoengineering Research, which was held at the Conference Center of the Carnegie Endowment for International Peace in Washington, DC on March 24, 2017. The Forum was co-hosted by the Solar Geoengineering Research Program at Harvard University and the Emmett Center on Climate Change and the Environment at the University of California, Los Angeles, and funded through the generous support of the Alfred P. Sloan Foundation. The paper provided background information on geoengineering and associated debates for Forum participants unfamiliar with these issues, and framed several key questions to be addressed at the Forum. In addition, since the context for discussing solar geoengineering research changed substantially in the year between when the Forum was planned and when it took place, the paper briefly discussed the current context and its implications.

Importantly, while this background paper was initially intended for Forum participants, we hope it proves useful for those who are seeking to gain background information on solar geoengineering more broadly.

Background: Geoengineering Methods, Effects, and Concerns

Geoengineering – also called climate engineering, climate intervention, or climate remediation – is a third class of potential responses to global climate change, additional to mitigation (cutting greenhouse-gas emissions) and adaptation (reducing vulnerability to climate change). While geoengineering responses have been recognized for decades and periodically discussed in scientific assessments – going as far back as the first official report to a U.S. President on global warming, President Johnson in 1965 – they received little attention until the past ten years.

Geoengineering is defined by intentionality and scale: intentional intervention to alter the climate at global scale. Of the two broad types of geoengineering – modifications of the global carbon cycle, or of Earth’s radiative balance – the Forum mainly addressed the latter, which we call solar geoengineering. Solar geoengineering alters the energy balance of the Earth, either by slightly increasing the fraction of incoming sunlight that is reflected from the Earth rather than absorbed; or by increasing the Earth’s ability to cool by emitting thermal (infrared) radiation.

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Three proposed methods of solar geoengineering are most prominent in current debate. Stratospheric aerosol injection would involve the distribution of reflective aerosols in the upper atmosphere. Marine cloud brightening would involve modifying the properties of low-altitude marine clouds to make them more reflective. Cirrus thinning would reduce the density of ice particles in high-altitude cirrus clouds, which would increase the emission of thermal radiation to space. Several other approaches have been proposed but have fallen out of serious consideration due to early indications of limited effectiveness, high cost, or risk. It is likely that new forms of intervention, or improvements to existing forms, will be identified.

The most promising of these methods offer the prospect of modifying global-scale characteristics with extremely high leverage. Several of their prominent characteristics are related to this high leverage. First, solar geoengineering could act fast. Like large volcanic eruptions, some methods could, if deployed at large enough scale, significantly cool global temperatures within months. The aerosol particles that figure in these methods have lifetimes of only a few days in the lower atmosphere and a few years in the upper atmosphere, the stratosphere. The benefit of these short lifetimes is that aggregate cooling can be started, modified, or – if some unfavorable consequence is discovered – stopped, quickly. A corresponding risk arising from these short lifetimes is that, if a large program of solar geoengineering were suddenly terminated, the heating being offset by the program would occur rapidly, which would bring even more severe risks than if geoengineering had not been done and the same heating had occurred more slowly. This is because many of the risks of climate change arise from the *rate* of change, not simply the change itself.

Additionally, most solar geoengineering techniques would have a global, not local, impact. One country, for example, could not deploy solar geoengineering to slow global warming over its own borders without affecting other nations and ecosystems around the globe. This fact poses many governance challenges, particularly when combined with a second fact: that solar geoengineering is inexpensive, at least by comparison of the direct cost of making the interventions to the cost of achieving the same total cooling by carbon removal or mitigation.¹ Indeed, the direct costs of solar geoengineering are likely to be trivial relative to other risks and benefits. As a result, the capability to deploy solar geoengineering and change the global climate may be within reach of many nations. This makes the problem of governing geoengineering the inverse of that posed by mitigation – a strategic structure that has been called a “free-driver” problem, in contrast to the “free-rider” problem of mitigation.

All solar geoengineering methods, however, offer only imperfect corrections for the harms caused by elevated greenhouse gases. They target only certain climate effects of elevated CO₂, not its effects on the chemistry of the oceans that makes them more acidic, its alteration of competitive relationships among plants, which depends on how they use CO₂ in photosynthesis, or other key factors.² All identified methods also have environmental side effects in addition to their targeted climate effects. For different methods, these side-effects may include alterations of stratospheric

¹ Mitigation can only reduce future heating, not cool the climate relative to heating already realized or committed.

² Solar geoengineering will affect the carbon cycle indirectly via temperature-carbon feedbacks, for example by reducing the thawing of permafrost and associated emissions of methane and CO₂

chemistry, in particular stratospheric ozone (noting that ozone decreases for some methods, but increases for other recently proposed methods); changes in the appearance of the sky; and the effects of any material injected into the atmosphere when it is deposited on the ground surface.

Moreover, no solar geoengineering method could perfectly offset the climate effects of elevated greenhouse gases. This is mainly because the effects of reducing absorption of light at the Earth's surface are quite different from the greenhouse effect, which occurs aloft. As a result, compared to greenhouse heating, solar geoengineering reduces precipitation and evaporation more strongly than temperature. In addition, some methods – marine cloud brightening and cirrus thinning – operate by modifying naturally occurring phenomena (in this case, clouds), so their potential impact is limited by the spatial distribution of those phenomena. These methods may thus have patchy effects, or quantitative limits to their global effect. Still, model studies show mismatches of effect that are smaller than was initially expected. Compared to climate conditions with projected increases in greenhouse gases, model studies suggest that solar geoengineering interventions may be able to move both temperature and precipitation closer to pre-industrial values over a large fraction of world land surface. As the Intergovernmental Panel on Climate Change (IPCC) stated, “Models consistently suggest that [solar geoengineering] would generally reduce climate differences compared to a world with elevated GHG concentrations and no [solar geoengineering]; however, there would also be residual regional differences in climate (e.g., temperature and rainfall) when compared to a climate without elevated GHGs.”³

These basic properties of solar geoengineering interventions – fast effect and controllability, cross-border impacts, low cost, and imperfect correction for the effects of elevated greenhouse gases – define the large-scale nature of the governance problem they pose. They also explain why we are discussing these interventions, and why now.

Debate on solar geoengineering became prominent ten years ago. The trigger for the debate was a widely-noted essay by eminent atmospheric scientist Paul Crutzen, who argued these interventions merited investigation because their risks might be less severe than those of continuing climate change. But beyond the specific triggering event of Crutzen's essay, the broader cause of renewed attention to solar geoengineering lay in the underlying realities he described: increasingly severe risks from projected climate change, continued uncertainty about the character and timing of these risks, and increased recognition that mitigation and adaptation may be inadequate to manage the risks. Adaptation may fall short due to limited knowledge or experience of how to do it, resource constraints, political conflict, or institutional failure – as well as the possibility that climate changes may overwhelm adaptation capability. Mitigation may fall short because it cannot reverse realized or committed climate change, due in part to the huge amount of installed plant and equipment that must be changed – and the high costs of transitioning this infrastructure – and due to the slow response of the climate system to changes in forcing. With the exception of measures that target short-lived gases, even intense and successful mitigation efforts will only significantly deflect climate risks after a few decades.

³ IPCC Assessment Report 5, Working Group 1, Chapter 7. (Different terminology: “solar geoengineering” replaces “Solar Radiation Management (SRM)” in the original.)

Moreover, even if emissions are reduced rapidly to zero, there are still risks of global warming because of carbon's long atmospheric lifetime and the presence of carbon-climate feedbacks, such as the release of carbon dioxide and methane from melting permafrost, which could accelerate warming. As a practical matter, mitigation may also fall short because, despite nearly three decades of attempts, nations' mitigation efforts have not been intense – or even, in many cases, serious.

The Prospect of Future Operational Use: Benefits, Risks, Conditions

In this context, solar geoengineering offers a high-stakes, two-sided prospect. On the one hand, it may, under some conditions, be able to substantially reduce climate-change risks and harms in ways that mitigation and adaptation alone cannot. On the other hand, it could be ignorantly, incompetently, dangerously, and illegitimately used in ways that cause severe harms to humans in the environment – greater than those posed by climate change. The conditions for the potential benefits to dominate, broadly, are that interventions are identified that work well with limited harmful side-effects, and that they are developed and used competently, prudently, and legitimately.

Assuming these conditions, three broad ways have been proposed that solar geoengineering might be beneficially used – each of them subject to various scientific and socio-political limitations and concerns.

First, it might be used in response to some future severe climate-change impacts being experienced or imminently anticipated. This mode of use has been described as “emergency response,” or “Plan B.” Used this way, solar geoengineering deployment would be delayed, rapid and strong – not deployed at all in the near term, but then deployed quickly and intensely at some future time.

Second, it might be used in conjunction with aggressive mitigation, adaptation, and carbon removal, as part of a strategic, integrated, multi-decade climate response. This mode of use has been described as “buying time,” or “shaving the peak” (reducing the 50 to 100 year period of heating that even extreme mitigation and carbon removal are too slow to avoid). Used this way, deployment would be immediate, incremental, and temporary – ramping up, then down, as the other responses grow to full scale. Even if carbon capture were not included in such an integrated response – which would imply that climate change could only be stopped, not reversed – such a temporary program of solar geoengineering could still reduce risks by slowing the *rate* of heating toward whatever hotter climate the given level of mitigation effort is moving the world toward.

Third, deployments at less than global scale have been proposed, to target large-scale regional processes of global concern, such as summer loss of Arctic sea ice or tropical cyclone formation. Early research suggests that such proposals could have the potential to bring certain benefits, such as reduced sea level rise, but there are also many uncertainties as well as several potential risks, including changes to regional hydrology. Like all methods, more research would need to be done to increase our understanding of the potential benefits and risks.

Moreover, for any of these modes of use to be beneficial, certain conditions must hold. Some of these conditions are matters of knowledge and technical capability: are feasible methods identified that would confidently have the intended effect and not carry severe side effects? Other conditions are matters of the social, ethical, institutional, legal, and political setting in which interventions would be considered, decided upon, and (if adopted) implemented and managed: is there basis for confidence that these decisions would in fact be competent, prudent, and legitimate? Of these two groups of conditions, the first are fundamentally about research – research into proposed methods, and the natural systems with which they would interact. The second are fundamentally about governance, mainly at the international level because of the international scope and impacts of these interventions.

The governance requirements posed by potential future proposals for operational use of solar geoengineering are novel and severe. Many serious governance-related risks have been identified related to geoengineering being used incompetently, recklessly, rivalrously, or relied on too much. Examples of such dangerous conditions of geoengineering use are easy to imagine: for example, use in a crisis with inadequate risk assessment; uncoordinated or opposing interventions by multiple states or other actors; relying on these imperfect interventions too much, making the neglect of essential mitigation and adaptation measures even more severe; use in ways that undermine or destabilize institutions for international cooperation, on climate or related issues; or use in ways that generate international destabilization and conflict, particularly in the event of wide differences in severity of climate impacts, or interventions that suggest the prospect of regional climate control.

While we recognize the novelty and high stakes of these governance challenges raised by the prospect of future operational interventions, these were not the focus of the Forum. Rather, the Forum focused on the first class of conditions identified above: the need for solar geoengineering-related research, the risks and challenges associated with research, and the governance needs posed by research. In contrast to the larger but more distant governance challenges raised by the prospect of future operational deployment, these research issues are immediate and concrete. Longer-term questions related to operational governance were on the table at the Forum, but only insofar as they were implicated by, or likely to be influenced by, near-term decisions related to research.

Solar Geoengineering Research: Arguments in Favor, Experience, Proposals

The basic argument for expanded research is straightforward. If it is likely that future decisions will have to be made regarding proposals, demands, or charges about operational geoengineering deployment – whatever the outcome of such decisions, whether to authorize, prohibit, or regulate and control proposed interventions – then providing any basis to inform those decisions requires research. Research is needed to identify and characterize methods and capabilities, to design possible implementation scenarios, to identify and characterize efficacy and associated risks, and to understand the social, ethical, institutional, legal, and political setting within which they might be used.

Beyond informing such future decisions, there are also additional reasons research is needed, including developing the ability to detect, identify, and monitor interventions (for example, to protect against clandestine interventions, or to improve our understanding of legitimate interventions by observing their risks and efficacy in the natural environment); and informing the particulars of future governance needs, since these will be strongly influenced by specific technical capabilities and anticipated risks.

Certain research into solar geoengineering has already been conducted. There have been many computer-modeling studies, including comprehensive inter-comparisons of climate-model projections driven by standardized scenarios of future greenhouse-gas emissions and solar geoengineering interventions conducted under the Geoengineering Model Intercomparison Project (GeoMIP). There have also been many observational studies of natural or already existing anthropogenic (human-influenced) processes relevant to likely effects of solar geoengineering methods, e.g., atmospheric aerosols, volcanic plumes, and tracks left by ships and aircraft. Moreover, there have been lab-bench studies of related processes and a few preliminary engineering studies of potential methods to estimate performance, effectiveness, technical requirements, and cost.

One of the key sites of controversy over solar geoengineering research – and the key margin of near-term decision that made the Forum timely – concerns active outdoor perturbation experiments. These would involve intentional introduction of materials into the open environment or some other active manipulation of environmental conditions in ways that aim to inform understanding of the efficacy and risks of potential future interventions.

The case for doing such studies that are small in scale appears strong. All such studies thus far proposed (and the few that have been attempted or done) are of tiny scale, posing negligible environmental risk, yet offer to substantially advance knowledge on atmospheric processes crucial to understanding what potential future interventions might do. The proposed studies would add knowledge to that gained by laboratory or computer-model studies, which cannot fully replicate conditions in the open environment of potential relevance to the effects of interventions. They are thus likely to inform understanding of whether and how potential geoengineering interventions can be done, what their effects are likely to be (both intended and unintended), how interventions can be detected, what risks they may carry, and how these risks can be managed.

But few to no such active perturbation studies have been done. Two small-scale interventions that are known to have been done, both using existing funding on related topics, include one in the United States (the 2011 E-PEACE experiment sprayed smoke and salt particles from a barge off the California coast to study effects on cloud formation), and one in Russia (a 2009 experiment sprayed smoke from a helicopter and a truck and observed resultant radiative effects). In addition, one study, a proof-of-concept experiment to spray water from a tethered balloon (the SPICE experiment), was proposed, funded, and partly implemented in the United Kingdom, then delayed due to objections that the associated public consultation process was inadequate, and cancelled

after the (unrelated) discovery of previously undisclosed financial conflict-of-interest of one of the researchers.

Several additional solar geoengineering experiments have been proposed in scientific literature and some have taken various degrees toward technology development and implementation. None of these has yet been implemented or fully funded, however, and all have raised controversy and opposition. Leading examples of these include:

1. A stratospheric controlled perturbation experiment (SCoPEX), which would use a balloon to release 100 g to 1 kg of aerosol material in the stratosphere, to study resultant aerosol size distribution, radiative forcing, and chemical effects;
2. An experiment in marine cloud brightening, which would loft sea salt spray into the marine boundary layer to study resultant effects on cloud formation and properties;
3. A study, described in the scientific literature, which would seed high-latitude cirrus clouds with aerosols to reduce their optical thickness and so increase infrared radiation from the top of the atmosphere.

Solar Geoengineering Research: Concerns and Arguments Against

The slow pace of developing, funding, and implementing solar geoengineering field research reflects not just constrained resources and bureaucratic inertia, but also widespread nervousness about the endeavor, based on existence of significant concerns and some political opposition. We briefly outline these concerns and objections, grouped in five categories:

First, some objections to expanded research originate in concerns that pertain, reasonably, to potential future deployment – e.g., difficulties of control, disruption to the climate-policy agenda, risk of excessive reliance (potentially leading to future termination-shock scenarios), or international conflict – but extend these concerns to assert that they also support opposition to research. But opposing future deployment does not necessarily imply opposing research, particularly since research can inform and benefit any future decisions about deployment, including the decision to reject it. One way to make this inference from opposing deployment to opposing research valid would be by making an extreme prior assumption: that operational deployment is certain never to be warranted, at any time or under any circumstances. Such categorical opposition to deployment might be based on prior certainty that the consequences of future deployment can only be worse than the consequences of the climate change that it might reduce or delay. But such opposition is more typically based on some non-consequential moral stance: geoengineering deployment would be intrinsically wrong – e.g., because it is messing with nature, is hubris, or is an impermissible step to the Anthropocene – and cannot be redeemed by any evidence that it might bring benefits relative to the available alternative. We find this extreme premise implausible, but if you accept it, the argument for research to inform future decisions is greatly weakened – although not completely: even under this assumption, research could still be warranted to build capacity to monitor and detect unauthorized or clandestine use.

Second, some related objections state that there is no way to distinguish between small-scale field research and global-scale operational deployment. In part these objections rely on the continuity of intervention scale, from tiny to global. They thus reduce to a “where-to-draw-the-line” argument, and are vulnerable to the normal rejoinder to arguments of this type: we might not know precisely where to draw the line, yet still be confident that these things lie on one side, those things on the other. A subtler form of this argument relies on the complexity of atmospheric processes, which makes the effects of any intervention always uncertain until it is actually done. Tiny-scale experiments give information about atmospheric processes that can help understand likely responses to larger interventions. But some uncertainties about large interventions – including the overall quantitative response of the climate system – can only be partially informed or constrained by any smaller intervention. There is thus an important sense in which any future operational intervention will also be an experiment – uncertain of outcome, and so needing active monitoring and real-time adaptation and control. But this inference only goes one way. It does not follow that tiny experiments are also operational interventions: they are not. The line between experiments and operational deployment becomes muddier if and when experiments at larger scales than presently proposed are being considered, perhaps using new intervention methods. Such larger experiments would still be research, even as they grow in size and so come to raise the same concerns and governance challenges as global operational interventions. But this does not mean that all research interventions, even the smallest, raise these concerns and governance challenges.

A third type of objection is based on the expectation of substantial direct risk – environmental, health, or safety – from any active-perturbation research, even the smallest experiments. Like the prior objection, this one is also a line-drawing question. The direct environmental risks from currently proposed experiments do confidently appear to be negligible. But if field experiments were to expand in scale or intensity, at some point their direct risks would cease to be negligible. Since it is unclear in advance where this fuzzy boundary will be crossed, it is necessary to conduct serious assessment of potential risks and risk-limitation measures for even the smallest proposed experiments. But whether risks are non-negligible is – at least to a large degree – an empirical question, to be resolved by examining specific experiments. The prospect of non-negligible risks emerging from future research does not support wholesale opposition to all active-perturbation research.

Fourth, one objection has been raised that potentially applies to both future deployment and research. It is the prospect that solar geoengineering – doing it, considering it, or even knowing about it – might weaken or distract from mitigation. This is a plausible concern, and is often the first concern that comes to mind on initially hearing about geoengineering. But similarly plausible accounts can be constructed that support the opposite effect: that the mere prospect of geoengineering seems so extreme or unnatural, or makes the severity of climate-change risks so salient, that people are more, not less, serious about cutting emissions. Which direction this effect goes is an empirical question, which has been investigated by a few studies using surveys, focus groups, and social experiments. Results have been mixed, with different studies finding both directions of effect. Moreover, studies of individual attitudes are at best imperfect proxies for the crucial questions: how geoengineering effects mitigation commitment in political systems –

national and international – and whether strategies can be implemented to make geoengineering and mitigation mutually reinforcing, e.g., how can increased efforts around geoengineering occur alongside increased efforts around mitigation. These questions have been clearly framed, but not yet investigated by any empirical study. The risk of displacing mitigation thus remains an identified possibility, uncertain as to the severity of the effect and whether and how it can be controlled or reversed. In view of the evident challenges of any research persuasively resolving these questions, it might be most fruitful to regard these concerns as challenges to governance – challenges to identify conditions of research program design and governance, or conditions to shape decision agendas on geoengineering and climate change more broadly, that would persuasively limit the prospects for geoengineering undermining mitigation, or even turn it to supporting mitigation.

Fifth, some objections to solar geoengineering research are based on “lock-in” or “slippery slope” mechanisms. These posit political, bureaucratic, or other social processes by which small, seemingly innocuous early actions (e.g., research) create forces that favor subsequent expansion, or otherwise impair ability to exercise meaningful societal control. In the extreme, such mechanisms would mean that starting even small field studies would impair future ability to stop or control full-scale deployment, even if what was learned in the interim confidently demonstrated that such deployment would be harmful. These objections usually rely on metaphors or analogies to other social processes that have demonstrated lock-in, such as technology adoption with positive returns to scale (VHS versus Betamax), or escalation dynamics such as arms races. In our view, there are good reasons for skepticism about the presence and strength of proposed mechanisms for geoengineering – no explicit causal mechanism driving lock-in from solar geoengineering research has been proposed, and the oft-cited analogies from other issues do not fit this issue well – but these do not fully rebut the concerns. Research to better characterize potential lock-in mechanisms, their relevance and severity for solar geoengineering research, and how they might be avoided or limited, is lacking and needed. Still, it is hard to see how to do research on such a speculative and novel issue that would persuasively resolve the concerns one way or the other. Perhaps, like the previous concern, this one is best addressed by re-framing it as a practical problem of governance and research program design: how can research programs be designed, funded, and managed to ensure maintenance of legitimate societal control over continuance or expansion of the program, and that new information on alternative approaches, effectiveness, societal costs, and risks is adequately taken into account?

A final set of objections to solar geoengineering research are based on claims of public opinion and democratic legitimacy: people do not want it. This is also an empirical question, which is likely to depend strongly on social conditions and on how people’s views are elicited. But in contrast to the previous two concerns, this one readily lends itself to practical research strategies to investigate whether people support or oppose solar geoengineering research; which people, under what conditions, and why; how their support or opposition interacts with their views on climate change and climate policy; and what, if any, decisions on the management or design of experiments or research programs are likely to be associated with greater opposition or greater support?

The Forum: Solar Geoengineering Research and its Governance

In their strongest form, some of the preceding objections would imply categorical rejection of all solar geoengineering research – possibly including not just field experiments, but also passive observational research and indoor (climate-model and lab-bench) studies. In our judgment, however, those objections that would categorically reject any research are the least persuasive. Rather, we find the best-founded objections to solar geoengineering research to be those based on: 1) the risk of displacing other necessary elements of climate-change response; 2) lock-in or slippery-slope arguments; and 3) public acceptance and/or opposition.

These objections share two notable attributes. They all pertain to empirical questions that are themselves subject to research, at least in principle. And they all hold the prospect of being mitigated by appropriate decisions on research governance and program management. They thus lead directly to the focus of the Forum: solar geoengineering research and its governance. While this background paper addressed some of the objections at a conceptual or theoretical level, the Forum also addressed concrete and practical matters: specific types of research that have been or might soon be proposed; risks potentially associated with these, or with research programs to support them; governance challenges or needs these may pose; and concrete actions and decisions that might mitigate these risks or meet these governance needs. We considered these questions mainly in the U.S. context, while also aiming to be attentive both to insights from other jurisdictions and to implications for other jurisdictions.

Examples of specific questions that were and still need to be considered include the following:

- What types of solar geoengineering research proposals are likely, including both field experiments and other potential new proposals?
- Do the governance needs for solar geoengineering research differ from normal governance practices in other research fields? If so, how and why do they differ, and how should the meaning and boundaries of “geoengineering research” be defined that trigger these different governance requirements?
- How (if at all) are the implications of the above objections, or specific governance needs, likely to vary among research projects? How are they likely to vary with other characteristics of proposed research, e.g., the identity and affiliation of project participants; funding sources; or other characteristics?
- How do these concerns or governance needs vary with larger-scale aspects of the organization and management of research, e.g., on whether research is conducted under a separate federal program, or under several federal programs in related areas, or with multiple and diverse sponsoring organizations and funding sources?
- How should expanded research and development of governance be sequenced? Given the widely noted chicken-and-egg dilemma – research is needed to inform governance needs, but governance is needed to manage risks of research – many observers have called for the two activities to co-evolve adaptively. While this sounds good in principle, it leaves practical first steps unspecified. Can the two activities start simultaneously, and what

would that mean concretely? If not, which should move forward first? Moreover, in view of the polarization of views on expanded research, including some categorical opposition, how can prudent early governance steps be distinguished from provisions that aim to be so burdensome as to block all research?

- What specific governance requirements would be implied by concerns about undermining mitigation, lock-in, and public opposition? Do governance requirements vary, depending on which of these concerns they aim to address?
- Several specific governance functions have been proposed as needed for geoengineering research: research program design and management; external advice and oversight; proposal evaluation and approval; risk assessment; transparency; public consultation; treatment of private IP; and program evaluation and adaptation. For each of these, what are the main options and the factors favoring each?
- How do risks and concerns differ between government-funded and privately funded research (foundation, philanthropic, and commercial)? Is it reasonable to assume, as in other areas of controversial research, that privately funded projects will follow the practices of public funding agencies? What additional institutional structures might be desirable to deploy consistent governance for all solar geoengineering research?
- If research governance is developed at the national level in the United States – whether just for federal programs or comprehensively in some new institutional structure – what is the role for informal or formal international co-operation, and how should it be pursued?
- Is national governance of solar geoengineering research sufficient? If so, for how long or under what conditions will this remain the case? What scale or other attributes of research projects are likely to make them objects of international concern? What form and site of governance would be appropriate response to those concerns?
- What implications do the prospect of future geoengineering deployment and concerns about its governance needs have for near-term governance of research?

Closing Thoughts: Context for the Forum, Recent Changes, and their Implications

The proposal for the Forum was developed in summer 2016, nearly a year before it was held in April 2017. At that time, it seemed timely to discuss solar geoengineering research governance because it appeared that research program managers, in the U.S. government and elsewhere, were growing more interested in supporting such research. Since then, the political events of the past year have changed the context for these discussions, having implications that are not entirely clear to us, but which we judge it useful to lay out explicitly.

First, while the future of a well-conceived federal U.S. research program is uncertain, to say the least, there has been a significant increase in resources coming into the field from other sources, including both national research programs outside the United States, and foundations and other private philanthropies. Following from these new resources, several new research programs and projects are being established – including at UCLA and Harvard, the two convening institutions for the Forum, and the Carnegie Climate Geoengineering Governance Initiative. Much of this new

activity is supporting activities already underway, such as computer modeling, social science, and governance studies. But the increase in resources also represents an increased likelihood that funding will be available, perhaps soon, for outdoor field experiments.

Second, at least one of the proposed field experiments is taking steps toward implementation. The Harvard team developing the SCoPEX experiment is investigating hardware options and governance structures to assess viability of a test flight in the second half of 2018 or later. While the Forum did not aim to focus on any particular example of these funding sources, projects, or proposed experiments, they all provided concrete illustrations of the governance issues that the Forum sought to address. This confluence of trends – increased resources, including substantial increases from private foundations and philanthropies, and the development of concrete research proposals – also has the effect of raising the saliency and immediacy of the research governance questions the Forum considered.

Finally, while it was also not the aim of the Forum to speculate on the implications of the change of U.S. administration for solar geoengineering research, it is not possible, or helpful, to fully avoid the implications of this elephant in the room. While concrete steps by the new administration on climate change and scientific research are still emerging – and possibly contested inside the administration – it strikes us as reasonable to guess that U.S. commitments to cuts in greenhouse-gas emissions, to international consultation and collaboration on global problems, and to support for and authority vested in scientific research, are all likely to be substantially weakened. If these trends are realized and sustained, several speculative – and worrisome – implications for solar geoengineering research and governance may follow. We sketch a few of these speculative possibilities:

- To the extent current U.S. trends contribute to a widespread and sustained weakening of expected greenhouse-gas mitigation, the likelihood that some major world state or states seriously proposes solar geoengineering interventions over the next few decades, as their experienced climate-change impacts grow more severe, is increased.
- If the United States pulls back from constructive international engagement in a significant and sustained way, the prospects for effective governance grow weaker, particularly before some crisis or challenge demands an international response, grow more problematic.
- The risk that solar geoengineering is perceived or characterized not as an additional option to strengthen climate risk management beyond the capabilities of mitigation and adaptation, but as an alternative to them, may grow more serious.

The implications of these and other, related speculative trends for responsible near-term decisions about geoengineering research and its governance are obviously unclear in details, but the associated stakes may be high.

Some Thoughts on Solar Geoengineering Research

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The invitation to write a note on this topic asks for each author's perspective on *United States'* solar geoengineering research, implying that US policy on this matter can be viewed in isolation of what other countries do or can be expected to do. It seems to me, however, that geoengineering research must be looked at in a strategic context. Geoengineering deployment is more obviously strategic in nature, but research and deployment are intimately connected activities. Because deployment is strategic, a program for geoengineering research must also be strategic.

If the US had a free hand to decide about deployment, it would still want evidence that the use of geoengineering would address the problem it was meant to address, and that, from a US perspective, the risks of using it were less than the risks of not using it. At a most basic level, these two issues should be the highest priorities for US geoengineering research.

But the US will not have a truly free hand to deploy geoengineering. It would need to justify its plans to other states. At a minimum, the US would need to convince other powerful states that the risk-risk tradeoffs were not unfavorable to *them*. Relatedly, if the US believes that other countries might someday deploy geoengineering, then the US will want to do research on the effects such deployment would have on the US, and on the things the US could do to deter or prevent these states from geoengineering or to reduce the negative impacts of the geoengineering that the US could not deter or prevent, to include possible "counter-geoengineering."

What might solar geoengineering entail? Will it be global in nature, aimed at influencing global mean temperature, or will it be more targeted, aimed at influencing the regional climate (Quaas et al. 2016) or a particular geophysical system (such as Arctic summer ice or the Greenland Ice Sheet; see MacCracken 2016)? The main advantage of a more targeted approach is that it can limit collateral harm—and, hence, limit the risk of a response by other countries to a US-led solar geoengineering effort. (Of course, this limit is merely a matter of degree, for there will inevitably be "spillover" effects to regional geoengineering.) Another implication of targeted geoengineering is that a multiple of regional efforts might be attempted, perhaps by different countries or coalitions. Research into this coordination problem is also needed.

All of the world's countries have agreed that concentrations of greenhouse gases in the atmosphere must be limited so as to prevent global mean temperature change from exceeding 2 °C, but despite the new Paris Agreement, "[t]he world is still moving along a trajectory that can lead to 3-5 °C of warming by 2100, and probably more after that" Knutti et al (2017: 17). Even if countries fulfill the pledges they made in Paris, the 2 °C goal is virtually certain to be missed; and there is reason to believe that countries will not fulfill these pledges (Barrett and Dannenberg 2016). Concern is often voiced that knowledge of the effectiveness of geoengineering will

discourage efforts to limit emissions (the incorrectly labeled phenomenon of “moral hazard”), but it’s really the failure to limit emissions that is making it necessary for the world to consider doing solar geoengineering. Getting the world to reduce emissions is a colossal collective action problem. Solar geoengineering, by contrast, can be done unilaterally and at relatively little financial cost (Barrett 2008).

If limiting temperature change to 2 °C were a true imperative, research on solar geoengineering would be a global priority; and yet it isn’t. Why? One reason might be that the goal of limiting temperature change to 2 °C was a mere tactical device meant to spur action. As there are very real threats to climate change exceeding this target, however, I don’t find this explanation satisfactory. Another reason might be that the risks of deploying geoengineering are too great. I also don’t find this explanation satisfactory, because we don’t know that this is true. This is why more research is needed on the full consequences of geoengineering, the good and the bad. A third reason geoengineering has not become a priority for research is that people feel uneasy about doing geoengineering, even if they could be convinced that the risks from doing it were small.

A best guess is that about half of the “global warming” due to the increase in atmospheric concentrations has been masked by the effect of aerosols (Ramanathan and Feng 2009), principally sulfur emissions from burning coal. This has a similar effect as geoengineering, only the intervention isn’t deliberate. One of the things that I think really bothers people is that geoengineering entails altering the climate *deliberately*.

The distinction between deliberate and inadvertent interventions (known as the doctrine of double effect) has been studied extensively in moral philosophy (Thomson 1985) and demonstrated empirically in moral psychology research (Greene et al. 2001). People respond very differently to actions that lead to precisely the same consequences depending on whether those actions are perceived to be deliberate or a side effect. The idea is neatly demonstrated by contrasting two well-studied dilemmas. In the first, a runaway trolley is sure to kill five people unless you pull a switch that will divert the trolley onto another track where it will kill one person. Will you pull the switch? Most people say yes. In the second dilemma, a runaway trolley is sure to kill five people unless something is done to stop it, but this time you are standing on a footbridge next to a large stranger, and the only way you can stop the trolley is by pushing the stranger onto the tracks below. Would you push the stranger? Most people say no. In the first instance, people think like consequentialists, reasoning that it is better for one person to die than five. In the second situation, people think more like deontologists, believing that it is wrong to kill one person, even if doing so would save five others (again, see Greene et al. 2001).

Geoengineering is more like the second situation, and I think the repulsion people feel about this intervention may cause us to make a bad decision: a decision not to use geoengineering when the evidence suggests that we should use it. Research into how to address this repulsion should be another priority.

Finally, we must also begin thinking about the consequences of possibly using geoengineering someday—the consequences not only for the climate and the environment but for the

relationship humans have with the environment. The biggest challenge posed by geoengineering is unlikely to be technical, but rather involve the way we govern the use of this unprecedented technology (Barrett 2014).

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The Past, Present, and Future of Social Science on Solar Geoengineering

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The past: After ten years of social science research, we have some experience discussing solar geoengineering with publics – but very little of this may apply to a US context

Around 30 empirical social science studies have been done on solar geoengineering worldwide. About half were large-*n* surveys, and half were deliberative workshops or focus groups.⁴ Findings included: (1) framings around “naturalness” or “climate emergencies” matter; (2) publics are concerned with unexpected side effects as well as governance challenges; (3) discussing solar geoengineering may improve the will to mitigate, as well as decrease it, in differing contexts; and (4) there is conditional or ambivalent support for research.⁵

Little is known about US perspectives on solar geoengineering, and there has been virtually no engagement with US publics. The United Kingdom, Sweden, and Japan have had deliberative public engagements on geoengineering.⁶ In the US, empirical research has been limited, and almost entirely in the form of surveys. My initial qualitative fieldwork on perceptions of solar geoengineering in the US has suggested significant differences between the US and other developed countries, due to climate skepticism, political polarization, loss of trust in institutions, and the politicization of climate science.

The present: Policymakers should consider a “CDR first” agenda

Given an extremely polarized electorate, the risks of pressing for a federal research program may outweigh the benefits. Eagerness on a federal level could torpedo the social acceptability of

⁴ For an overview, see E. Burns et al, “What do people think when they think about solar geoengineering? A review of empirical social science literature, and prospects for future research,” *Earth’s Future*, doi: 10.1002/2016EF000461, 2016.

⁵ Caution should be used in interpreting the findings of research support, as the phrasing of the question matters immensely. Respondents may support research in the sense that they believe in scientific freedom, and wouldn’t want to restrict someone’s *right* to do research — but this type of “support” would play differently than the support of someone who believes research on this *in particular* should take place.

⁶ See S. Asayama et al, “Ambivalent climate of opinions: Tensions and dilemmas in understanding geoengineering experimentation,” *Geoforum*, <http://dx.doi.org/10.1016/j.geoforum.2017.01.012>, 2017; V. Wibeck et al, “Questioning the technological fix to climate change – Lay sense-making of geoengineering in Sweden,” *Energy Research & Social Science*, <http://dx.doi.org/10.1016/j.erss.2015.03.001>, 2015; also R. Bellamy and J. Lezaun, “Crafting a public for geoengineering,” *Public Understanding of Science*, doi: 10.1177/0963662515600965, 2015.

research on solar geoengineering. More social science research could indicate whether this is actually the case. If it is seen that the Trump administration or Republican Congress is funding research into geoengineering, the field of research would be tarnished by association; expect outcry from the left worldwide. Conversely, if it is seen that liberal scientists and NGOs are pushing for research, it will be derided by those on the right as crazy/stupid. The latter situation would likely be a short-lived, inconvenient media flare-up rather than an ongoing issue. But the former scenario would delegitimize solar engineering research and could delay it by a decade or more — potentially making the technologies unavailable in a future where they might be useful. Social scientists have pointed out that a stratospheric aerosol field trial, for example, should be seen as a “social experiment” with unknown and uncontrollable social and political consequences.⁷ Researchers and policymakers must appreciate that the context for this social experiment has shifted dramatically.

Other countries and institutions must take the lead on solar geoengineering research, because the USG is not currently in a position to lead. Ideally, private funders and regional or international bodies can carry on laboratory-scale research with the same standards of transparency and access that a large-scale public program might use. Important aspects include: (1) review of proposals using established public-interest criteria, with the process open for bright minds from various backgrounds to apply, (2) integration of social science, (3) balancing perspectives to mitigate groupthink, (4) transparency and data-sharing.

Certain research activities should still be promoted right now by US federal agencies, as unlikely as this may be. These include:

1. R&D for carbon removal practices / technologies. This is what I call a “CDR first” strategy. Respondents in my research preferred the idea of SRM being a temporary measure rather than an end game. If that’s going to be a plausible scenario, CDR needs to be much farther along, technically and socially. The influential taxonomy of the 2009 report by the UK Royal Society was misleading in that it depicted discrete geoengineering “choices”. From a solar geoengineering policy standpoint, SRM & CDR need to be looked at as a package deal. CDR is unlikely to advance without strong policy incentives.
2. International consortium-based or co-financed projects on solar geoengineering that continue to build an interdisciplinary research network.
3. Educational opportunities for building climate science capacity in developing countries, perhaps within a mitigation-adaptation-geoengineering framework.

The future: Multi-stakeholder engagement should bring solar geoengineering under a sustainable development frame

The next four years should be used to build solid partnerships between climate engineering researchers and organizations working in sustainable development, in order to ground

⁷ Asayama et al, 2017, also see Stilgoe, J, “Geoengineering as collective experimentation”, *Sci. Eng. Ethics*, <http://dx.doi.org/10.1007/s11948-015-9646-0>, 2016.

geoengineering within this frame before pursuing a large-scale federal research effort. If SRM emerges from a development-oriented frame, then the research goals draw upon a broader conversation. This could inform the design of both solar geoengineering strategies and research questions, influencing aspects of solar geoengineering such as timing, deployment locations, or amounts deployed.

There are three basic reasons to ground geoengineering in sustainable development. First, development practitioners are used to thinking about the future we want, not just the future we want to avoid. They can apply valuable experience from both successful and failed environmental management projects and social interventions. Second, acknowledging climate change is at root a development problem, and not just an “environmental” or a “science” problem, brings us to a more honest discussion that can recognize inequality and incorporate it into the problem definition.⁸ Third, research indicates that publics want to discuss geoengineering not as a yes/no verdict on a particular technology, but in the context of a broad array of climate futures. NGOs and community organizations already hold these types of conversations around mitigation and adaptation pathways and “deep decarbonization”. If science can address whether solar geoengineering can ameliorate harms to species and vulnerable peoples, civil society organizations may be more open to facilitating conversations.

In the future, four key interdisciplinary lines of research include:

1. Worldwide understandings about climate engineering, in order to incorporate people’s visions, preferences, concerns, or goals into the research process — particularly beyond the global north, with social scientists in the global south designing the research.
2. Ecosystem interactions of solar geoengineering: impacts on biodiversity and species’ adaptation, and what this means for communities that use biological resources.
3. How citizens seek, find, and interpret information about climate engineering.
4. Public understandings of climate engineering in the US.

⁸ See the discussion of “moral responsibility” in D.E. Winickoff et al, “Engaging the Global South on climate engineering research”, *Nature Climate Change*, doi: 10.1038/NCLIMATE2632, 2015.

Solar Geoengineering Research and the Social Sciences

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There is a rich body literature examining the potential social and political implications of an imagined future solar geoengineering program. From this corpus of work a number of serious issues have been highlighted, including: convincing arguments that solar geoengineering would be ungovernable (in any desirable sense) [1]; that it would be unable to solve the problems associated with climate change at the local and regional scales that matter [2]; that it would inevitably have unexpected, and endlessly contested, negative consequences due to its fundamentally experimental nature [3] [4]; that it would necessitate a hugely costly, militarized security infrastructure, with potentially destabilizing consequences for global security [5]; and would be susceptible to ‘lock-in’, being difficult or impossible to change even under conditions of crisis [6]. Although inevitably speculative to a degree (given that solar geoengineering remains a socio-technical imaginary), the severity and magnitude of these issues suggest that solar geoengineering would be non-viable as a policy option for dealing with climate change, and calls into question the wisdom of continuing to carry out research in this domain. But then ... is it perhaps the case that we just need to do more research to be sure one way or the other?

Proponents might justify such a need in terms of a ‘gap’ in knowledge that needs filling, or of uncertainties that need reducing. However, with regard to contentious socio-technical imaginaries like solar geoengineering the notion of a ‘gap’ in knowledge is a somewhat dangerous fiction built on dubious assumptions. Framing knowledge production in this way implies that (with ‘the right’ kind of research) such a gap could be filled: uncertainty reduced to the point of clarity about the best way forward, providing closure or justification for a particular course of action. In turn this implies that the kinds of uncertainties associated with the social and political (and indeed physical) dimensions of solar geoengineering are indeed reducible. As Dan Sarewitz remarks: *‘by presenting uncertainty as a vague but putatively coherent concept that is “reduced” through more research, the scientific community assures that the phenomenon of uncertainty remains located in our imperfect (but always-improving) understanding of nature, and is not an attribute of nature itself, of the structure of disciplinary science, or of the social and political context within which research is conducted.’* [7] On the contrary, with regard to both the social and physical aspects of geoengineering, it is not simply that there exists uncertainty, but there is much that is radically *unknowable*. Furthermore, what we do already know is that there are multiple, *competing meanings* [8] associated with geoengineering and that notions such as feasibility, desirability, purpose, relevant knowledge and so on, are all fundamentally contested. Despite powerful political pressure for research to provide artificial closure, further study will not reduce the diversity (or incommensurability) of these perspectives: it is a widely recognized but oft-made mistake to believe that ‘more science will reduce political or value disputes’ [9] when in reality the opposite is often the case. With regard to solar geoengineering, uncertainties, ambiguities and contestation will only increase as more actors (e.g. in the global south) are brought into these conversations.

Secondly, such calls for more research, imply that knowledge production is a neutral activity, that knowledge and action are separate, and that the process of investigating, instigating conversations, canvassing opinion and so on, does not itself change the material social context. It is entirely plausible that the reverse is true, and that the flow of research funds, and the sustained attention from researchers and others, has important material consequences (this is related to the so-called 'slippery slope' argument [10], [11]). Thus even what is intended to be a 'balanced' discussion might inadvertently lend discursive policy momentum towards geoengineering, through for example: establishing the credibility of the discussion or lending tacit legitimacy to the idea itself through association with particular institutions; drawing policy attention (with consequent opportunity costs for other approaches); or providing a discursive resource for active strategic manipulation by protagonists. Similarly, apparently 'neutral' activities such as calls for 'governance before deployment' or 'crafting a governance framework', may also have important facilitatory effects, and risk repeating in the social domain the fallacies of control which notions of geoengineering embody with regard to the natural/physical environment.

Despite these concerns, given the sheer scale and ambition of scientific research into the physical feasibility of climate geoengineering, barring a moratorium (which seems unlikely even if, perhaps, desirable?) it is inevitable that social scientists will be drawn to the topic to better understand and contribute to these discussions. What role then, should they play? There will be pressure from some quarters for social scientists to gather 'social intelligence' (in the military / surveillance sense of intelligence provision), to provide a body of information and knowledge about society to 'decision makers' framed as somehow outside or above those being studied in order to pre-empt or overcome dissent (they might ask such questions as: *'what framings of solar geoengineering resonate with 'the public'? What proportion of people are already open to the idea? How can one craft a governance framework that will be seen as 'fair', or ensure the legality of research?'*) On the other hand, one might understand the notion of providing social intelligence differently: as intelligence of the collective, aimed at alerting those who would embark on research in this domain to fundamental 'questions emerging from human imagination and public concern' [10]. In this guise, social scientists, along with other social actors such as NGOs, might play a critical role facilitating spaces (both physical and conceptual) for collective societal reflection, to examine whether this direction for research, and the associated implications for life on earth, is ethically, socially and politically acceptable or desirable. But in order to avoid tokenism, or become simply a 'tick box' public engagement exercise, there has to be a sense that dissent will be taken seriously. Which raises a key question that remains unanswered by those who wish to pursue scientific research in this area: *'what would constitute a sufficiently grave critique to warrant abandoning this line of inquiry?'* If the answer to all critique and dissent is simply to dismiss these as minority or 'special interest group' concerns, or to frame them as 'areas requiring more research', then the notion of a slippery slope may be apt indeed, and the danger of co-option of social sciences in the service of facilitating this endeavour, seems highly likely.

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A Perspective on Solar Geoengineering

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My perspective on solar geoengineering arises from many conversations I have been fortunate to have over the last decade with colleagues who have done serious work in this field, on my reading of some of the seminal papers on the topic, and also on what I have learned from my efforts to inform those who are inclined against any kind of climate action about both the risks and the opportunities posed by anthropogenic climate change.

The political, ethical, economic, legal, scientific, and technical aspects of solar geoengineering are so tightly interwoven as to render problematic a discussion of any of these aspects in isolation. Even pure research on the issue constitutes a political act as it sends a message that we might be able to engineer our way around the consequences of greenhouse gas emissions. Perhaps for this reason it seems prudent to begin with a discussion of ethics as it affects the question of whether we should even be undertaking geoengineering research.

Here my own view evolved somewhat in response to a conversation my MIT colleague Penny Chisholm had with the Dali Lama a few years ago. She and I and several others had been invited to have a public conversation with the Dali Lama about climate change, and I had just briefed him on the current state of the science. Penny was charged with explaining geoengineering, which she did with great proficiency. He listened intently, and when she was done he stated, to our surprise, that in his view we should begin to do solar geoengineering immediately. We thought he might have missed Penny's description of the risks, which she repeated for him. But he held fast and expressed that to do otherwise would be unethical. Needless to say, he had absolutely no qualms about researching the topic.

It occurred to me later that perhaps our surprise was grounded in a fundamental rift between Eastern and Western ethics. We in the West attach great importance to agency in judging the morality of any action. Actively and knowingly doing harm is considered worse than doing something harmful as an unintended side-effect of some activity, and this is reflected in western law. Not saving someone when we have the power to do so, while heinous, is put in a different category from pre-mediated murder. Apparently the importance of intention relative to outcome is not as important in Tibetan philosophy. Thus perhaps the Dali Lama felt that not to geo-engineer our way out of the adverse effects of climate change was as serious an ethical failure as causing the problem in the first place, in spite of the risks of geoengineering.

It seems to me that we have a moral obligation to explore all plausible responses to the risks associated with global warming, from carbon-free energy, to carbon capture, to geoengineering, and to adaptation. Only by fully understanding the risk landscape and our various options will we be able to make intelligent and compassionate decisions. I do not buy the idea that we should not research any form of geoengineering on the grounds that it will discourage investment in

alternative energy sources. On the contrary, by quantifying the downsides and risks of geoengineering, we will be able to argue, if necessary, against deploying such technology. Especially since solar radiation management is so cheap, we would need strong arguments to stop renegade governments or individuals from pursuing this approach, if it indeed is shown to have unacceptable risks.

Much has been written about harmful side-effects of solar radiation management. But there may also be beneficial side-effects beyond the intended benefits of lower temperature and mitigation of sea level rise. Some of my own work is on the response of tropical cyclones to climate change, and we have been able to show that variations of solar radiation are roughly twice as effective as changes in longwave radiation, per unit sea surface temperature change, in changing tropical cyclone potential intensity. This means that if sea surface temperature is first raised by increasing longwave emitters and then brought back to baseline by decreasing solar radiation, there will be a net decline in the thermodynamic potential for tropical cyclones. This is generally good news, as tropical cyclones cause far more damage than benefits, globally.

This finding should not be interpreted as advocacy for solar radiation management, but as an illustration of the importance of a full accounting of the potential risks and benefits of any geoengineering strategy. But we should not be tempted to think that even a comprehensive risk-benefit analysis will lead to straightforward decisions. Reasonable people will differ in weighing the unanticipated harmful consequences of an intended action (solar geoengineering) against the unintended but known harmful side effects of an ongoing activity (greenhouse gas emissions). It may take a great deal of the latter before the former becomes the preferred option.

Reflection on the Forum on U.S. Solar Geoengineering Research

Peter Fiekowsky⁹

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Where are we going (climate-wise)?

The Forum on Solar Geoengineering (also called solar radiation management or SRM) was a valuable gathering reflecting significant technical progress and political change in the last year. With the new US administration, things could move quickly, forward and / or backwards. It's up to us to make sure that things move towards success. To succeed, we must define success clearly and as something we want.

What would successful SRM achieve?

One of the panelists at the forum said that SRM success is staying below two degrees warming. That goal is arguably too vague to elicit specific and effective action. I think experts will agree that SRM actions as a whole have been indecisive and hesitant; actions consistent with a vague and unappealing goal.

As a parent, I'm clear that success is restoring a healthy climate for our children, and doing it before we lose much more of the beauty and glory of our planet. Although the IPCC may disagree with that goal, that is I want, and what almost everyone I speak with wants, and what the clergy I speak with now demands. We have a moral obligation to give our children and grandchildren a climate close to that which we were given. If we don't yet know how to achieve it then we are obligated to invent the methods required. Not knowing how to do it does not absolve us from that obligation to our children and grandchildren.

As an SRM outsider with children here's what I want from SRM:

Be prepared to cool the planet with SRM during the time during which carbon dioxide removal is operating.

Assume that we will implement carbon dioxide removal (CDR) and reduce atmospheric CO₂ back to levels that have supported humans in the past, i.e. below 300 ppm. We should target achieving this by 2050, although it could take until 2100. Recent work confirms what Dr. Jim Hansen said in 2008, that CDR investment of about 1% of global GDP could remove the trillion tons of excess atmospheric CO₂ in 20-50 years. This requires removing 50 GT / year, which scale could be achieved by any one of at least seven techniques, using direct air capture (DAC), or ocean processes.

⁹One participant, Peter Fiekowsky, responded to our request to all Forum participants, offering these reflections.

Be ready to start SRM within 2-3 years—by 2020.

Waiting longer is too late, arguably criminal, given rapidly worsening climate trends from the arctic to the equator. We need the insurance policy of SRM. If we don't provide that, our children should sue us for dereliction of duty—perhaps as part of “Our Children’s Trust” lawsuit. Insofar as we are the leadership for SRM, we are morally, if not legally liable. This is a harsh assertion, but arguably true.

This isn't saying that we must implement SRM—implementation is a moral decision. This community must prepare to implement SRM. As technologists, our obligation is to provide the tools. Society could in the end insist that SRM not be implemented, although that could well be the pathway into the sixth extinction. With good data available, I consider such an SRM veto to be unlikely. Without this data, we've seen that few people are willing to seriously consider SRM.

In addition to the extensive literature on SRM risks, we must provide critical data about benefits of SRM:

1. What are the best options for stopping sea-level rise, and for halting ice sheet collapse in Antarctica and Greenland?
2. What are the best options for weakening the cyclones decimating the Philippines and other areas?
3. What are the best options for stopping permafrost melt and a “methane burp”?
4. What are the best options for restoring the Gulf Stream and other ocean currents?
5. What are the benefits to society and nature of implementing SRM? We have dozens of articles about the risks, but precious little about the benefits. Given the public data, it's no surprise that there is low public support for SRM.
6. If SRM is required, what are the real options for implementing SRM quickly? What are the technical, financial, and logistical options? There is great fiction about that, but little policy work.

I am proposing that a “Climate Restoration” center be established in 2017 to host research to answer these critical questions which will allow progress towards restoring the climate.

The Siren Call of US Funding for Solar Geoengineering Research

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Mounting evidence now indicates that even very aggressive reductions in greenhouse gas emissions may not be sufficient to meet the Paris Agreement's long-term goal of limiting the increase in global average temperatures to well below 2 degrees C above pre-industrial levels. As a consequence, vexing questions around whether, when and under what conditions society might need to consider deploying other large-scale "climate interventions" are increasingly coming to the fore.

The state of knowledge of such interventions was prominently summarized in two 2015 National Research Council (NRC) reports, written by a committee chaired by Marcia McNutt. The Committee separately considered technologies to remove carbon dioxide from the atmosphere at scale, and "albedo modification" or solar geoengineering technologies to reflect sunlight and lower temperatures.

In their solar geoengineering report, the NRC Committee firmly opposed deployment, noting both significant risks that include secondary impacts on "the ozone layer, precipitation patterns, terrestrial and marine ecosystems, and human health, with unknown social, political, and economic outcomes," and important limitations in our current earth system monitoring capacity to understand these impacts.

The Committee did, however, cautiously endorse field experiments, calling for relatively "small-scale field experiments with controlled emissions" that could advance both basic understanding of the climate system and quantify some impacts, both intended and unintended. Recognizing that field experiments themselves have important and uncertain ethical, social and political ramifications, the NRC Committee also called for an open and deliberative research planning process, informed by the active participation of civil society, to weigh options for their governance.

The Committee's recommendations serve as a valuable starting point for the narrower question on the table for this Forum: that is, whether and under what conditions *the US government* should fund solar geoengineering research. For researchers who have long sought to move forward with field experiments, the allure of such funding is surely strong. But the risks are also strong that such funding, if ill-timed or ill-designed, would, like the call of the Sirens, draw us onto dangerous and

rocky shores and undermine the goal of ensuring that both civil society stakeholders and other governments see US-funded solar geoengineering field research as a legitimate endeavor.

To build and sustain a research program with legitimacy in the eyes of key stakeholders within the US and around the world, we argue that the following four conditions should be met *before* the US government funds solar geoengineering field research:

1. The US is aggressively supporting climate mitigation and adaptation and substantially investing in clean energy research and development;
2. An earth system monitoring capacity is in place that is sufficient to detect and attribute environmental impacts, both intended and unintended, from field research;
3. The US is part of an international coalition of nations supporting solar geoengineering research – a coalition that includes nations particularly vulnerable to climate change and high carbon-emitting nations fully committed to emissions reductions; and
4. A research governance system is in place that is sufficient to address concerns over transparency, liability and equity and is open to civil society input into its design and review.

We are, unfortunately, far from meeting these conditions today.

With regard to conditions 1 and 2 (US commitments to mitigation and adaptation and a viable earth system monitoring system), it is almost surreal to be discussing US funding for solar geoengineering research in the early months of a new Administration and Congress that are bent on backing away from our nation's emissions reductions commitments under the Paris Agreement and slashing climate science and clean energy research and development budgets across the federal government. The Trump Administration has also proposed deep cuts in satellite-based earth system monitoring systems that are so essential for this research.

Funding under these conditions would violate a core premise of the Forum (as characterized in the invitation to participate in it) that “[d]ecisions about solar geoengineering research, and possibly deployment, must be established with the understanding that it could only be a supplement – not a substitute – for emissions reductions” ...and that “[t]he world must continue to fully implement and go beyond, the commitments in the Paris agreement.”

In this political climate, a strong push for US funding for solar geoengineering field experiments would almost certainly be met with very strong opposition from a wide swath of civil society organizations – opposition that would jeopardize the societal acceptance that such research would need to be sustained and policy-relevant.

With regard to condition 3 (an international coalition of nations), the history of another contentious climate debate is instructive. When the Kyoto Protocol was established, a question hotly debated was whether measures to slow tropical deforestation should be included for carbon credits in the Protocol's Clean Development Mechanism. The scientific justification for their inclusion was strong: tropical deforestation accounted for roughly 20% of the source of annual

anthropogenic carbon emissions at the time. A Special Report of the Intergovernmental Panel on Climate Change on this issue provided firm scientific support and several major US-based NGOs, including the Union of Concerned Scientists and the Environmental Defense Fund, advocated forcefully that climate policies to reduce emissions from tropical deforestation would complement energy sector reductions in emissions from the US and other major industrialized countries.

But despite good science and the support of prominent NGOs and major US foundations, efforts to build support for slowing deforestation as a climate mitigation measure were angrily denounced by international NGOs and developing countries that were sure this was a trick to allow the US and other major emitters off the hook. Advocates for it were not seen as legitimate messengers and our efforts failed.

It was only several years later, when a small group of rainforest nations, led by Papua New Guinea with Norway as a major funder, stepped forward to embrace and lead support for this that an idea to which many were deeply hostile became widely embraced. Today, support for measures to reduce emissions by protecting and restoring tropical forests are largely uncontroversial and firmly established within the Paris Agreement.

The tropical deforestation case reminds us that legitimacy depends on the participation of trusted actors. Establishing legitimacy of solar geoengineering research will likely only be achieved once there is an international coalition of collaborators that includes nations that bring a legitimacy that the US acting alone cannot, i.e., vulnerable developing nations and other major emitting nations unequivocally committed to domestic emissions reductions.

Finally, with regard to condition 4 on developing an inclusive process of research governance, there are clearly many unanswered questions on what this would look like and much work still needs to be done in this domain. We look forward to the outcomes of the governance initiative led by Janos Pasztor through the Carnegie Council. It is essential that meaningful “civil society” participation not be limited to large US-based NGOs, but that the process brings into the dialogue participation from organizations representing diverse constituencies and communities around the world. This will take a good deal of work, but it will be critical to build and sustain legitimacy.

Today, a very small number of experts and thought-leaders are wrestling with questions of solar geoengineering. The potential value to society of understanding more about the risks and possibilities of solar geoengineering technologies is not currently on the radar screen of the vast majority of colleagues working within the climate science advocacy and policy communities. Nevertheless, the salience of understanding these technologies will only increase as the societal risks of temperatures rising well above the Paris targets become more widely apparent and acknowledged.

The opportunity and responsibility in front of us is to ensure that research is designed – and funded – with great care and inclusion to ensure its credibility, salience and legitimacy.

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Letter to the Editors of the U.S. Solar Geoengineering Symposium

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Thank you for your kind invitation to participate in this symposium on U.S. solar geoengineering. My reflections on this emerging area of climate law and policy aim to situate our discussions at this meeting within a wider global frame. It is from the particular vantage point as a scholar of international law that I share my perspective on U.S. solar geoengineering research and its governance implications internationally.

Solar geoengineering methods, in particular, stratospheric aerosol injection (SAI), stand apart as the more “radical” approaches for addressing human-caused climate change.¹⁰ Estimates suggest that SAI has the potential to offset some of the risks of rising global temperatures in a relatively cheap and quick way. Atmospheric modelling experiments predict that, depending on how it is deployed, such methods have the potential to reduce some of the risks of climate change. On the other hand, SAI also poses new risks and uncertainties, including possible distributional consequences.

SAI necessarily acts globally. Casting our eyes to the long-term horizon, a full-scale use of such methods raises the prospect of environmental management at an earth systems level. A deployment of this nature clearly engages obligations of international law, and would require significant, perhaps unprecedented levels of international cooperation and coordination to be carried out effectively.

At the moment, however, solar geoengineering proposals currently only exist in atmospheric models or in the laboratory. Some scientists and policy-makers argue that it is time that research moves outdoors so that we can learn more about the potential efficacy and risks of solar geoengineering. Furthermore, environmental perturbation experiments may provide a more fundamental understanding about the atmosphere and changing climate. A recent legally non-binding decision taken by countries party to the Convention on Biological Diversity (CBD) reflects an evolving global institutional understanding of the need for research into geoengineering methods, noting that “more transdisciplinary research and sharing of knowledge among appropriate institutions is needed in order to better understand the impacts of climate-related geoengineering on biodiversity and ecosystem functions and services, socio-economic, cultural

¹⁰ International Bar Association (IBA), *Climate Change Justice and Human Rights Task Force Report, Achieving Justice and Human Rights in an Era of Climate Disruption* (July 2014) <<http://www.ibanet.org/PresidentialTaskForceClimateChangeJustice2014Report.aspx>> accessed 9 February 2015, 176–77.

and ethical issues and regulatory options.”¹¹

The next step in solar geoengineering research is likely to involve very small-scale outdoor field research along the lines of what Professor Keith and others have proposed in their 2014 article in a special issue of *Philosophical Transactions of the Royal Society A*.¹² The SCoPEX experiment entails seeding a small volume of sulphate particles and/or water vapor to test the reactions that limit ozone loss in the stratosphere. Presumably, SCoPEX would be conducted on U.S. territory and pose “very small” direct environmental risks from injecting a mere 1 kg of sulphuric acid in the stratosphere, “an amount that is less than the amount of sulphur released by one commercial passenger jet in 1 minute of flight time.”¹³

Yet if we do cross the Rubicon by conducting field tests involving solar geoengineering, what other considerations should be taken into account? Social scientists point to the social, political, and ethical risks of solar geoengineering, which include socio-technical lock-in and creation of vested interests. The importance of experiments to the development of a technology to deliberately alter the global climate system highlights the geographically unbounded risk profile of solar geoengineering – even from the outset. What is the international interest in experiments that pose no risk of transboundary environmental harm? How do these interests shape the design of a governance architecture for solar geoengineering research looking ahead?

It may sound absurd to ask such questions at this particular moment in which serious reservations are being raised about the fate of the international system as a whole. Recently *Foreign Affairs* magazine featured a series of essays on the American retreat from its role as defender of the liberal international order towards more isolationist politics. But this marked shift in the U.S. administration’s foreign policy – particularly on the issue of climate – does not change the fact that we live in an increasingly interconnected world. Richard Haas points out in his piece that “[c]limate change is in many ways the quintessential manifestation of globalization. It reflects the sum total of what is going on; countries are exposed to and affected unevenly by the problem regardless of their contribution to it. Borders count for naught. There is broad, if not universal, agreement that climate change is real, caused in large part by human activity, and constitutes a major threat to the future of the planet and its inhabitants.”¹⁴ These ideas are eloquently summed up in countries’ declaration in the UNFCCC that “change in the Earth’s climate and its adverse effects are a common concern of humankind.”¹⁵ As an emerging issue of climate law and policy, solar geoengineering touches upon many global common interests, including the protection of the environment and sustainable development, peace and security, human rights, and equity. This

¹¹ Convention on Biological Diversity (CBD) “Climate-related geoengineering” (8 December 2016) UN Doc UNEP/CBD/COP/13/L.4.

¹² John A Dykema, David W Keith, James G Anderson and Debra Weisenstein, “Stratospheric controlled perturbation experiment: a small-scale experiment to improve understanding of the risks of solar geoengineering” (2014) 372 *Phil Trans A* <<http://rsta.royalsocietypublishing.org/content/372/2031/20140059>>

¹³ *Ibid.*

¹⁴ Richard Haas, “World Order 2.0: The Case for Sovereign Obligation” (2017) 96 *Foreign Affairs* 2, 5.

¹⁵ United Nations Framework Convention on Climate Change (adopted 9 May 1992, entered into force 21 March 1994) (1992) 31 ILM 851 (UNFCCC), Preamble.

global public goods character of solar geoengineering argues in favor of a degree of early international cooperation and coordination of research, and that it should be carried out in a way that is respectful of core principles and values, particularly those expressed in the 2015 Paris Agreement.

Jurists distinguish between *lex lata* and *lex ferenda* – concepts that demarcate the difference between “law as it is” and “law as it should be”. This spread is significant when one considers the current legal landscape of national and international law relevant to geoengineering research (which in my view remains underdeveloped and not fit for purpose) and more ‘optimal’ governance conditions proposed in the academic and policy literature. From the perspective of advancing scientific understanding of solar geoengineering, development of a robust governance framework could actually facilitate research by providing legal certainty in the form of clear processes and ground rules given that solar geoengineering is so controversial. The examples of nuclear energy and genetically modified crops demonstrate the possibility of a backlash if we do not handle solar geoengineering governance correctly. Bottom line, it is too important to get wrong.

Research and governance will have to evolve in parallel, each informing the other. Moreover, one can envisage that governance will be a multi-staged process, involving different levels and actors. A useful contribution at this stage would be to initiate a process to develop a new governance instrument, such as a code of conduct, to provide early, flexible guidance for different research projects, together with general principles and procedures to guide responsible research and to inform governance processes for innovation as it develops.¹⁶ Core governance principles include the precautionary approach, risk assessment, public participation and transparency. The instrument could provide a gap-filling function by promoting early cooperation and coordination of research consistent with the general principles, and notions of equity and sustainable development adopted in the 2015 Paris Agreement.

¹⁶ Anna-Maria Hubert and David Reichwein, “An exploration of a code of conduct for responsible scientific research involving geoengineering: introduction, draft articles and commentaries” (2015) IASS Working Paper, InSIS Occasional Paper No 1. Potsdam & Oxford < <http://www.insis.ox.ac.uk/occasional-papers/a-code-of-conduct-for-geoengineering-research/>>. See also Geoengineering Research Governance Project <http://www.ucalgary.ca/grgproject/>; Anna-Maria Hubert, Tim Kruger and Steve Rayner, “Code of Conduct for Geoengineering” (2016) 537 *Nature* (Correspondence).

Thoughts About Future Geoengineering Research

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Co-development of climate intervention technology and governance

Calls for geoengineering research continue to grow. The topic remains highly controversial, in part because any possible choice about deployment of a global intervention requires governance that does not yet exist and perhaps never will. At least some governance capacity could grow by developing governance simultaneously with research. Research should start small with outdoor experiments that pose negligible risk but illuminate physical, chemical and biological processes that underlie the behavior of intervention technologies. Such experiments provide an ideal opportunity to develop some of the basic elements of governance before there any serious risks are involved. Imagine how difficult it would be to govern experiments that actually posed some risk if none of the basic elements of governance had been assembled and exercised.

Independent Advisory Body

Proto-governance can start with the formation of an independent advisory board that researchers can consult for guidance. An advisory board can provide advice on many of the issues discussed below, including the interface between science and society, methods to make transparency meaningful, how to assess the value of research to society, and develop requirements and methodology for review and assessment of the research. Learning about how to charter and staff such a board should start early, perhaps informally, with the start of one-off early outdoor research.

An advisory board can help with the interface between science and the public and policy communities. Even early research can benefit from the creation of a public and policy interface. The interface should become an identifiable effort rather than talking across a sharp line between what is science and what is society. It takes special skills to represent the science in a way that is meaningful and enables discussion of societal concerns and needs. Even in early research this interface effort can function to articulate key questions for research that both scientists and members of society can relate to. For example, scientists might be trying to answer the question: Is technology X safe? More specifically: We know this potential harm that could accrue from phenomena Y. This experiment will help to answer the question: Will X affect Y? Members of society might agree (or not) that they would like the answers to these questions, but they might also have their own questions, such as: Will X affect Z? The dialogue can help to focus and articulate research questions. This may be conceptually easy, but in practice it takes time and attention. Even if an engaged public agrees with the research questions, they may question the need for the proposed experiment to answer them. Dialogue at this interface can help to get everyone involved to understand the value of answers to the questions being posed and whether the methods proposed are truly efficacious and necessary.

Reliable Research

Research programs should be designed to increase trust and confidence in the results. Many have identified transparency as important for trust, but transparency will have to mean more than revealing what research is being done or posting the experimental data. Meaningful transparency will include exposing the intent of the work, why it is being done, what were the alternative methods of getting these results, what the quality of the associated information is, what isn't known, what are the researchers' hypotheses about the result, and after the experiment, how do the results comport with that hypothesis, what was learned and what should be done next and why.

We can never hope to have a precise prediction of the results of a climate intervention. We can hope research increases the accuracy of our understanding about the direction an intervention will go. If over time researchers become better and better at predicting the outcomes of their experiments, this will increase confidence. If predictions are not made *a priori*, this opportunity is truncated. Twenty-twenty hindsight has much less impact on confidence building than *a priori* prediction and *post facto* comparison of predictions and actual outcomes.

Reliability will also require more than the normal peer-review process to ensure that the geoengineered system as a whole has been properly defined and appropriately investigated. Consequently, research review and assessment process will likely need to use other methods such as funding teams of researchers to identify weaknesses or errors may be one way deal with this issue. An advisory board can help guide such a review process.

Strategic Research

One of the common ethical concerns about geoengineering is that it will distract people from the necessity of mitigation, known as the "slippery slope" problem. In truth, geoengineering-type technologies could not keep up with an ever-growing concentration of GHGs in the atmosphere. The research community knows that geoengineering as currently defined makes no sense without a vigorous attempt to mitigate green house gases and that adaptation will be necessary. However, the research community has – likely unwittingly -- played into the "slippery slope" concern by differentiating different types of geoengineering according to what they think the governance issues are. For example, the recent NAS report on geoengineering was separated into a report on SRM and one on CDR because these technologies are currently seen as quite distinct. Such a split serves the interests of scientists because it could minimize or tailor required governance of research projects. But separating the governance of these technologies forfeits the opportunity and requirement to develop a holistic climate strategy.

Geoengineering should only be *used* (if at all) in concert with every other tool we have to control climate change. Geoengineering should never be thought of as an independent technology. But, unlike mitigation and adaptation, the character of geoengineering intervention is *fundamentally* strategic. Because geoengineering cannot be used alone and the very idea of intervention is strategic, the research enterprise on geoengineering creates the environment to at least discuss holistic climate strategies. To capture this opportunity, geoengineering both current categories of geoengineering should be brought under the same governance umbrella with mitigation and

adaptation the ever-present context for research and whenever – if ever - possible, all strategies should be encouraged into the same governance umbrella.

Mission-Driven, Systematic Research

Early exploratory research to date has largely been investigator driven. As research becomes more serious and focused on specific technologies, the nature of research should become more organized. Geoengineering represents a large and complex systems problem involving many moving parts. Investigator-driven research will not necessarily engage all the various interconnected aspects. For these reasons, at some point a geoengineering research program must be a systems-investigation. After all, the fundamental characteristic of geoengineering is that it is *engineering*, i.e. a solution designed to solve a problem. An engineering project, particularly one of this magnitude and complexity requires a thorough investigation of the entire system, often called a “systems approach”.

Mission-driven research was common in the past, but has fallen out of favor for several reasons. Researchers often find that top-down management of research leads to corrupt, narrow control or a reckless disregard for collateral damage. Examples include the nuclear weapons enterprise that created significant long-lasting environmental insults, the Challenger disaster that lacked a bottom up communication mechanism, and even some recent top-down basic research programs that led to management perceived as corrupt and self-serving. Never-the-less, defining the geoengineered system and insuring a thorough investigation requires some organized effort.

Careful thought about how to reinvent mission-driven research should attempt to ensure systematic research in the public interest while individual creativity and initiative remain strong. This should start with careful thought about defining the mission itself. Certainly, the mission should not be simply to develop a technology for use. The definition will have to be much more nuanced and include articulation of a requirement to find out as much as possible about the effectiveness, advisability and feasibility of given concepts. It should also include a requirement to report findings that indicate a technology is not suitable for deployment.

The definition of the mission of research could be an excellent topic for engagement with policy makers and publics, especially if these goals can be articulated in terms of questions people have. For example, nuclear test ban treaties were enabled by answering the question: Can nuclear tests be detected? Geophysicists demonstrated they could detect any weapons test conducted anytime, and this in turn enabled ratification of the nuclear test ban treaty. (Likely detection and attribution will also be among the goals that policy makers would like for geoengineering research as well.)

Institutional design for mission-driven research will require care. All of the above functions need to have a home or defined procedures and processes to update them. Beyond that, both individual and institutional motivation and special interests will require moderation. Researchers are likely to push for research on ideas they think could be important and they will naturally feel identified with their success. But, the research charter needs to somehow reward both researchers and their

institutions for finding that a proposed technology is a bad idea. Our current research enterprise rarely rewards negative results.

Summary

Research should start soon because there may only be decades before climate conditions become extremely difficult and the knowledge base we have about geoengineering remains thin. Starting carefully with small, very low risk experiments but in a way that develops governance capacity in case it becomes advisable to do higher risk experiments seems wise.

Comments on Solar Geoengineering

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To avoid dangerous anthropogenic climate change, the international community has agreed on a target of holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the increase to 1.5°C. However, current commitments to mitigation of CO₂ emissions are expected to result in a temperature rise of order 3°C. Achieving a 2°C target without solar geoengineering remains theoretically possible, but would require an immediate transformation of our energy system on a massive and unprecedented scale, along with rapid deployment of unproven “negative emissions” technologies; achieving 1.5°C would be roughly twice as hard. Furthermore, (i) the threshold for “dangerous” climate change is unclear, and 2°C may be insufficient, (ii) estimates of the climate sensitivity to increased CO₂ concentrations remain uncertain and there is a 1/3 chance that the temperature rise from current mitigation commitments would exceed 3°C, and (iii) this 3°C estimate assumes that governments follow through on commitments to reduce emissions. The substantial gap between ambitions and likely outcomes, combined with these additional risks, means that the potential role for solar geoengineering technologies needs to be seriously considered.

Solar geoengineering, such as adding aerosols to the stratosphere to reflect some sunlight, cannot be a substitute for cutting emissions, as that would require large forcing levels to be sustained for millennia (Figure 1). However, climate modeling research to date suggests that solar geoengineering used in addition to mitigation has the potential to reduce many climate risks.

The current state of knowledge is insufficient to assess whether the risks of deploying geoengineering outweigh the risks of not deploying it. Neither of these risks are well understood, and future decisions could be driven as much by an increase in the perceived risk of not deploying as they are by improvements in our understanding of geoengineering. The world could pass 1.5°C within the next few decades, and there is a risk of poorly-informed decisions being made if research is not conducted with some degree of urgency. Developing the required knowledge demands a strategic (mission-driven or goal-oriented) research program.

Informed decisions will require identifying different options for deployment (including no deployment), projections of the climate response and human/ecosystem impacts for each option, together with an assessment of the confidence in those projections, and strategies for managing a deployment; decisions will also require increased confidence relative to today.

This focus on the end-goal of supporting informed decisions leads to broader research questions that go beyond the exploratory research conducted to date. For example, climate impacts will depend on how geoengineering is deployed (e.g., the latitude(s) for injecting stratospheric aerosols). How well could we design a deployment to achieve specified objectives, while minimizing risks, in the presence of uncertainty in the climate response? This problem is an

engineering design challenge requiring a systems-level approach, and not simply a climate science question. Questions such as “what happens if we inject aerosols at the equator” have a role in understanding the climate response in models, but should not be interpreted as an indication of what geoengineering might do. As a second example, simply stating that impacts are uncertain is not sufficient. Assessing the confidence in projected impacts requires an assessment of uncertainties in climate models: how uncertain some process could be, how sensitive the conclusions are to that uncertainty, what data or experiments might reduce that uncertainty, and whether there are strategies that could manage the remaining uncertainty. Large engineering projects maintain a formal risk registry to prioritize and track such issues; a strategic research program might benefit from similar methodology. These examples are not exhaustive; for example, research will also be required to more thoroughly explore strategies for attribution, and interdisciplinary research between the physical and social sciences is also essential, as society is the ultimate “customer” of this research. However, these examples are sufficient to illustrate the need for systems-level, mission-driven strategic research, with the first step being to clearly define what such a program would look like, taking input from the climate-policy community on what they need as outputs from research, and defining a plan to generate that knowledge.

Mitigation alone is unlikely to avoid serious climate damages, and we need to explore geoengineering as part of an integrated portfolio of options for managing climate change. There will always be both known and unknown impacts from either the choice to deploy geoengineering or the choice not to. However, ignorance is not an option. We urgently need a strategic, goal-oriented research program with the aim of supporting informed decisions in no more than 15 to 20 years. This program needs to determine what geoengineering can and can't do, what the impacts would be, and what the uncertainties and risks are.

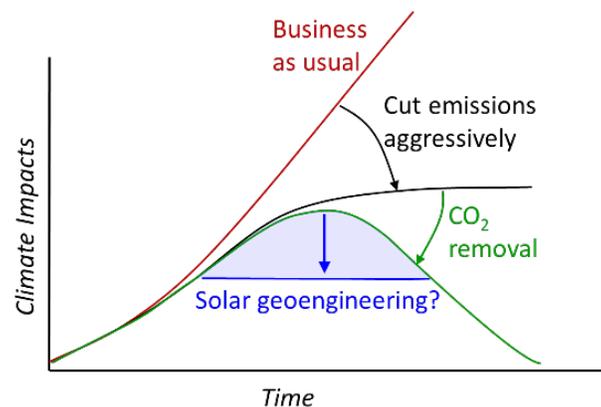


Figure 1. Reducing greenhouse gas emissions, combined with future large-scale atmospheric CO₂ removal, may lead to long-term climate stabilization with some overshoot of desired temperature targets. There is a plausible role for temporary and limited solar geoengineering as part of an overall strategy to reduce climate risks during the overshoot period. (Geoengineering instead of mitigation would require extremely large forcing to be sustained for millennia, and is thus not realistic.) This graph represents climate impacts conceptually, not quantitatively.

Essay for the Forum on U.S. Solar Geoengineering Research

Joseph Majkut

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The record high global temperatures of the past few years have previewed of a world inching closer to dangerous warming. Encouragingly, the falling costs of low-carbon energy and political agreement achieved in Paris also suggest a world moving toward decarbonization. However, it is increasingly clear that averting dangerous climate change through mitigation alone will be a big reach. Solar geoengineering could complement mitigation and further reduce climate risk; but little is known regarding how or when to use it. We should not leave future leaders in such ignorance.

Research into solar geoengineering has always had a frustrating dual character. Scientists interested in the climate have routinely supported geoengineering research programs and sporadically offer specific plans. Yet a dedicated research program has not found political support in the United States. Conservatives maintain that climate risks are not worth much concern, and environmental groups are wary of implementing solar geoengineering, worrying that even researching the idea will diminish support for reducing CO₂ emissions. Without political backing, the idea remains on the shelf.

The prospects for solar geoengineering research depend on how much political support can be built within the Administration and Congress. Support would ideally be durable and widespread, to provide stable funding and a governance process for any solar geoengineering experiments, especially in situ. Examining the reasons why different constituencies would support solar geoengineering may reveal opportunities of the moment.

Republicans

General ambivalence about climate risk amongst Republicans in Washington is increasingly untenable. Mounting political pressure and shifting public opinion are starting to crack the bedrock of climate skepticism on the political right, resulting in increasing interest in climate solutions from congressional Republicans. This presents an opportunity to build support from Republican members of Congress for solar geoengineering research programs.

Supporting solar geoengineering research could help Republicans gain some political legitimacy on climate change. Unlike smaller forays into clean energy research and development, solar geoengineering research is responsive to the actual scale of climate risks, and could be particularly attractive if the costs of adaptation or mitigation suddenly appear too high. Moreover, some conservatives may be swayed by the national security argument for beefing up the capability of the United States to monitor whether other countries are testing or implementing solar geoengineering themselves.

Further study may reveal that the risks of solar geoengineering are unacceptable, or the same reluctance to accept central planning and internationalism hindering support for mitigation policies may keep Conservatives from fully embracing solar geoengineering. The political questions about who sets and pays for the global thermostat are immense and might not have politically acceptable answers for conservatives. Yet we may also find that support for solar geoengineering could help climate-interested Republicans move toward a strategy of managing climate risks through other policies. Doing so could inspire positive developments not just for climate engineering research and governance, but mitigation and adaptation policy as well.

Environmental Groups

Environmental groups fear that policymakers will embrace solar geoengineering as an excuse to allow unmitigated greenhouse gas emissions. Indeed, this seems like the central reason why environmental groups have been reluctant to support research programs. This is valid concern, but not a guaranteed outcome of a research program.

Basic cost-benefit analyses predict massive returns associated with solar geoengineering, far beyond those of mitigation policies. The calculations can look almost comical, with solar geoengineering returning incredible reductions in climate damages and implying that development of solar geoengineering capability should be a priority. Indeed, Bickel and Lane supported massive funding for solar geoengineering research¹⁷ based on cost-benefit calculations showing that it pays back at a huge rate. It is reasonable to think that solar geoengineering, once properly vetted, could be too good for policymakers to ignore. The political costs of climate action and internalizing the costs of climate change to businesses and consumers globally are large. For those wary of the costs of climate change, solar geoengineering could look like an easy out from the hard work of mitigation.

To what extent should environmentalists fear the temptation to replace mitigation with solar geoengineering? The Paris Agreement established international climate action as the norm. As financial investments shift to low-carbon energy infrastructure and cost curves plummet, the questions about decarbonization seem more about “when” than “if”. These developments drain some power from the arguments that solar geoengineering research will create a moral hazard by disincentivizing mitigation activities. The fear that solar geoengineering will give fossil fuels a free pass to raise atmospheric CO₂ and burden future generations with the need to forever counter an enormous greenhouse warming seems out of date.

There is a large range of possible climate outcomes between the worst-case and best-case emissions scenarios. A key insight from Bickel and Lane is that the benefits of solar geoengineering are largest when mitigation policies fall short in terms of ambition or participation. As temperatures climb higher, marginal reductions from some solar geoengineering have a larger impact for the same cost of deployment. While this finding results from the relatively neat cost-benefit analysis of an integrated assessment model, it makes intuitive sense that solar

¹⁷ http://www.copenhagenconsensus.com/sites/default/files/ap_climate_engineering_bickel_lane_v.5.0.pdf

geoengineering interventions will be most needed if mitigation policies fall short. Despite recent progress in clean energy and climate politics, we may well find ourselves on too anemic a mitigation path, and environmental groups should consider this possibility.

Trump Administration

If a serious effort to research solar geoengineering is to begin soon, the Trump Administration is the crux. The new Administration is uninterested in addressing climate risk and plans to cut funding for climate science and monitoring efforts. Despite generally favoring technological progress and increased use of space, the Administration is unlikely to pursue a sober and careful solar geoengineering research program.

While funding support can come from Congress, a reasonable research program for solar geoengineering is impossible without administrative support. Making solar geoengineering research acceptable to the public, members of Congress, and other countries requires interagency coordination and executive branch oversight. U.S. government oversight will be key to avoid treaty conflicts or conflicts from domestic environmental regulation and lawsuits. The potential legal liabilities, political opposition, and international discord that could come from anything but the smallest experiments are massive. Lack of administration support may be the biggest challenge to getting a research program off the ground in the next few years.

Finding a way to convince the Trump Administration to judiciously support solar geoengineering research will probably be a task of trial and error. Given its focus on national security and defense, a research program geared toward national security and competitiveness is a decent first bet. With growing research programs in China and Europe, the United States is in danger of falling behind the forefront of research into solar geoengineering. Whether a competitive disadvantage will spur the Administration's interest is up in air.

Path Forward

In any dedicated research program, the gap between research and implementation should be clearly articulated. While geoengineering technologies might provide a viable and relatively inexpensive way of warding off the worst impacts of warming, there are plenty of reasons to be wary of their implementation. How the climate will respond and how any implementation of solar geoengineering would be monitored and governed must be thoroughly explored. Near term research into these questions will help future generations make better decisions.

But before we get to near term research, we will need to perform a political balancing act to work against deflating research budgets, ambivalence about climate risk in the Administration and some parts of Congress, and the reluctance of the environmental groups. The strange brew of some climate action, but not enough, and the new prominence of climate-interested Republicans could help us get there.

Lessons for Geoengineering from Same-Sex Marriage

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It is easier to change your mind than to change the physical basis of how you live; but you still need a reason to do so

Some years ago, in a public debate about geoengineering, a liberal American brought up the subject of same-sex marriage. It demonstrated, he argued, how quickly a policy objective could go from being more or less unthinkable to being pretty nearly unstoppable. If that could happen for same sex-marriage, he asked, why could it not happen for swift and deep emission reductions? And if it could, surely it would be better to concentrate on making that happen rather than distracting ourselves with ideas of geoengineering?

I saw this as a flawed – indeed, rather silly – analogy. The shift away from fossil fuels raises huge issues about investment, vested interests and infrastructure, as well as technological readiness, in a way that the fight for same-sex marriage – demanding though it was – simply did not. But later it struck me that, while the rapid and linked shifts in policy and opinion on same-sex marriage held few lessons for emissions reduction, they might be illuminating in terms of what could be possible in the field of geoengineering itself. After all, the objections to pursuing policy and research agendas that might result in geoengineering are not that it would be very difficult to try it out. They are that it would be a bad idea to try it out – just as many people thought that trying out same-sex marriage was a bad idea. And as the example of same-sex marriage shows, arguments about ideas that are unpopular but not particularly impractical can be turned around fairly quickly.

Two aspects of the fight for same-sex marriage seemed particularly salient. One: it had to overcome opposition based on a distinction between the “natural” and the “unnatural”. Two: it encountered significant opposition from established advocates for the rights of gay people – the very rights that the marriage activists sought to extend.

Many opponents of same-sex marriage considered homosexual acts unnatural--though they are, as it happens, common throughout the animal kingdom--and/or held that the natural role of marriage was primarily as a setting for procreation. Their sense of the natural in these matters was often conflated with a belief that in these respects nature reflected the will of God. Countering these arguments was not a matter of showing them to be wrong, but of providing other plausible and indeed attractive frames in which same-sex marriage looked much more natural. Thus proponents stressed the natural urge for humans to form loving pair-bonds and an interpretation of human nature as something which included the possession of certain natural rights.

To weaken resistance to geoengineering, then, the task would be to find ways in which it might seem more natural. Stressing the fact that volcanic eruptions already cool the Earth in similar ways might help, but probably not that much: the key to geoengineering is the intention, and volcanoes

have no plans when they blow their tops. More promising, perhaps, would be to stress argue a natural urge to care for the environment – a biophilia that can be its own justification. Naturalize the reasons for geoengineering, not the process.

Linked, but not identical, to the idea of the natural is that of the normal. Marriage was, and is, normal; successful same-sex-marriage rhetoric sought to simply extend this normality (perhaps the most influential book on the subject in the 1990s was Andrew Sullivan’s “Virtually normal”) to people not at the time licensed to enjoy its charms. The analogy is not tight, but something similar might be done for geoengineering if it were regularly portrayed, say, as a novel expression of a normal activity, such as collective mobilization in response to a threat, rather than something fundamentally other.

The second point of comparison is opposition from those who ostensibly share the same goals. In its early years the issue of gay marriage was sidelined by mainstream gay activism for a number of reasons. Some saw it as a freedom that would never be granted, or would be of interest to very few, and thus that putting effort into it would not be worth the opportunity cost. Others held that the purpose of gay liberation was to establish freedoms of behavior that went beyond the institutions of heterosexual society, and that seeking to buy into an institutionalized norm of monogamy on the straight world’s terms was not merely a waste of time but antithetical to that broader emancipating ideal.

Both these arguments have analogues in the way that many in the environmental movement think about geoengineering. Some think that it will simply not happen, perhaps because people would never want it to, and thus is not worth taking seriously. Others think that the purpose of environmental activism is to create a new relationship between humans as political and economic actors and the world around them. The prompt downfall of extractive industries fits this agenda; the maintaining of the status quo that they see in geoengineering seems to run counter to it.

Here the response for people seeking to promote a climate of opinion more open to geoengineering might be to stress the reduction of harm, both to humans and to the wider environment, and a commitment to a broad church. Successful strategies would include never portraying geoengineering as an alternative to other forms of environmental action, and instead always portraying it as a complement to all sorts of other climate action that is aimed specifically at reducing harm. The shift in climate negotiations to a greater focus on damage and loss, as well as a growing apprehension of near term risk should be useful developments to this end. But they have yet to prove so.

If this provides some hope for those who want to see a greater focus on proposals for geoengineering in discussions of climate action, though, other lessons from the fight for marriage equality are less helpful. Same-sex-marriage campaigners were able to fight piecemeal, in many different jurisdictions, through legal action; those fights both helped to change public opinion and could go on without its support. There may be some analogies here for geoengineering research (and if there are, they might call into doubt the wisdom of attempting to fix ex-ante universal

standards for the governance of such research). But discussions of deployment would, and should, be very different.

Another point of divergence is the question of harm. Opponents of same-sex marriage claimed that it would do harm to marriage as an institution. Never a particularly plausible argument, it was fatally weakened as a result of the increased visibility of people in long-term gay relationships – especially those with children – and through victories in the courts. The evidence that gay marriage had no real effect of any sort on anyone else’s marriage built up quite quickly well before the fight was won — as did the evidence that being able to lead married or close-to-married lives added to many gay people’s happiness. Making some people happy while not really harming anyone else became a relatively easy sell (though it should be noted that there remains a significant residue of opposition to same-sex marriage). This provides no message of cheer for geoengineering. The potential for damage and harm due to geoengineering is far more persuasively disturbing than was the case for same-sex marriage, and it would not be easily reduced through a few proofs of principle.

And then there is a third, and perhaps definitive, point of divergence. There were people who really wanted same-sex marriage, both for the good of society and as a personal possibility. Only a few, to begin with – but enough to come together, to strategize, to influence others and to campaign. And there were also people who thought it made sense not simply to ignore these people, but to fight them – thus raising their visibility.

There is no equivalent constituency which believes in geoengineering. There are some who think that the possibility needs to be explored much more thoroughly than is currently the case, with an eye to developing safe, just and governable interventions for which it would be possible to campaign. But that is a far more nuanced position than “My right to marry the person I love is being abridged and I am suffering”. And even in its nuanced form, there are few who adhere to it. Without anyone fighting for it, there is no need for anyone to fight against it – and thus it is possible for mainstream discourse to ignore the subject more or less completely.

It may be much easier to shift opinion on geoengineering than people think; it is quite likely that it would be easier to shift opinion on geoengineering than it would be to radically accelerate emissions reduction. But it will never happen unless there are people campaigning for it to happen, and making a fuss when people do not consider it a possibility, or laugh about it as an aside. In the absence of proponents for change, there will only ever be the status quo.

Toward Governance Frameworks for Solar Radiation Management

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Climate geoengineering – large-scale, deliberate interventions in the Earth system to counteract climate change – has been a subject of growing interest and debate within the scientific community, but is still a new object of consideration within policy circles and in the public sphere. The potential deployment of climate geoengineering interventions raises many questions, including uncertainty regarding their effectiveness and indirect effects, as well as questions regarding the ethics of their use and their governance.

Achieving the ambitious temperature goals of the Paris Agreement would require rates of mitigation far in excess of what has been achieved to date. A growing number of scientists and policymakers believe that actions well beyond existing mitigation plans may be necessary to keep temperatures between 1.5-2°C above pre-industrial levels.

It is in this context that attention is turning towards a wide range of proposed geoengineering techniques to cool the planet. Such techniques are usually grouped into two categories: carbon dioxide removal techniques, which address the primary source of climate change - excess carbon dioxide in the atmosphere, while solar radiation management techniques address the symptom – increasing temperatures – by reflecting a proportion of the sun’s radiation back into space. The latter could provide a breathing space to undertake a radical decarbonization of the global economy.

Ultimately, in order to achieve a stable climate, it will be necessary to achieve zero net emissions – reducing emissions significantly and counteracting any remaining emissions through carbon dioxide removal. Until we reach this point, policymakers may consider a combination of both sets of techniques as a means to avoid the worst effects of climate change.

However, governance issues arising out of the broad range of proposed geoengineering techniques, in particular solar radiation management, pose a range of challenges. There is currently no systematic, coherent set of global governance frameworks in place to guide further research, facilitate decision making and guide potential deployment. Governance, in this instance, goes beyond control and decision making, and includes the effective participation of those who would be affected and impacted, as well as their access to prior, relevant information.

A growing number of scientists believe that the aggregate risks of environmental and socio-economic impacts from solar radiation management would be small in comparison to the benefit of reducing global temperatures. However, the distribution of benefits and harms would be

unequally spread both in terms of regions of the world and in terms of between current and future generations. In addition, current scientific knowledge leaves a significant margin of uncertainty regarding the exact effects of interventions, including their nature, scale and location. Deployment therefore raises issues regarding the criteria and, most importantly, the mechanisms used to make decisions about ways of balancing possible positive global impacts and negative regional or local impacts, including the need for potential compensation to affected populations.

Another set of issues relate to the dangers of unilateral interventions. In the absence of multilateral agreements there is a possibility that a small group of countries, a single country, a large company or indeed a wealthy individual might take unilateral action on climate geoengineering. This raises the possibility that those who do not like these actions and their impacts could engage in counter-climate-geoengineering. Clearly, it would be best to avoid such a chaotic and dangerous future.

Climate geoengineering would require global governance frameworks, of which, at best, only some elements exist today. These frameworks would have to be developed in parallel to the technologies themselves.

Within the current global governance architecture, it would seem that, given its global impacts, only the UN General Assembly could give legitimacy to any governance framework guiding the potential deployment of climate geoengineering. Actual work, however, could be made more efficient by other measures. One option could be to undertake it within a professional international authority with a mandate from the UN General Assembly, similar to the way the international community addresses peacekeeping or nuclear proliferation. There is scope for the development of other and possibly better approaches involving all relevant stakeholders.

The following questions would need to be addressed in order to develop robust governance frameworks. Who would control the “global thermostat”? How would decisions be made to balance the need to reduce the global temperature with unequal regional and local impacts across the globe? How would trans-border and transgenerational ethical issues be addressed? How would decisions be made to balance the costs and benefits of traditional mitigation methods versus climate geoengineering? What would be the impacts in terms of local and global justice, and in terms of human rights, and how could these be addressed? How would the required governance frameworks withstand potentially substantial geopolitical changes over the decades and possibly centuries that they need to be deployed? How might such techniques be deployed in a manner that does not undermine the will to cut emissions? How would decisions relating to the profile of deployment – the rate of starting, continuing and stopping such techniques – be governed? This last issue is of particular concern with respect to proposed solar radiation management techniques, as a sudden cessation of deployment (the “termination effect”) would result in a rapid rise in temperatures.

The research community has been addressing many of these issues, but the global policy community has not, and it is time to begin to do so.

Governance of research in this area also needs to be developed – ideally parallel to the development of further scientific and socio-economic understanding, so that as research progresses, governance mechanisms evolve and vice versa. The results of further research in this area could be much strengthened, and better accepted by different constituencies, if accompanied by transparent procedures for sharing research plans and expected outcomes of research *ex ante*; having independent bodies review research plans and provide feedback *ex ante*; and committing to meaningful public engagement in the process both *ex ante* and *ex post*.

Governance in this space has two roles: on the one hand it could act to control, regulate and potentially restrict research, while on the other hand it could act to enable research. Developing such governance requires active engagement with the public and policymakers and would need to be congruent with the achievement of agreed objectives for sustainable development.

The recently initiated Carnegie Climate Geoengineering Governance Initiative (C2G2) seeks to help fill the governance gap in relation to research and potential deployment of climate geoengineering by encouraging policy dialogues; through transparent engagement of relevant stakeholders; and by catalyzing the development of different elements of the governance frameworks needed.

Geoengineering Using Aerosol Particles: Knowns and Unknowns

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Solar geoengineering promises to be able to decrease Earth surface temperatures to stave off dangerous increases caused by greenhouse gases. Yet, any such decrease is only a “mask” for the underlying causes that would almost immediately return if geoengineering stopped. While some may think that a temporary masking, in combination with mitigation of CO₂ emissions, could prevent the highest temperatures caused by CO₂ increases to be avoided, it is not at all clear how efficiently this might be accomplished, nor is the maximum temperature change that might be avoided clear. A program of research that included a set of realistic field experiments would benefit both the uncertain knowledge of how effective any given geoengineering strategy might be and would also benefit important uncertain aspects in Earth System Science.

Solar geoengineering works by reflecting incoming solar radiation, thereby decreasing the amount available to warm the Earth. There are two main mechanisms that have been studied: 1) injecting SO₂ into the lower stratosphere, similar to large-scale volcanic eruptions; and 2) injecting particles (mainly sea salt particles) into the boundary layer near the Earth’s surface over the oceans.

While volcanic aerosols have been shown to decrease the Earth’s temperature, the impact of the most recent (and best studied) large-scale eruption, Pinatubo in 1991, on Earth’s surface temperature is debated (Canty et al., 2013), and so, even though we have estimated the magnitude of the injection of Sulfur (approximately 20 Tg SO₂), we are not entirely sure of its temperature impact.

In addition to being able to predict the temperature impact of any given strategy for geoengineering, in order to plan any mitigation augmentation, we need to be able to determine how any given injection strategy impacts incoming solar (and outgoing terrestrial) radiation. In order to know this, we need to know the size of the particles that will form, the rate at which the particles are removed from the stratosphere (and then their rate of removal from the troposphere), and finally whether these particles might form cirrus clouds within the troposphere, and if they do, whether these cirrus further cool or warm the climate. How the injection changes the Earth’s radiative balance is termed its “radiative forcing” and all the above questions are aimed at getting a better handle on the radiative forcing associated with a given injection. Models have been used to try to estimate the efficiency of injection of SO₂ (Cirisan et al, 2013; English, et al., 2012.; Niemeier et al., 2011; Niemeier et al., 2013; Pierce, et al, 2010). Interestingly, the efficiency of stratospheric injection appears to decrease with increasing injection rates of SO₂ (Niemeier et al., 2015).

Beyond the radiative forcing, as noted above, we need to be able to predict the temperature response of the Earth's surface to a given injection strategy. As noted above, even this is uncertain (as is the response of climate change to CO₂). In addition, other "climate responses" are not well known. These include the extent to which precipitation might change, and where these changes might occur, the extent to which stratospheric O₃ might change, and whether such changes might cause additional stratospheric circulation changes, and the extent to which vegetation might be affected by the decreased direct solar radiation (and increased diffuse radiation, caused by the scattering of the direct beam by particles).

Barring another near-term large volcanic eruption that is well-instrumented, field experiments to determine the radiative forcing associated with SO₂ injection seem the most feasible way to advance our understanding of the effectiveness of a given geoengineering strategy. Improving our understanding of the climate response to a given radiative forcing, unfortunately, invokes the entire suite of issues involved in predicting climate change, and thus, seems beyond our ability to advance using field experiments. However, we may be able to test our understanding of microphysics and the size distribution of particles predicted by models using field experiments. However, I believe rather large injection experiments would be needed to enable sufficient signal to noise, and we would want to accompany these with aircraft measurements designed to determine the resulting particle numbers, size and lifetime in the lower stratosphere. Injection of perhaps 2 million metric tons of Sulfur (as SO₂) into the lower stratosphere might be sufficient to determine the particle response to injection, to allow testing of models and to determine the time history of removal of the particles. But injections of this size, are large enough that they get close to actual deployment. Moreover, it is unlikely that effects on temperature, cirrus clouds and water vapor, could be determined with sufficient accuracy.

Marine cloud brightening is the second mechanism proposed to decrease incoming solar radiation. Sea salt particles are naturally formed over the oceans as a result of the wind and resulting turbulence created at the ocean's surface. One proposal is to enhance the production of sea salt aerosol particles, through a design involving ships cruising over the open ocean and spewing up sea salt particles (Latham, 1990).

The primary scientific uncertainty associated with marine cloud brightening has to do with the extent to which increased particle concentrations within the marine boundary layer alter clouds. This aspect brings up one of the largest uncertainties associated with understanding historical climate change: How do particles interact with clouds to change their microphysical nature (e.g. drop or crystal size), the amount of water stored within clouds (e.g. the liquid water path) and their cover (e.g. the sky cover associated with clouds, or cloud fraction). While the expected change in droplet number concentrations is fairly well known (e.g. Painemal et al., 2015), the more macroscopic changes to clouds (i.e. water vapor path and cloud fraction) are not well quantified and remain the subject of intense research. All these responses of clouds to particles must be quantified to know how effective this solar geoengineering technique might be in reducing incoming solar radiation.

There have been small ship-based field experiments performed already to try to understand this phenomena (the E-PEACE mission, Russell et al., 2013). Unfortunately, some ship tracks can increase the reflection of solar radiation, while others decrease the reflection (Chen et al. 2012). Thus, quantifying the true impact of this geoengineering strategy requires a further set of experiments, perhaps of larger magnitude (i.e. larger injection) and probably taking place in different cloud regimes, since it is thought that the response of clouds to increasing aerosols depends on the regime (e.g. low-level stratocumulus clouds off continental coasts, and the regime characterized by clouds undergoing transition from stratocumulus to cumulus clouds (e.g. Williams and Webb, 2009)). Moreover, important improvements to current climate models are needed to capture improvements to cloud parameterizations that would allow the correct prediction of the response of clouds to aerosols (Zhou and Penner, 2017).

In summary, solar geoengineering offers the potential to shave off some of the future predicted climate changes associated with increasing CO₂. Nevertheless, we have much to learn in order to be able to utilize such a strategy. Moreover, we need an agreed upon governance strategy to avoid the “slippery slope” of initiating research via field experiments, leading to ever larger experiments that might lead to full deployment without understanding the risks associated with the response of the climate system to increases in particle concentrations.

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The Inchoate Politics of Solar Geoengineering Research

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Policy may largely be an outcome of politics, but as economist Robin Hanson asserts, politics is (usually) not about policy. This is particularly true for solar geoengineering, which elicits strong feelings and runs counter to typical relations between means and ends in environmental policy. Here, I offer my perceptions of solar geoengineering's inchoate politics, and a forecast of how they might unfold as research is advanced. Such forecasting, always uncertain, is even more so as the US enters uncharted political terrain.

Speaking with gross generalization, I observe three primary cohorts in solar geoengineering politics. First, *research advocates* have, almost exclusively, a history of studying anthropogenic climate change and of calling for aggressive greenhouse gas emissions cuts ("*mitigation*"). However, they are pessimistic about the prospects for mitigation alone to prevent dangerous climate change. This cohort is dominated by scientists and, to a lesser degree, a few moderate environmental groups. They reluctantly argue that solar geoengineering appears to offer a feasible and effective means to counter climate change and, in turn, to protect vulnerable people and ecosystems. Second, *research opponents* advance a variety of arguments, the most common of which is that solar geoengineering research would undermine already insufficient mitigation efforts. They also often highlight physical risks and uncertainties, questions of control and potential conflict, matters of justice, and the hubris of messing with nature. Some opponents accuse the research advocates of unwittingly--or even consciously--aiding the vested interests that benefit from fossil fuels' continued use. Third, less noticeable are the *conservative opponents of mitigation* who have largely remained on the sideline of solar geoengineering debates. Occasionally a right-of-center voice suggests that solar geoengineering offers a simple solution, while a climate change denier mocks it as another unnecessary response to a nonexistent problem. Meanwhile, the lay public remains mostly ignorant and, if asked, exhibits a wide range of responses to solar geoengineering.

Initially, I was a research opponent when I encountered solar geoengineering. The assertions that it is simply a risky effort by fossil fuel interests to avoid mitigation both seemed logical and confirmed by preexisting views. Yet the closer I looked, the more I saw that solar geoengineering was driven by despondent environmentalists; that realistic mitigation scenarios could no longer keep global warming within the internationally agreed-upon 2°C limit; that climate models consistently indicated that solar geoengineering could effectively reduce climate change; and that the ability to implement it could serve as a type of insurance against future climate risks. Notably, many other research advocates followed a similar path.

To some degree, the climate change discourse has likewise evolved with respect to solar geoengineering. As actual mitigation continues to disappoint and as the forecasts for climate change become more dire, calls for research have been more common, as seen in the 2015 US

National Academies reports and the recent update to the National Global Change Research Plan. Although this evolution may be a source of strange encouragement among research advocates, many of them are understandably cautious. Our greatest fear is that conservatives will pivot, suddenly embracing the proposed techniques. If this were to happen, then solar geoengineering would be widely perceived--rightly or wrongly--as a means to perpetuate our unsustainable reliance on fossil fuels.

I believe that this concern may be somewhat misplaced. Seeing why requires differentiation within two of the broad political cohorts. First, although conservative opponents of mitigation are often lumped together and smeared as “denialists,” they actually profess a range of views. The more extreme ones indeed deny that the climate is changing or that humans are the primary cause thereof. They are unlikely to embrace solar geoengineering, as doing so would require them to alter their foundational beliefs. Instead, they will continue to dismiss it--if they discuss it at all--as grandiose nonsense from power-hungry scientists. However, a substantial portion of opponents of aggressive mitigation do acknowledge anthropogenic climate change but argue that its impacts will be moderate and that mitigation would be too expensive. In fact, some of these “lukewarmers” emphasize that the world’s poor would be served better by reliable access to affordable energy. To them, solar geoengineering could offer a means to reduce the real but--in their opinion--moderate risks of climate change without hindering development. Although research advocates may bristle at the prospect, given their dedication to mitigation, they may need to choose whether to cooperate with those who have seriously considered climate change and, in apparent good faith, come to different conclusions regarding aggressive mitigation.

Turning now the other direction, research opponents’ heterogeneity can be gleaned from considering the means and ends of climate change policy. Some research opponents, particularly advocates of “deeper green” environmentalism and social justice, have more ambitious goals than simply preventing climate change. As evidenced by their rhetoric and actions, they variously aim to reduce the human footprint on nature and to redistribute power and wealth in a more egalitarian way. Because mitigation might further these more ambitious goals, their support for it has always been a means to an end. And because solar geoengineering would not necessarily further these goals--and possibly threaten the prioritization of mitigation in climate policy--their opposition to solar geoengineering will remain fast. Yet there is another segment of research opponents: those who have been calling for mitigation for years, often under hostile political conditions. For them, mitigation has been the sole means to a critical end for so long that it appears to have become the end itself. They are now reflexively defensive to suggestions of any alternative. Solar geoengineering disrupts this, just as proposals to adapt society to a changed climate did two decades ago. For example, Al Gore initially called adaptation “a kind of laziness, an arrogant faith in our ability to react in time to save our skin.” It took years before he and others supported adaptation, which now stands alongside mitigation as an equally essential response to climate change risks. Many of these defensive opponents may warm up to solar geoengineering, especially if we research advocates engage with them seriously and proceed cautiously. But if we fail to do so, then they may harden their position. To me, this is the real risk of advancing solar geoengineering research.

Benefits, Risks, and/or Opportunities of U.S. Solar Geoengineering Research

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Research has demonstrated that, in climate models at least, solar geoengineering has a tremendous potential to reduce the amounts and rates of regional climate change caused by rising atmospheric greenhouse gas concentrations^{1,2}. Solar geoengineering is far from being a perfect substitute for emissions reductions – it has different effects counteracting temperature and hydrological changes, does nothing to reduce ocean acidification, and may introduce its own risks such as increased amounts of stratospheric ozone destruction³. Nonetheless, with global warming continuing apace and high levels of uncertainty about the extent to which mitigation policies can limit global temperatures to 1.5°C or 2°C above pre-industrial, solar geoengineering research can't be ignored.

There are a few areas where I think the current state of the geoengineering literature is problematic and where there are opportunities to improve the discussion.

Scenarios

Climate modeling always requires choosing between transparency and realism when deciding what scenarios to simulate. The first generation of geoengineering modeling experiments sensibly focused on idealized scenarios that provided a sound basis for understanding physical mechanisms associated with geoengineering forcings, but conclusions about impacts that solar geoengineering implementation might have the real world were then extrapolated from these results (often based on intuition). I don't know anyone who believes solar geoengineering is a panacea, but it is often implemented as one in idealized simulations. As solar geoengineering research becomes more mainstream, this research community should try to catch up with the broader climate modeling community in terms of formulating geoengineering scenarios based on sound socioeconomic assumptions and interdisciplinary expertise.

Impacts Assessment

There's been an explosion of research on socioeconomic impacts of climate change in the past decade based on econometric analysis⁴. Temperature shocks (and sometimes precipitation shocks) have been robustly linked to a whole host of micro- and macroeconomic effects. But application of this work is problematic in a solar geoengineering context because compensating for greenhouse gas forcings with solar ones divorces temperature from hydrology. The signal of precipitation effects on impacts is often not statistically discernable because at the levels of analysis used, temperature and precipitation strongly covary. We need to find better ways to tease out particular impacts contributions directly attributable to temperature versus factors such as precipitation and soil moisture. There's no way to make a good case either for or against the use

of solar geoengineering without having a more solid grasp on the impacts of the particular climate conditions solar geoengineering creates.

Behavior, Economics and Societal Transitions¹⁸

Because decarbonization of energy systems, negative emissions technology, adaptation and solar geoengineering are all tools to mitigate climate risks, an economy in which all are viable must exhibit some substitution effects between solar geoengineering and other more conventional approaches. Many scholars have also raised the possibility of a moral hazard effect associated with solar geoengineering, whereby people under-account for risks from CO₂ once learning of the potential of solar geoengineering to cheaply mitigate its effects. There is also some empirical evidence that an opposite effect exists in which people want more emissions reductions in the presence of a geoengineering option. Understanding how solar geoengineering decisions will interact decisions about implementation of mitigation and adaptation is a major challenge.

Support for major policy initiative is always going to depend on tradeoffs between costs and benefits. One could imagine a situation in which the threshold for implementing solar geoengineering is lower than that for a major overhaul of the energy system. Under such circumstances, it's possible that solar geoengineering designed to reduce suffering in the short term could ultimately increase net suffering.

The figure below illustrates a highly simplified thought exercise on how this could happen, based on the assumption that the threshold for deploying solar geoengineering is lower than that for reducing greenhouse gas emissions because solar geoengineering deployment is: 1) cheaper than greenhouse gas reductions and 2) requires less international coordination (from a technical perspective). Panel A shows impacts from climate change over time as illustrated in a world where there is no solar geoengineering. As climate changes, impacts (and suffering) increase. At the threshold point, impacts become so intolerable that strong and lasting actions are taken to eliminate greenhouse gas emissions. Because of carbon inertia, even after such a policy shift, impacts would likely continue to rise until CO₂ concentrations and rate of climate change can be stabilized.

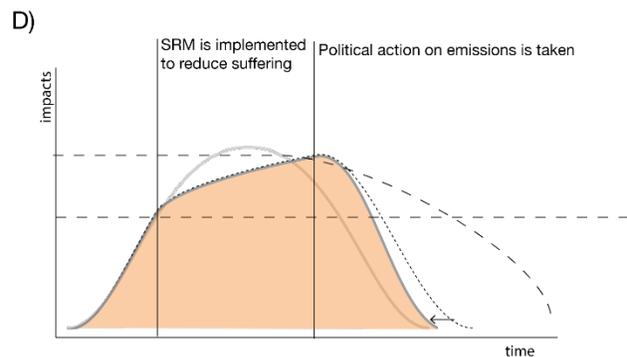
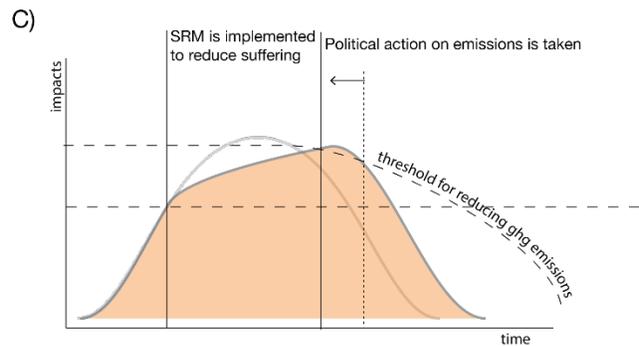
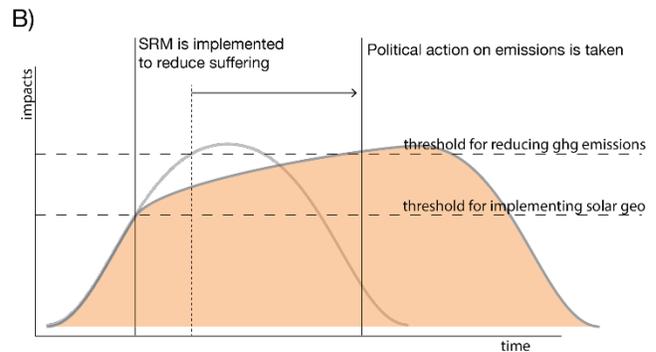
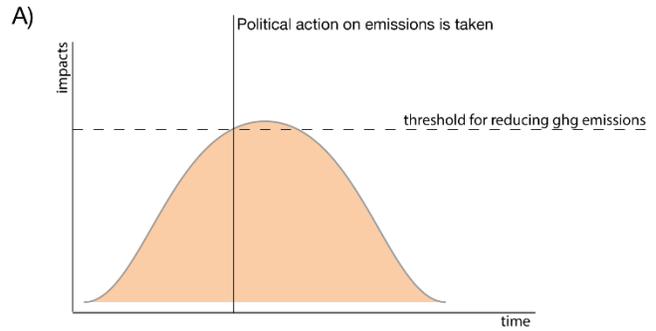
Panel B shows how impacts/suffering from climate change over time might change in a world where solar geoengineering is a possible means of reducing suffering at a lower cost than GHG reductions. Geoengineering slows the rate of impact increases (or could perhaps even reverse it for a time), but because it is an imperfect substitute for GHG reductions, eventually under such a scenario, total impacts -- as illustrated by the area under the curve -- could be much greater than in a world without solar geoengineering.

Of course, even with differential thresholds for intervention for solar geoengineering and GHG emissions reductions, solar geoengineering may not necessarily increase net impacts as in Panel B. For example, the impacts threshold for reducing emissions could diminish over time due to the development of cheaper mitigation technologies or changing social tolerances for suffering (panel

¹⁸ Portions of this section are adapted from Chapter 5 of Ricke (2011)⁵.

C). Or the rate at which impacts could be reduced may be greater if the threshold for action is passed later (panel D). Even under such scenarios, though, when solar geoengineering is implemented, some impacts are likely being pushed onto future generations. The way such dynamics play out is subject to huge uncertainties, but it would be helpful to start thinking about the conditions under which it would be “socially risky” to implement solar geoengineering (e.g., rapidly rising emissions, no strong mitigation policies) versus those under which it is unlikely to result in indefinite delay in reducing GHG emissions (e.g., after renewable energy has become cost-competitive with fossil fuel based energy). This would aid in the formulation of policies and institutions that can facilitate solar geoengineering implementation if it turns out it’s urgently needed, and also restrict its use under conditions that may lead to a catastrophic endgames.

Characterizations of geoengineering as “high risk” are contingent upon implementation approaches that aren’t necessarily consistent with reasonable objectives for use. Hopefully, as the field matures, discussions about solar geoengineering can shift toward evaluations focused on more realistic scenarios for impacts, objectives and constraints on implementation.



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The Benefits of U.S. Solar Geoengineering Research

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This paper draws heavily on my recent essay on the same topic [Robock, 2016].

Summary:

Research on albedo enhancement by stratospheric sulfur injection inspired by Paul Crutzen's paper a decade ago has made clear that it may present serious risks and concerns as well as benefits if used to address the global warming problem. While volcanic eruptions were suggested as innocuous examples of stratospheric aerosols cooling the planet, the volcano analog also argues against stratospheric geoengineering because of ozone depletion and regional hydrologic responses. Continuous injection of SO₂ into the lower stratosphere would reduce global warming and some of its negative impacts, and would increase the uptake of CO₂ by plants, but research in the past decade has pointed out a number of potential negative impacts of stratospheric geoengineering. More research is needed, and should be funded by the U.S. government, to better quantify the potential benefits and risks so that if society is tempted to implement geoengineering in the future it will be able to make an informed decision.

At my first meeting on geoengineering, the Managing Solar Radiation Workshop at NASA Ames Research Center, Moffett Field, California, November 18-19, 2006, I was amazed and shocked to find so many engineers and physicists enamored of this idea, and ended up writing down 20 reasons why it might be a bad idea [Robock, 2008]. The hubris of some, who thought that this was just a mechanical or physical problem to solve, and their lack of awareness of the science of climate change and the natural chaotic variability of climate, was very scary. A number of those potential risks were already understood 10 years ago, and were discussed by Crutzen [2006] and in the accompanying essays, particularly by MacCracken [2006], but work in the past decade has produced much better understanding and identification of those risks, in particular that temperature and precipitation cannot both be controlled at the same time [e.g., Jones et al., 2013], that summer monsoon precipitation would be reduced [Tilmes et al., 2013], that even if global average temperature could be kept from increasing, there would be cooling and warming in different places [Kravitz et al., 2013a], that ice sheets melt from the bottom, and changing insolation would not be very effective at slowing their melting [McCusker et al., 2015], and that abrupt implementation or termination of geoengineering would produce serious impacts on ecosystems [Trisos et al., 2017]. The history of past weather and climate modification attempts provides strong lessons about the difficulty of governance and the dangers of military applications [Fleming, 2010].

Table 1 of Robock [2016] gives a list of five potential benefits of stratospheric geoengineering and 27 risks or concerns. Number 1 on the benefits side, that stratospheric geoengineering could reduce global warming and many of its negative impacts, may be so important that society in the future may decide to implement stratospheric geoengineering to reduce some amount of

warming and live with and adapt to the negative consequences of geoengineering. (The only rational way to do this would be for a limited amount of time while mitigation and carbon dioxide removal from the atmosphere reduce the radiative forcing from greenhouse gases.) Each of the potential benefits and risks needs to be quantified so that society can make informed decisions in the future about how much and what type of geoengineering to implement and for how long.

Some of the potential benefits and risks can be addressed by climate modeling. With Ben Kravitz and others, I have started the Geoengineering Model Intercomparison Project [GeoMIP, <http://climate.envsci.rutgers.edu/GeoMIP/>; Kravitz *et al.*, 2011, 2013b, 2013c, 2015a, 2015b; Tilmes *et al.*, 2015], in which various scenarios of anthropogenic stratospheric aerosols, marine cloud brightening, and cirrus thinning are being evaluated with climate model experiments as a response to global warming. In addition to the standard experiments, GeoMIP also establishes a GeoMIP Testbed for new experiments to be conducted by one or a few climate models as demonstration projects for future possible model intercomparisons.

Some of the potential benefits and risks can be studied by looking at the analog of volcanic eruptions [Robock *et al.*, 2013], but some cannot be addressed at all by scientific investigation. In 2012, I thought that the governance problems, some of which were discussed by MacCracken [2006], would be insoluble and that stratospheric geoengineering will never be implemented by international agreement [Robock, 2012a], and have yet to change my mind. In fact the more we look at stratospheric geoengineering, the more unlikely implementation becomes because of the associated risks. In particular, risks associated with unknowns, governance, and ethics will be very difficult to address. Nevertheless, much is still unknown, and we have an obligation to continue the research.

The ethics of doing geoengineering research also needs to be addressed. Both Lawrence [2006] and Cicerone [2006] made a clear case that we have an obligation to better understand the benefits and risks of potential geoengineering deployment so that policymakers in the future, should they be tempted, would be able to make informed decisions. I agree [Robock, 2012b], provided that outdoor small-scale experiments are subject to environmental regulation and governance. However, as discussed by Robock *et al.* [2010], large-scale experiments would have to be conducted for decades to distinguish the signal of small injections from the noise of weather and climate variations. This would be no different from actual geoengineering implementation. Furthermore, only by injecting SO₂ into an existing sulfate aerosol cloud could the growth of aerosols be studied. Perhaps, after the next large volcanic eruption, this could be tested on part of the cloud, but that would require development of monitoring equipment that could follow the air parcel.

The American Meteorological Society policy statement on geoengineering [AMS, 2009], which was subsequently adopted by the American Geophysical Union [AGU, 2009], recommends “Enhanced research on the scientific and technological potential for geoengineering the climate system, including research on intended and unintended environmental responses.” Strong recommendations for geoengineering research have also come from Keith *et al.* [2010], Betz [2012], and GAO [2011]. The recent U.S. National Academy of Sciences report [McNutt *et al.*, 2015]

recommends “an albedo modification research program be developed and implemented that emphasizes multiple-benefit research that also furthers basic understanding of the climate system and its human dimensions.” Yet a U.S. national geoengineering research program has yet to materialize. Now that the stigma of doing the research is over, it would be relatively cheap to evaluate the many suggested techniques, by continued computer modeling and study of analogs, and also by conducting small outdoor experiments, as recommended by Crutzen.

Crutzen started an international research effort on geoengineering, yet much more remains to be learned. All scientists working on geoengineering that I know of make a strong call for mitigation and adaptation to address global warming, and this is also the recommendation of the U.S. National Academy of Sciences report [McNutt *et al.*, 2015]. In fact, a rapid transition to solar and wind power can keep global warming close to the 2015 Paris goal of 2°C above pre-industrial levels [e.g., *International Energy Agency*, 2016]. So far geoengineering research concludes that there is no safe “Plan B,” and provides enhanced support for mitigation and adaptation. Additional research support for these efforts will make clear over the next decade whether this current understanding is robust, and it would be irresponsible for the U.S. and other nations not to make this investment in research.

Acknowledgments

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Some Informal Comments on Solar Geoengineering

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In the discussion of appropriate actions to mitigate global climate change, solar geoengineering has often been described as an emergency option, if perhaps the rate of climate change accelerated over the next few decades, or if the consequences of climate change looked much worse than anticipated. I find this framing to be a little troubling, as it makes it seem like solar geoengineering should only be used if there are surprises, failing to accept our own climate studies that show truly catastrophic impacts from every-increasing atmospheric CO₂ levels in the most likely emissions scenarios. Perhaps it comes from a psychological desire to cling to visions of a non-fossil energy system that could be achieved (or at least largely implemented) by mid-century (now only three decades away), regardless of how unlikely this scenario is.

What seems to be missing is the realization by the climate science community that deep emissions reductions are extremely unlikely – still worth fighting for, as emissions reductions must occur at some point, even if hopeful targets are missed – but extremely unlikely. For example, in a recent study of climate risk (King et al., 2015), we looked at the likelihood of the world achieving a low-carbon emissions pathway, and found that a moderate emissions pathway (CO₂ reaching 600 to 700 ppm by the end of the 21st century) was the most likely, and emissions pathways that kept CO₂ below 550 ppm were extremely improbable, as they require multiple technological innovations, well beyond current capabilities (including ambitious reductions in cost) in multiple sectors over the next few decades.

Thus, I suspect that there will be a transition in the way our community thinks about solar geoengineering over the coming decades, as the impacts of climate change become more and more apparent. I suspect that we will stop framing solar geoengineering as an emergency option, but accept that we already are experiencing a planetary emergency (albeit, one with a long time constant), and that solar geoengineering is likely to be a necessary component of a climate change response – that includes investments in adaptation and emissions reductions. The questions that remain will be how and when to implement different solar geoengineering strategies, and how to control it. This means that the linkage between the science and engineering of solar geoengineering and the governance of solar geoengineering are deeply entwined, in part because of the potential for complex geoengineering schemes that are driven by divergent national and regional interests.

Many studies emphasize that solar geoengineering is not a substitute for emissions reductions, and that emissions reductions must inevitably occur. Some have used this as an argument against solar geoengineering. For example, Archer and Brovkin (2008) argue that, because of the long lifetime of CO₂, sustaining such an engineering system for tens of thousands of years or more is

not feasible. This fails to consider that engineering the climate for a few centuries could be combined with a variety of ways of removing CO₂ from the atmosphere, albeit at relatively high cost, so that the problem was completely abated by the end of a few centuries or so.

I do not mean to imply that we currently understand enough of what solar geoengineering will do to the Earth system to state confidently that it will be safe and effective. Just the opposite – I believe we are in the infancy of our understanding. In my own work, I have worked with my graduate student (Katie Dagon) on how solar geoengineering interacts with terrestrial ecosystems in terms of effects on evapotranspiration. We have found that the coupling of physiological effects of higher CO₂ levels (through water use efficiency and stomatal conductance) with impacts of radiation and temperature effects are extremely sensitive to different parameters used in climate models, and can lead to a wide range of effects including increases in soil moisture and temperature stability in some regions and extreme deficits in others. Many more studies are needed to understand how solar geoengineering interacts with weather systems, and not simply the average climate response that has been the subject of the vast majority of modeling studies thus far.

But at the same time, it is important to acknowledge that there is no study I have seen that looks at potential effects of solar geoengineering that shows that impacts of solar geoengineering are worse than a world with higher CO₂ without solar geoengineering. In other words, everything we know today points to the fact that including solar geoengineering as a component of our response to climate change is far better than not. Again, this is not to say that we understand how to do solar geoengineering, or that we understand all of the ways that solar geoengineering may create various climate impacts that are harmful. We clearly do not understand this very well. But what we do know suggests that minimizing the most catastrophic impacts of climate change will likely involve some investment in solar geoengineering. Thus, there is an imperative to accelerate a research effort to understand what it might do, and how to make it as effective as possible.

What form of geoengineering should we study? This is a place where our initial approach to the problem has been too simplistic. Most studies that use climate models to understand the impacts of solar geoengineering use very simple representations of solar geoengineering. Many simply turn down the solar luminosity in the model – a very useful way to look at the tradeoffs of reducing shortwave radiation to compensate for higher greenhouse gases, but this obviously ignores the complexity of stratospheric transport of aerosols and the potential for large regional variations in albedo. Other studies have used chemical transport models, coupled with climate models, but have used a relatively simple scenario in which there is a single solar geoengineering approach, with the aim of reducing the impacts of climate change from a global perspective.

The truth is that any real solar geoengineering system will almost certainly have regional differences in effectiveness. Different countries and different regions, quite rationally, will try to ensure that the solar geoengineering approaches are done with their interests in mind. For example, we cannot imagine the U.S. allowing a solar geoengineering system to be deployed that may have a strong net benefit to most countries, but has a detrimental effect to rainfall in summertime in the U.S. Midwest. Similarly, it is difficult to see how a geoengineering system that

is intended to slow down or stop the melting of ice in Greenland would avoid having a negative impact on Russian investment in ports along its northern coastline, opened up by the rapid warming in the Arctic in recent decades. I suspect the potential for multiple solar geoengineering systems to be deployed simultaneously is quite likely – and this makes coordination and governance an even more important issue. Perhaps some scientific studies of solar geoengineering should look at the potential for harmful consequences from dueling systems, without coordination or control, where local benefits are valued over broad, global stability.

Solar Climate Engineering Research: A Whole-Systems Approach

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Climate change poses grave risks to human welfare and the stability of the earth system that sustains human life. Changes are occurring rapidly, and may outpace efforts to address their causes.

Increasing the reflection of sunlight from the atmosphere to reduce warming, ‘solar climate engineering’, may reduce damage and stabilize the earth system while we reduce greenhouse gases in the atmosphere. But, climate risks grow as changes occur, and time may be short for assessing and developing solar climate engineering options to reduce these risks.

The Mission of Solar Climate Engineering Research

In this context, what do we need from solar climate engineering research, in what timescale? In defining the aims of research, one might start with the question such as:

For solar climate engineering, what questions do we want to have the answers to, and what capabilities would we like to have available, within 10 years?

Questions we would like answers to within ten years might include:

- Do we have any viable alternatives?
- If so, what are their environmental effects and risks?
- What are their societal effects and risks?
- What are the requirements for a system (or systems) to deliver solar climate engineering capabilities?
- What information is required to manage and govern solar climate engineering activities?
- What are the costs, benefits and risks of solar climate engineering versus unabated climate change?

High-level capabilities we might seek to have available in ten years might include:

- Multiple viable approaches, with reasonable understanding of their effects and risks
- Core technology for each approach
- System design and operating model for each approach and/or approaches in tandem
- Governance models for different geopolitical conditions and different solar climate engineering approaches (or multiple approaches in tandem)

- Actionable information (observational and analytical systems) for managing climate

While these are some among many possibilities, the dialogue about what we want to know, and what capabilities we would like to have available, in what timescale, is critical to defining solar climate engineering research programs. In determining these, we establish a mission for research. Once we have agreed on the mission, we can develop research programs designed to meet its objectives.

Whole-Systems Approach

To assess and develop options for solar climate engineering, it is critical to move from discussions centered on isolated parts of the problem, such as radiative forcing efficacy or governance of mature systems, to thinking about the entirety of what we need from a climate engineering system, across physical and societal dimensions, or “whole systems”.

In a whole-systems approach, we would first describe at the highest level, the purpose, or ‘end-user vision’, of a system. For solar climate engineering, this might be: “*managed reduction of solar radiative forcing*”, where “managed” includes all the physical and societal conditions required to successfully engineer reduction in radiative forcing in the atmosphere in a controlled way.

With a shared end-user vision, we could then proceed to define, at the highest level, the requirements for such a system.

For the physical aspects, high-level requirements might include:

- material of the right characteristics (non-polluting, nanoscale, etc.)
- managed delivery of material into the atmosphere (platforms, operations, etc.)
- actionable information for managing delivery (data and analysis platforms)

For the societal aspects, high-level requirements might include:

- governance and legal framework
- public acceptance

For each of these high-level requirements there are a broader sub-set of requirements that will be iteratively adapted as new findings are made. These requirements will drive assessment of feasibility, risks, costs and benefits, and surface, at every stage of progress, disqualifying conditions.

Mission-Driven Interdisciplinary Collaboration

To deliver against the mission, in a whole systems approach, research programs must encompass all of the disciplines required to assess and develop an entire solution, with collaborators working to a shared set of objectives along a shared timeline. For solar climate engineering, this includes engineering, atmospheric and environmental sciences, computer and data sciences, economics

and risk analysis, policy, law and behavioral sciences – with arenas of focus ranging from nanoscale particle interactions to global delivery and governance.

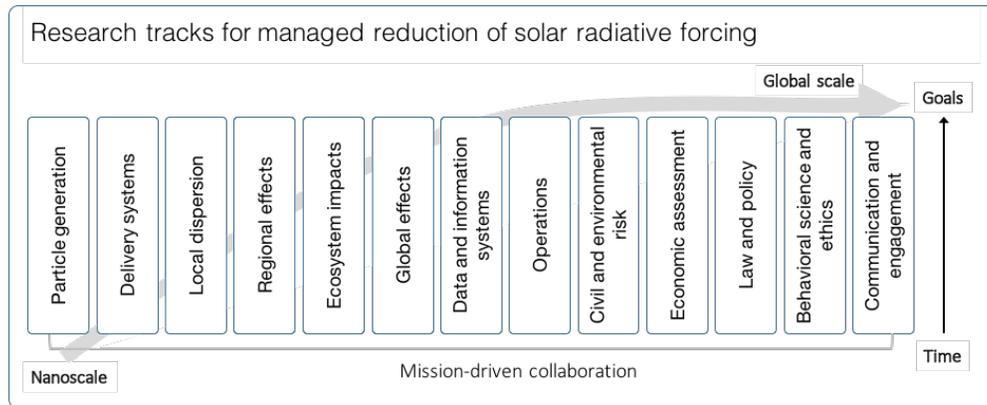


Figure 1. Parallel research efforts in a mission-driven solar climate engineering program

Within each discipline, there is a set of research questions and goals (with emphasis on identifying risks and disqualifiers) and a timeline that corresponds to interdisciplinary milestones for the program. This elevates the importance of program strategy and management, to align research efforts, evaluate new information and adapt plans, and ensure the success of the mission.

The importance of portfolios

In a whole-systems approach, to increase the odds of success and minimize points of failure, it is important to pursue a portfolio of promising solutions, preferably with differing risk and benefit profiles.

Given the high-stakes and numerous risks of solar climate engineering, it is critical to research and develop multiple methods for generating reflectivity in the atmosphere. A research portfolio would optimally include approaches with different deployment characteristics (e.g. localized and temporary versus global and sustained), differing side effect risks (e.g. precipitation impacts, agricultural and biological productivity) and different societal risk profiles (governance, public acceptance, etc.). It may also be critical to understand and develop multiple governance models that map to different possible geopolitical constraints and different levels of information and control.

Within each research sub-specialty, until a definitive answer is reached, parallel study of reasonable alternatives (e.g. different designs for aerosol generation) will help minimize the risk of failure to deliver, and ensure the ability deliver against the milestones of the larger effort.

Engagement and decision-making

Whole-systems thinking should also help shift high-level discourse about solar climate engineering research from the arena of academic specialists to broader engagement.

The mission, end-user vision and high-level requirements of a whole-systems solution for solar climate engineering can, and should, be debated and agreed by experts, policymakers, affected communities and society at large. They operate above the level of category expertise, allowing for widespread input and participation, and the possibility of broad consensus.

Once agreed, the mission, vision and requirements serve as guidelines for experts to deliver solutions of shared importance to society. As research surfaces information, and innovations emerge, they are also framework for assessing progress and making decisions, in a way that supports transparency.

It is critically important that we rapidly begin to define a whole-systems framework for solar climate engineering research. We could begin by asking, “What questions would we like to have the answers to, and what capabilities would we like to have available, within 10 years?”

Practical Needs for Geoengineering Policy

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Science policymakers have a tricky job. First, scientific findings and innovations that initially boggle the mind actually come along fairly often, and policymakers are usually made aware before the general public. At these times, they must be far-sighted and flex their imaginations to anticipate the implications for perhaps billions of people across current and future generations. But as they seek to chart a policy course in order to balance technological promise with human safety, these policymakers must be relentlessly practical. They have to educate their peers and shepherd their policy vision through the same arcane political process as everyone else.

Solar geoengineering and even geoengineering research may be among the most profound, consequential “science ideas” to confront American policymakers yet. If deployed at scale, geoengineering would necessarily have enormous consequences. There may be no such thing as pilot scale solar geoengineering. (It is worth noting that the climate course we have already charted for ourselves is equally consequential). While I will not endeavor to make the case for research more eloquently than the other contributors to this Forum, I believe that the time has come to initiate more serious discussions on solar geoengineering within the federal government. Both the research and the governance aspects of this field need to mature quickly, with federal participation forming the bedrock.

Given such daunting implications, what actions and tools are needed for science policymakers and regulators to navigate the practical political pathways to enable safe geoengineering research? How can researchers, climate advocates and civil society help wrestle this challenging subject matter into something more concrete, more manageable?

First, we must at last rally around a common vocabulary for solar geoengineering. Many scholars have pointed out that the word “geoengineering” is both loaded and perhaps inaccurate, indicating a level of technical control over earth systems that could likely never be achieved. In its 2015 report, The National Academies elected to use the term “Climate Intervention” as a more appropriate designation for the scope of its inquiry, which considered both solar and carbon removal approaches. In the 2009-2010 Congressional hearings, the House Science Committee used “climate engineering.” Nonetheless, “geoengineering” seems to be the buzzword adopted by the media, and it is well established as a term of art. Continued dispute about nomenclature only takes away from the more important policy questions.

By the same token, “geoengineering” should refer to solar geoengineering only. While carbon removal has long been lumped together with solar radiation management as a ‘Plan B’ approach to climate effects, they are not similar on either technical or governance terms. Carbon removal ultimately seeks to address the cause of climate change – by reducing concentrations of greenhouse gases in the atmosphere – while solar geoengineering seeks to address only some of

the effects. In a sense, carbon removal belongs in the mitigation family, while solar geoengineering is a type of adaptation. While many carbon removal proposals are not free of risk, they generally seek to harness natural carbon cycling processes and expanding the scope of capabilities that are already well-established in the global industrial gases sector.

Second, in its February 2015 report, the National Academies recommended that the federal government allocate serious research dollars to geoengineering. The political will to actually do so will follow more readily if researchers and the climate community can draw out and communicate with policymakers about the *specific* science topics within the broader field that need attention. A generic call for “geoengineering research” without additional detail is not actionable. Identifying the finite topics within cloud physics, systems engineering, etc., and recommending the tools and funding levels needed in the near term will give lawmakers something they can work with.

It is worth noting that federal support for geoengineering research does not have to begin with a new, independent program. There are many ways the existing science capabilities at research agencies, especially DOE, NSF and NASA, can be expanded and directed to unpack the many remaining technical questions. For example, some NASA satellite systems are more effective than ever at recording and evaluating the enigmatic cloud-aerosol effect. Enhancing these observational tools will tell us more about the level of “accidental geoengineering” already taking place from global sulfate emissions, which will in turn help researchers consider how – if - this effect can be harnessed and used deliberately.

Third, a most successful research venture should begin quietly, without political fanfare and without any commitments in the media or budget justifications as to what the research could potentially yield. Geoengineering research at this time is a fringe field of study within the broader partisan quagmire that is climate policy. If a dedicated effort to commit more resources is to move forward, it must be a sustained effort that takes place across many sessions of Congress, and any association with a particular political ideology or party will only undermine the quest for unbiased scientific understanding.

Fourth, legal experts must begin to focus their geoengineering thought exercise to a more finite set of concepts centered around the most mature proposals being offered today. The universe of theoretical geoengineering proposals is vast, and thus their policy and legal implications – and side effects – are never ending. As long as the policy discourse around geoengineering remains theoretical, stakeholders will think first of the furthest-reaching scenarios and will form opinions accordingly. But there are only a handful of serious research efforts that might soon seek to plan for field studies. Their plans will be specific in scope and duration. It will be possible and truly useful to put these concepts under the lens of the various environmental policy laws we have today – the National Environmental Policy Act, the Clean Air Act, the Clean Water Act, and so on – and see how adaptable they are to these new applications and where we might see regulatory gaps. Projects like the Carnegie Climate Geoengineering Governance Initiative and the Environmental Defense Fund’s SRM Governance Initiative will be important forums for these activities.

Thank you

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Harvard's Solar Geoengineering Research Program:
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Emmett Center on Climate Change and the Environment at the University of California, Los Angeles:
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