GOVERNANCE OF THE DEPLOYMENT OF SOLAR GEOENGINEERING

Harvard Project on Climate Agreements

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The Science and Technology of Solar Geoengineering: A Compact Summary

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Solar geoengineering is a complicated, contentious, emerging issue in climate policy that poses serious governance challenges. While there are several reports and longer review papers on the science of solar geoengineering (Irvine *et al.* 2016; NRC 2015; Schäfer *et al.* 2015), there are few concise summaries suitable for an experts. In writing this compact point-form summary, we assume our audience is familiar with climate science and its policy context at the level of an IPCC report. We focus on the physical science and technology of solar geoengineering, while (mostly) avoiding claims about social science, public policy, or politics. This is not a judgment about relative importance – the hardest and most important problems raised by solar geoengineering are non-technical. Finally, this is not a comprehensive review. It is our summary judgment of the current state of knowledge strongly shaped by our biases.

Some definitions

- *Radiative Forcing* (RF) is the most relevant quantitative global measure of the human drivers of climate change. It is useful to make a sharp distinction between (a) radiative forcing from aerosols or greenhouse gases (GHGs), (b) the climate's *response* to this RF, measured by changes in climatic variables, such as storm frequency or sea-level, and (c) the *impacts* of changes in climate on humans and ecosystems.

- *Solar Geoengineering* (SG) is the reduction in RF achieved by deliberate large-scale alteration of earth's radiative balance, with the goal of reducing climate changes and climate impacts from GHGs.

Technically plausible solar geoengineering methods

- **Stratospheric Aerosols:** adding aerosols to the stratosphere, where they reflect some (~1%) of incoming sunlight back to space (Irvine *et al.* 2016; NRC 2015; NAS 1992).

- **Marine Cloud Brightening:** adding cloud condensation nuclei (a specific class of aerosols), such as sea salt, to specific kinds of low-lying clouds over the ocean, with the goal of increasing the reflectivity or lifetime of these clouds (Latham 1990).

- **Cirrus Thinning:** adding ice nuclei (another class of aerosols) to high-altitude cirrus clouds, with the goal of reducing the density of such clouds (Mitchell and Finnegan 2009).[1]

- Other methods include space-based reflectors, tropospheric aerosols, and increasing the reflectivity of crops or other land cover.

- It is worth noting that SG proposals often mirror human actions or natural processes that alter RF (Robock *et al.* 2013). Tropospheric aerosols from combustion, for example, scatter light and increase the reflectivity of clouds, producing a negative (cooling) RF that offsets a significant fraction of the positive RF from GHGs. Some major volcanic eruptions (e.g. Pinatubo, Tambora, Krakatoa) released substantial amounts of stratospheric aerosols into the stratosphere, producing a large transient cooling that provides a valuable natural analog to stratospheric aerosol geoengineering.

Climate response to radiative forcing from solar geoengineering

- SG cannot eliminate all GHG-driven climate change even if the net RF is reduced to zero (Kravitz *et al.* 2013).

  » Put simply: SG is not anti-CO_2. Climate variables respond differently to the RF from SG and GHGs. For example, to restore global-average precipitation to pre-industrial conditions, SG would need to be adjusted to offset roughly two thirds of the RF from GHGs, and global-average temperature would be significantly above pre-industrial.

- Strong evidence shows that if SG is spatially uniform and adjusted to offset roughly half the RF from GHGs, then the change in important climate variables would be reduced in most locations and increased in only a small percentage of the land surface.[2]

  » Non-uniform or strongly patchy RF – as might be produced by marine cloud brightening – will generally produce more unevenness in the climate response.

- Around half of the long-run climate response to a change in RF is realized within a decade, which means that rapidly scaling up or ending SG deployment would produce sudden changes in climate.[3]

1 Low clouds tend to cool the earth's surface, so increasing them has a cooling effect, while high clouds tend to warm the surface, hence reducing them will also tend to cool the surface.

2 Our quantitative analysis demonstrating this result is currently under review but Keith and Irvine (2016) reviews the literature to present an argument why this is likely (Keith and Irvine 2016).

3 See Parker and Irvine (2018) for a discussion of the risks of a so-called "termination shock" arising from a sudden cessation of large-scale SG deployment.

- The uncertainty in climate predictions grows with total RF. Thus, it is plausible that the climate response to a scenario where SG offsets some RF can be predicted with greater confidence than a scenario with the same amount of GHGs alone.
  - » Reducing uncertainties in the climate response to RF from GHGs will also improve our understanding of the climate response to RF from SG.
- Much of the uncertainty in the impacts of climate change, e.g. on ecosystems, arises from climate conditions moving away from observed conditions. As solar geoengineering could generally reduce the magnitude of change in most variables in most places, systems could remain closer to these observed bounds.

Specifics of Stratospheric Aerosols

- There is high confidence that stratospheric aerosols could achieve sufficient RF to offset half the RF from a doubling of CO_2 concentrations (~2 Wm-2) (Boucher, O. *et al.* 2013).
- Techno-economic assessments suggest that stratospheric aerosols could be delivered with aircraft at a cost of less than $10 billion per year for 2 Wm-2 (McLellan *et al.* 2012).
- By choosing where to release aerosols, a fairly uniform global aerosol layer could be created, or the aerosol layer could be thicker at high latitudes or in one hemisphere or the other (Dai *et al.* 2018). The circulation in the stratosphere strongly limits what can be achieved; it is not possible to limit cooling to one country. The roughly 1-2 year lifetime of stratospheric aerosols constrain how rapidly this pattern of cooling could be adjusted.
- The direct health risks arising from increased particulate matter and decreased stratospheric ozone from stratospheric aerosols are small – one or two orders of magnitude less than climate impacts/benefits. If, for example, stratospheric sulfate aerosol injection was adjusted to produce the same RF as is produced by tropospheric sulfate aerosol pollution, the mortality from the stratospheric sulfates would be roughly 1,000-fold smaller (Eastham *et al.* 2018).

Specifics of Marine Cloud Brightening and Cirrus Thinning:

- There is much lower confidence that a substantial RF (~2 Wm-2) could be achieved with marine cloud brightening or cirrus thinning (Boucher, O. *et al.* 2013). The magnitude, and even sign, of the effect is uncertain in both cases, and both are applicable over a limited domain of susceptible clouds, so may not be scalable to achieve a substantial RF.

- Engineering estimates of the cost and technical feasibility of delivery are much less certain for marine cloud brightening than stratospheric aerosols (Latham *et al.* 2012), and no technical feasibility assessment of cirrus cloud thinning has yet been made.

- For both marine cloud brightening and cirrus thinning, the spatial pattern of RF could be adjusted on timescale of hours to days, a capability that would likely allow some form of weather control (Hoffman 2002). As stratospheric aerosols could only be adjusted over years, they could not be used for weather control.

- Marine cloud brightening is most effective in a specific kind of marine boundary layer cloud that covers ~10% of the earth's surface, so the RF produced is inherently non-uniform.

- Cirrus cloud thinning acts primarily by increasing outgoing thermal radiation, so the nature of its RF is more similar to GHGs than most other SG methods. However, unlike GHGs, its RF would be patchy.

There are several linked challenges that solar geoengineering research could address

- ***The forcing challenge (Can it be done?):*** To develop practical SG proposals that could achieve a substantial RF would require iteration between science and engineering to ensure the assumptions made in scientific studies align with the performance criteria of the engineering studies:

    » Scientific aspects: Research would evaluate whether the proposed intervention would result in a substantial RF, e.g. demonstrating that sea-salt aerosols with certain properties reaching the base of strato-cumulus clouds under certain conditions would result in a substantial increase in cloud albedo.

    » Engineering aspects: Research would evaluate whether the proposed intervention could be achieved through practical means – e.g., with a device designed to produce the required sea-salt aerosols and loft them to the required altitude.

- ***The climate prediction challenge (How would it change the climate?):*** Predicting the climate's response to a specific deployment of SG is a problem that is closely related to the problem of predicting response to other anthropogenic influences, such as aerosol pollution. Useful predictions require well-specified interventions. This is a challenge for climate science.

- ***The objective challenge (What's the climate goal?):*** The deployment of SG could be tailored to meet specific objectives, within the constraints identified by the forcing and prediction challenges. Research will not be effective without some specification of the goal. Defining the climate goal is a challenge for public policy, albeit one that ought to be coupled to advances in science and engineering of solar geoengineering, and to growing understanding of climate impacts.

- ***The management challenge (How to deploy SG to meet its goal?):*** To pursue a specific objective through SG deployment, it will be necessary to make short-term deployment decisions, despite substantial uncertainties. Decisions require observations likely including new climate observing systems, along with development of forecast tools and feedback controls.

Some policy relevant implications

- Solar geoengineering partially decouples cumulative carbon emissions from global-mean temperature. With SG, the 1.5 °C target could in theory be achieved for very large cumulative CO_2 emissions.

- Even with SG, net emissions (including removals) must eventually be brought to zero to achieve a stable climate.

- The climate in a 1.5 °C world achieved with SG and emissions reductions would differ from the climate in a 1.5 °C world achieved by emissions reductions alone.

- If SG is used to maintain a fixed net RF as GHGs increase, then differences from pre-industrial climate – and thus climate impacts – will grow with cumulative emissions.

- There is no way to deploy solar geoengineering that would be regarded as optimal by all actors in all regions (Ricke *et al.* 2013). The effects of SG would be different in different regions, different regions would be exposed to different risks, and different actors may have different preferences with regard to the climate state (some may *prefer* global warming and attendant impacts).

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Some Thoughts on Solar Geoengineering Governance

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Key points

- The default governance arrangement today is that any country or small group of countries could attempt to deploy solar geoengineering. However, in such a scenario, other countries would respond, most likely by promising climate adaptation assistance in exchange for non-deployment and by threatening to impose trade sanctions, to launch a military strike, or to undertake some other form of "counter-geoengineering," should the decision to deploy not be reversed.
- A treaty prohibiting solar geoengineering would have little effect, because the countries likely to use geoengineering would choose not to participate in the treaty.
- A treaty specifying basic rules for when and how solar geoengineering could and could not be deployed would be broadly acceptable to all countries because of the preference every state has for *mutual* restraint. Such a treaty is preferable to the default.

Context

Solar geoengineering should be looked at not in isolation, but in the context of all of the interventions that can be deployed to address climate change.

The world has tried, but failed, to negotiate a global reduction in emissions. This effort has failed mainly because the incentives for countries to reduce their emissions individually are weak, and the remedies proposed for overcoming free riding collectively have been ineffective. As a consequence, it is almost certain that countries will miss their own collective goal of limiting "global warming" to well below 2 °C relative to the pre-industrial level. It is often claimed that knowledge of geoengineering removes or at least lessens the incentives countries have to limit their emissions, but the opposite seems closer to the truth: at some point in the future, thanks to the failure to negotiate a preventive solution of emission reductions, at least some countries may feel that they have little option but to deploy geoengineering.

Long before this time comes, countries will adapt to climate change. Unlike emission reductions, the benefits of adaptation are local, meaning that countries have a powerful individual incentive to adapt. Some countries will find it easier to adapt than others, however, causing inequalities to widen. The countries most capable of doing geoengineering are also likely to be the most capable of adapting (at least in the sense of being able to do the engineering of adaptation). Adaptation may thus forestall deployment of geoengineering.

Finally, the world can remove CO_2 from the atmosphere using machines – the only backstop technology for addressing climate change. Industrial air capture will be expensive, but once the damages from climate change become very large, countries will have a stronger collective incentive to deploy this technology than to reduce their emissions, as industrial air capture requires financing, not behavioral change. At the same time, it will take a long time for air capture to have an impact on the climate, and so countries may want to deploy solar geoengineering alongside this effort to reduce concentrations. Indeed, because solar geoengineering is cheap to deploy, countries may choose to deploy it long before they invest substantially in air capture.

Solar geoengineering governance

Who decides if, when, and how solar geoengineering is deployed?

A private individual – to use David Victor's (2008) term, a "Greenfinger" – could potentially try to do it, but I find it impossible to believe that countries would allow this.

A state – almost any state – could potentially do it, but though the economics literature sometimes assumes that any state can be the world's "free driver" (Wagner and Weitzman 2012), it seems much more likely that, absent a broad consensus, other countries would publicly criticize the intervention and possibly impose sanctions or even intervene militarily to thwart a unilateral move. Two recent papers (still in draft form) have analyzed a game situation in which a country in opposition deploys "counter-geoengineering" (Bas and Mahajan 2018; Heyen, Horton, and Moreno-Cruz 2018). This is taken by both papers to mean a technology that can warm the Earth's temperature, countering the cooling effect of solar geoengineering. However, I think it is probably best to think of "counter-geoengineering" as a metaphor for any action that causes global temperature to change by less than originally intended. This decentralized or anarchic approach to governance might be called the "market outcome." This, I think, is the default today.

The opposite scenario would involve a rule binding on all countries, as in a peremptory norm in customary law. However, peremptory norms are prohibitive (applying to such matters as genocide, piracy at sea, and slavery), and many states would oppose an injunction never to deploy geoengineering.

Deployment could become a matter for the United Nations Security Council. Plausibly, the Security Council might intervene to prevent deployment by a third party; possibly it might intervene to deploy solar geoengineering collectively. Of course, decisions by the Security Council are subject to a veto by any of the five permanent members.

Rules for deployment could be enshrined in a geoengineering treaty. Some states might wish for a highly restrictive treaty. However, should they get their way, the consequence is likely to be that the states most likely to deploy geoengineering will opt out of it, leaving these states free to act as they please. A less restrictive treaty is not only plausible but desirable. While every state would like to have a free hand to act as it likes, no state wants other states to have a free hand to act as *they* like. States would be willing and perhaps even eager to negotiate an agreement involving *mutual restraint*. There is a case for negotiating such an agreement today. (The default, remember, is the "market outcome.")

Finally, there may someday be the need for an agreement, or a multiplicity of agreements, for deployment. For reasons mentioned previously, it seems unlikely that a state would deploy geoengineering unilaterally. At a minimum, a state would want to be part of a coalition of the willing, not least because doing so would add to the legitimacy of its intervention. Another advantage of a coalition is that costs could be shared. Of course, decisions would also have to be shared. But for a group of like-minded countries, this may not be very difficult. Groups of countries have collaborated successfully on big science projects, such as ITER (an experimental nuclear fusion project involving China, the European Union, India, Japan, Korea, Russia, and the United States) and the International Space Station (the principals of which are the United States, Russia, the European Union, Japan, and Canada).

A key feature of such a deployment agreement would be the rules for decision-making. Weitzman (2015) has analyzed a voting rule that, under certain conditions, supports an efficient outcome. However, a key assumption of his model is that all countries participate in the treaty and all agree to be bound by the decision of a (qualified) majority. In a world of sovereign states, this seems most implausible.

Ricke, Moreno-Cruz, and Caldeira (2013) take a different approach. They assume that an agreement chooses the level of deployment that maximizes the aggregate payoff of all parties, using side payments to ensure that every country gains individually from deployment. However, a key assumption of this paper is that non-parties to the agreement cannot deploy geoengineering, either alone or as part of another coalition, and this is also implausible. Parson (2014) considers linkage of geoengineering governance to emission reductions – for example, allowing only the countries that reduced their emissions to have a say on geoengineering deployment. This might ease the concern noted previously, that knowledge of geoengineering causes countries to do less to limit their emissions. However, this form of linkage requires that countries commit to a decision rule, and such a commitment would not be credible.

My concluding thought is that geoengineering governance is a subject we can and should think about, but that it is not a topic we truly understand yet.

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Solar Geoengineering and International Law

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Key Points

- Existing international law provides little guidance on solar geoengineering, either positive or negative.
- The only existing institution with relevant, binding decision-making authority is the UN Security Council, but it would not be able to limit solar geoengineering by the permanent five member states, which have veto power.
- International governance is not legally necessary for solar geoengineering deployment.
- A future legal regime on solar geoengineering might:
  - » Promote cooperation in solar geoengineering research and development.
  - » Provide general standards to evaluate solar geoengineering proposals.
  - » Establish procedural requirements for solar geoengineering deployment, such as environmental impact assessment, notification, and consultation.

In principle, international law could play several roles in governing solar geoengineering.

- *Prescribe regulatory rules*. These rules could be:
  - » Limiting, permissive, or facilitative. International law could serve to limit solar geoengineering, authorize it (possibly subject to conditions), or facilitate it (for example, through funding or cooperation mechanisms).
  - » Substantive or procedural. International law could regulate geoengineering substantively (e.g., through limitations, prohibitions, permissions, or liability rules) or procedurally (by requiring, for example, impact assessments or notice and consultation with other states).
  - » *Ex ante* or *ex post*. International law could regulate solar geoengineering in advance of deployment (e.g., through prohibitions or impact assessments) or after the fact (through liability rules and monitoring).

- *Provide evaluative principles to structure and guide debate.*
  - Environmental principles such as equity do not generally yield determinate outcomes. Rather, they provide evaluative standards that can be used to justify or criticize action.
- *Establish decision-making procedures for solar geoengineering deployment.*
  - Generally, a decision-making procedure presupposes a default rule that applies in the absence of a decision. For example, a procedure to authorize solar geoengineering presupposes that, in the absence of a decision, solar geoengineering is not permissible (and vice versa).

In practice, international law currently plays only a limited role in governing solar geoengineering.

- Existing international law does not prohibit or impose liability for solar geoengineering.
  - Many international agreements are relevant to solar geoengineering, including the UN Framework Convention on Climate Change (UNFCCC), the Paris Agreement, the Montreal Protocol on Substances that Deplete the Ozone Layer, the Convention on Long-Range Transboundary Air Pollution (CLRTAP), the UN Convention on the Law of the Sea (UNCLOS), and the Convention on Biological Diversity (CBD). However, none of these agreements was developed with solar geoengineering in mind, and none contains clear norms regulating solar geoengineering.
  - If stratospheric aerosol injection (SAI) adversely affected the ozone layer, then the Montreal Protocol would be relevant, but it does not specifically regulate any of the chemicals likely to be used in SAI.
  - CLRTAP regulates emissions of sulfur dioxide and hence could be relevant to sulfur aerosol injection in particular. But CLRTAP applies only on a regional basis within Europe and North America, and would limit SAI within that region only if sulfur emissions exceeded the emitting state's target.
  - Finally, although the UNFCCC's objective is formulated in terms of stabilizing atmospheric concentrations of greenhouse gases (and hence was relevant to carbon dioxide removal but not solar geoengineering), the Paris Agreement establishes a temperature objective, to which solar geoengineering could contribute.
- International environmental law establishes several procedural rules relevant to solar geoengineering deployment.

- The International Court of Justice has found that states have an obligation to undertake an environmental impact assessment before deciding to authorize or conduct an activity that is likely to have a significant adverse transboundary effect. Arguably, states also have associated duties to notify and consult with potentially affected states.
- These procedural requirements to assess, notify, and consult would apply to decisions by states to authorize or undertake solar geoengineering deployment.

- Several substantive principles of international environmental law are relevant to solar geoengineering and would help structure international debate, but do not yield determinate answers about whether solar geoengineering is permitted or prohibited.
  - Widely accepted principles of international environmental law include the duty of due diligence to prevent significant transboundary pollution, the precautionary principle, and the principle of inter-generational equity.
  - These principles are all implicated by solar geoengineering, but do not provide clear guidance. Rather, they provide arguments both for and against solar geoengineering in various contexts.
- To the extent that solar geoengineering deployment raises issues of international peace and security, the UN Security Council could make binding decisions to prohibit, limit, or authorize it.
  - The permanent five members of the Security Council (the United States, the United Kingdom, France, Russia, and China) can each veto decisions with which they disagree. So, in practice, the Security Council would be unable to adopt decisions that prohibit or limit solar geoengineering actions by one of these countries.
  - However, the Security Council could be effective in governing solar geoengineering by other states.

From a legal perspective, solar geoengineering deployment does not require international governance.

- It is sometimes said that solar geoengineering deployment requires international governance. But the accuracy of this statement depends on what we mean by "requires."
- Legally, unilateral solar geoengineering appears permissible, given the absence of any rule of international environmental law that limits its deployment.
- Technically, governance might be required in practice if "counter-geoengineering" is feasible, and other states were willing and able to use it to stop a state from unilateral deployment. In such cases, agreement among the states with geoengineering and counter-geoengineering capabilities would be necessary for solar geoengineering to be effective.
- Politically, states might be reluctant to engage in unilateral geoengineering without international approval. But, conceivably, a state might be willing to engage in solar geoengineering deployment *in extremis*.
- Morally, international governance is arguably required on the ground that one state is not entitled to make unilateral decisions that affect the entire globe. But a decision *not* to engage in geoengineering would also affect the entire globe. So, assuming states disagree about whether to deploy geoengineering, it is not obvious why opponents of solar geoengineering have any more right than proponents to make decisions that affect others around the globe.

Moving forward, only limited international governance functions are likely to prove acceptable to states.

- Looking beyond international law to international governance more generally, governance could potentially serve a variety of functions with respect to solar geoengineering. These include providing (1) a forum for discussions, (2) coordination, (3) information, (4) standard-setting, (5) decision-making, and (6) dispute resolution.
- **Forum –** One important governance function is to provide a forum for discussions among states and other relevant actors. Various international institutions could potentially serve this function, including the UN Security Council, the UN General Assembly, the UN Environment Assembly (UNEA), and the Conference of the Parties to the UN Framework Convention on Climate Change. These general forums appear preferable to more specialized forums such as the Convention on Biological Diversity, which have a limited purview with respect to geoengineering and are hence less equipped to consider the full range of issues relating to solar geoengineering.

- **Coordination –** Coordination is another important governance function that states interested in solar geoengineering may wish to employ in order to avoid duplication of effort, friction, and even conflict. International institutions, such as the International Science Council (formerly ICSU) and the World Climate Programme, could potentially play a role in coordinating research on solar geoengineering, and states could coordinate efforts to develop and deploy solar geoengineering either through an existing organization or through bilateral or plurilateral agreements.

- **Information –** International governance can promote transparency through information exchange, monitoring, and verification. Existing international institutions such as the World Meteorological Organization could potentially play this role, in which case it would not be necessary to establish a new institution.

- **Standard setting –** Negotiating detailed regulatory standards for solar geoengineering would likely be very challenging politically. A moratorium on solar geoengineering would be an easier type of standard to adopt, given its simplicity. However, it seems unlikely that states would be willing to foreclose their options indefinitely by adopting a legally binding moratorium with no time limit. A more feasible option politically would be to articulate additional evaluative principles that would help channel debate but not dictate conduct – for example, along the lines of those developed for the so-called Responsibility to Protect, which require that the use of force for humanitarian purposes be undertaken only as a last resort and with the right intent.

- **Decision-making –** International permitting or other *ex ante* decision-making procedures for solar geoengineering seem unlikely to be acceptable to large, powerful states, which will want to retain their flexibility to engage in solar geoengineering unilaterally. States might be willing to agree, however, to establish national permitting systems for solar geoengineering in order to control private conduct and ensure that solar geoengineering activities are assessed in advance and monitored – and that other states are notified of these activities. The London Convention on ocean dumping of wastes and the Convention on International Trade in Endangered Species are examples of international agreements that require parties to establish national permitting systems.

- **Dispute settlement and liability –** Given the reluctance of states to accept strong dispute settlement or liability rules in other contexts, it seems unlikely that they would be willing to do so with respect to solar geoengineering, where the risks associated with dispute settlement and liability could be almost limitless.

Governance of Solar Geoengineering: Learning from Nuclear Regimes

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Key points

- Deployment of solar geoengineering poses several different governance problems, including: prevention until collective decision-making bodies decide to act; collective decision that the time has come, using mechanisms seen as fair and legitimate; and sustaining the effort for decades to centuries.
- One possible governance approach, drawn from nuclear nonproliferation, is a treaty backed up by additional initiatives that develop to address problems over time.
- Governance of solar geoengineering should avoid decision-making processes that give every country a veto, as these can paralyze decision-making.

To learn lessons from one area of global governance that apply to another, it is important to understand the type of governance problem being considered and how close or distant the analogies are. Solar geoengineering presents governance issues that are in many ways unique – and yet, some important lessons can be drawn from the governance of nuclear technology.

Solar Geoengineering: The Shape of the Governance Problems

Solar geoengineering would potentially affect the interests of everyone on the planet, in good ways and bad – hence the need for collective decision-making. Solar geoengineering raises a range of different governance problems, from managing R&D to the sharing of good practices. In this short paper, I will focus on three problems especially relevant to deployment.

First, *prevention until collective decision-making bodies decide to act.* This will be a major challenge, as there are a large number of state and non-state actors who could implement solar geoengineering, and many might see the likely results as serving their interests. Near-perfection will be needed, as even a single actor could implement solar geoengineering on a global scale.

Second, *collective decision, using mechanisms seen as fair and legitimate, to decide whether the time has come.* This will also be a challenge, as in most circumstances, many will win, but some will lose, from implementing solar engineering.

Third, *sustaining the effort,* over the very long time-frames required – longer than the lifetimes of most human institutions and *much* longer than the terms in office of key decision-makers. Damages from the rapid temperature rise from stopping solar geoengineering abruptly could be severe; more research is needed on the effects of potentially intermittent geoengineering.

We may need different governance mechanisms to meet these different challenges, and different nuclear analogies are likely to be relevant.

Prevention

The obvious prevention analogy, to the taboo on the use of nuclear weapons, is not very useful. That taboo has been maintained in significant part by nuclear deterrence, convincing countries that the response to a nuclear use would be catastrophic for their interests. In the case of solar geoengineering, threats to respond with military action are unlikely to be credible enough to deter, for all the many actors involved.

The nuclear nonproliferation regime, with the Nonproliferation Treaty (NPT) at its core, offers a more helpful analogy. There, common global fears, coupled with the active cooperation of the world's two most powerful states at the time, made possible negotiation of a global treaty with (now) near-universal adherence. Since then, many initiatives and accords have been added that supplement the treaty, forming a broader "regime complex" (Keohane and Victor 2011) and strengthening what has become a strong norm against the spread of nuclear weapons. This "foundational treaty plus living regime complex" approach may be an important possibility for solar geoengineering governance.

One advantage of the treaty approach is that it can include verification provisions. Nuclear treaties have often been designed around what could be measured and verified. But what elements of capability or deployment of geoengineering could or should be measured and verified?

One important disadvantage of the treaty approach is that states that do not see the treaty as serving their interests will simply not sign up (or, more cynically, may sign up and then violate it). Israel, India, and Pakistan, for example, refused to join the NPT and then built nuclear weapons. Hold-outs and violators may be serious problems for a geoengineering regime, and a key part of governance design is likely to be thinking through how to give countries strong incentives to join whatever framework is ultimately designed and to comply with it over time.

UN Security Council Resolutions (UNSCRs) are an alternative to treaties. Chapter VII of the UN Charter gives the Council the right to make decisions that are immediately binding on all states, rather than having to wait for states to sign and ratify treaties, when doing so is necessary to international peace and security. That deals with the holdout problem, though *not* the compliance problem. UNSCR 1540 – which required all states to put in place "appropriate effective" controls of various types to keep nuclear, chemical, and biological weapons out of terrorist hands – is an example. The legitimacy of the Security Council effectively legislating for the world was challenged in that case, however. In the solar geoengineering case, with a less direct and immediate connection to the preservation of peace and security, the challenges might be severe enough to undermine states' willingness to comply.

Informal political initiatives are an alternative to creating binding law. In the nuclear case, some initiatives of this kind have been surprisingly successful – nearly all participants have complied with the agreed standards of the Nuclear Suppliers Group, for example. These initiatives make it possible to start with a small group of like-minded states, who can work out the core principles of the effort and then try to convince other states to join – as has been the case with efforts such as the Proliferation Security Initiative and the Global Initiative to Combat Nuclear Terrorism, for example.

All of these are ways of building up a common norm that no one should implement solar geoengineering unilaterally. But the norm one seeks to establish for geoengineering is more nuanced than just "don't do it." It is "don't do it until we've collectively agreed on it." In that sense, it may be more similar to the norm for nuclear energy – "do it only under international inspection, and with adequate safety and security" – than the norms for nuclear weapons ("don't get them and don't use them"). Nevertheless, one could imagine that over time, such a norm might become strong enough that anyone pursuing solar geoengineering would be subject to naming-and-shaming that imposes severe reputational costs, and conceivably to economic sanctions as well.

Collective decision

There are few examples from nuclear regimes where collective decision-making is both efficient and seen as legitimate. Decisions to take military action to prevent particular countries from getting nuclear weapons have generally been made by individual nations, not collectively. Most sanctions decisions in response to such programs have also been national, though since the mid-2000s, the Security Council and the European Union have acted collectively to impose sanctions on Iran and North Korea.

Realistically, international organizations such as the International Atomic Energy Agency can only do what the member states want them to do. In recent years, they have typically been dysfunctional, even as forums for member states to come together and discuss and make decisions, riven by politics and states' very different perceptions of their national interests. The Conference on Disarmament, for example, has now failed to do any substantive work for over two decades.

The UN Security Council is an exception, having proved able to act fairly decisively when the permanent members are in sufficient agreement that none of them exercises the veto. But again, the Security Council, representing only fifteen of the world's states, may not be seen as representative or fair as a decision-maker for solar geoengineering.

Technically, for geoengineering, a small group of like-minded states would be enough – they could decide on their own. But such a decision – affecting the well-being of everyone on earth, but made without representation for most – would be widely perceived as lacking legitimacy. How much such negative reactions would matter remains an open question.

From nuclear cases, a few hard-learned lessons stand out: (a) to be seen as legitimate, the decision-making group has to involve actors representing diverse interests and points of view – not, for example, a small group of rich and powerful countries; (b) to get anything done, it is critical to avoid an interpretation of "consensus" that gives every state a veto; and (c) on the other hand, simple majority voting among states may give too much weight to the large number of tiny states with few people living in them.

Given the importance of the issue to everyone's well-being, it may be that deciding to implement solar geoengineering in a substantial way should require some type of supermajority of the world's states, or states representing a majority (or supermajority) of the world's population, or some other form of weighted voting.[1]

Sustaining the Effort

There are few cases of success in sustaining efforts for decades in the nuclear realm (let alone centuries). It is a sobering fact that the lifecycles of nuclear reactors or nuclear weapons reach to many decades, yet all but a very few of the states with nuclear weapons have had either major war or violent revolution on their soil within the last century.

Nevertheless, the nonproliferation regime again offers an interesting example. The initial treaty was created in a very different bipolar world and had a term of only 25 years. It created a two-tier system in which some states received fewer rights, which intuitively seemed unlikely to last indefinitely. Yet when the time came, with some substantial arm-twisting by the United States and other major powers, the parties agreed to extend it indefinitely, and in 2018, we celebrated its fiftieth anniversary.

Crucially, many other initiatives and instruments have built up over the years to patch problems as they arose. The treaty and the broader regime complex face many challenges, but so far states continue to understand that the spread of nuclear weapons would be bad for non-nuclear-weapon states as well as nuclear-weapon states, so the parties have seen it in their interest to continue to take part and to patch it up as needed as they go along. Something similarly messy, with a variety of separate pieces contributing to a larger goal, might turn out to be the answer for sustaining a geoengineering campaign over the time required.

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Keohane, Robert O. and David G. Victor. 2011. "The Regime Complex for Climate Change." *Perspectives on Politics* 9 (1): 7–23. http://doi.org/10.1017/S1537592710004068.

1 See also brief by Weitzman in this volume.

Risk Governance and the Strategic Role of Uncertainty

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Key Points

- Because solar geoengineering (SG) carries uncertain downside risks, discussions of SG governance are embedded in a wider societal debate about regulating novel technologies that hold both great promise and great potential for harm.
- Decision theory offers little guidance for choosing between traditional cost-benefit analysis and the "precautionary principle," which emphasizes a margin of safety to avoid bad surprises, when dealing with uncertain and hard-to-quantify risks.
- SG would be deployed to address another risk (i.e, climate change) – thus, any debate over SG governance must be framed in terms of risk-risk trade-offs.
- Uncertainty about SG risks may helpful in a multi-agent world, both because it increases incentives for cooperation and because it may discourage free-driver behavior. Seen from this perspective, learning more about SG risks could actually be detrimental.

Solar geoengineering (SG) carries the risk of unintended consequences, such as changes to precipitation, stratospheric ozone loss, and loss of biodiversity (NRC 2015; IPCC 2018). The extent and likelihood of these side-effects are currently uncertain.[1] This brief makes two points in the context of SG and uncertainty. First, it argues that the presence of uncertain side-effects embeds SG in a wider societal debate about technological risks. Second, it touches on the intricate role that SG uncertainty can play in the interaction between multiple actors.

Governance of technological risks: How safe do we want to be?

The possibility of unintended negative consequences is a feature that SG shares with other novel technologies, such as artificial intelligence and biotechnology (WEF 2017). In this sense, SG is embedded in a wider societal debate about how to govern novel technologies that simultaneously hold huge promise and substantial danger.

This debate over risk governance is intense and ongoing. Proponents of cost-benefit analysis point to societal costs of regulation and cite evidence of cost-ineffective regulation that overemphasizes some risks over others (Nichols and Zeckhauser 1986; Viscusi *et al*. 1997; Sunstein

1 Side-effects of SG with respect to ozone and precipitation, as with uncertainty in regard to technical feasibility, fall in the category of "scientific uncertainty." Even more intricate are the socio-economic uncertainties surrounding societal responses to SG technology (such as moral hazard).

2002). Proponents of the "precautionary principle," on the other hand, emphasize the possibility of bad surprises (such as the carcinogenicity of asbestos) and recommend sacrificing some technological benefits in order to build a margin of safety (Myers and Raffensberger 2005; Randall 2011).

Decision theory provides no definitive guidance to settle this controversy. There is no agreement on how to deal with hard-to-quantify risks for which there is no empirically validated probability distribution.[2] The debate over whether decision rules that deviate from "subjective expected utility" (SEU) can be considered "rational" mirrors the controversy over whether risk governance should involve a margin of safety against potentially bad outcomes (Gilboa *et al.* 2009).[3]

We can therefore expect that SG will continue being discussed as part of a much wider debate. Successes or failures in other domains will also shape the controversy surrounding SG. A crucial difference between SG and other risky technologies is, however, worth noting. SG is not a risky technology that is being introduced into a risk-free world. Quite the contrary, since the main motivation for considering SG in the first place is as a measure to tackle climate risks. SG deployment may be uncharted territory, but so is human life on a significantly warmer planet. Whether we lean more toward traditional cost–benefit or precautionary approaches to regulating risk, this risk-risk trade-off must be an integral part of any comprehensive debate on SG governance.

Uncertainty may be helpful in multi-agent interactions

The societal challenge described in the foregoing section is to find an appropriate response to the uncertainties posed by climate change and SG. This challenge has the flavor of a single decision-maker, "society," acting against an uncertain "nature." In this simplified view, uncertainty is always detrimental as it requires preparation for different scenarios simultaneously. Reducing uncertainty, accordingly, is welcome and valuable. This intuitive principle, however, may be violated once we take into account interactions between different agents. The remainder of this brief explores reasons why learning about SG may be detrimental in a multi-agent world.

The first channel through which uncertainty may impact strategic interactions involves willingness to cooperate. It is often suggested that cooperation might be easier to achieve when actors are behind a Rawlsian veil of ignorance in terms of who would win or lose from a given action. Or, as Binmore (2006) puts it, "*Devil take the hindmost then becomes an unattractive principle for those bargaining in the original position, since you yourself might end up with the lottery ticket that assigns you to the rear*."[4] This analogy might have direct relevance for SG side-effects, such as

2 Either because there is not enough data yet, or because it is fundamentally unknowable.

3 For a justification and possible implementation of non-SEU preferences in environmental economics, cf. Heal and Millner (2018, p. 30).

4 Also see Na and Shin (1998): *"Since countries are more likely to be facing similar conditions ex ante rather than ex post, (i.e. before the resolution of uncertainty rather than after it), the possibility of coalition formation is enhanced the sooner the negotiations take place. The social value of better scientific information may well be negative in such circumstances."*

making some countries drier and other countries wetter. With more research on side-effects, it will become clearer which countries stand to benefit and which stand to lose from SG deployment. This might reduce countries' incentives to negotiate SG deployment in a cooperative manner.

Another reason why learning could be detrimental is if it aggravates the free-driver problem.[5] If the free-driver (in this case, a country that is inclined to act unilaterally on SG deployment) is uncertain about the extent to which he will incur SG side-effects, he would arguably deploy less SG than he would if all side-effects were known. Reduced incentives for SG deployment mean, from a global perspective, less over-deployment – in other words, a reduction in the negative externality the free driver imposes on the rest of the world. In this sense, uncertainty about SG side-effects can be beneficial, and learning about SG side-effects, in contrast to the case of a pure single-actor, could be detrimental.

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5 The free-driver concern (Weitzman 2015) is that the country with the strongest desire to cool the globe, the free-driver, could unilaterally deploy SG to an extent that is detrimental to the rest of the world.

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Assessing Solar Geoengineering – What, Who, and How?

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Key Points

Potential consequences of future SG deployment are assessed in a growing number of authoritative studies and reports, yet results are contested due to lack of clarity in three respects:

- Defining what *SG deployment* might be, requires making conscious choices throughout a pyramid of biophysical, socio-political, and value-laden assumptions.
- The prevalence of value-choices in assessments of SG deployment requires clarity on whose perspectives ought to be considered.
- The question of how and by which criteria SG deployment may be assessed requires clarity on relevant social objectives that SG deployment ought to advance or avoid infringing upon.

Outcomes from deploying solar geoengineering (SG) would be determined by an intertwined set of factors: the bio-physical and political dimensions of the action taken, the design of the technology used, and broader accompanying circumstances.[1] To provide a widely accepted basis for decision-making, assessments of SG deployment therefore require clarity on three distinct but interdependent questions: First, what is SG deployment? Second, who may authoritatively assess it? And, third, how and by which criteria may SG deployment be assessed?

What is solar geoengineering deployment?

As a subject of governance discussions, SG deployment is at an early stage. Just as climate change itself came to be viewed as an issue that required international governance years ago, the growing number of potential courses of action proposed to address it – including emission reductions, adaptation, and, most recently, carbon dioxide removal – are increasingly seen as demanding political consideration.

At this point, the question, "what is SG deployment?" is generating a swirl of often contentious ideas, categories, terms, and concepts.[2] Gaining more clarity on this question will also be crucial for assessments of SG deployment. This brief describes how understanding SG deployment as a policy proposal exposes a pyramid of assumptions that help answer the question of what SG deployment is. The outcomes of an SG deployment policy depend on situational conditions,

1 In addition to drawing inspiration from the discussion at the September 2018 workshop at Harvard, the observations and reflections discussed in this brief also stem from the author's involvement in the first exploratory assessment of potential implications of carbon removal and SG deployment for the achievement of the UN's Sustainable Development Goals (Honegger *et al.* 2018).

2 See Böttcher and Schäfer (2017) for an account of how this battle of ideas and concepts has evolved over the last 10 years.

design and deployment choices, and governance arrangements – they are not a mere function of the innate characteristics of SG technologies.

Analyses and commentary concerning the scientific and political aspects of SG increasingly acknowledge that deployment scenarios, technology design, and expected outcomes are intimately linked. Likewise, assumptions about climate sensitivity, future greenhouse gas concentrations, and about the timing, scale, and pace of SG deployment interact in important ways. This becomes dramatically evident when comparing findings from studies that assess climatic outcomes from SG deployment designed to fully counteract an abrupt quadrupling of CO_2 concentrations to findings from studies that assess a more gradual and partial counteraction that is designed to shave off only 0.5°C from a peak warming of 2°C. Because of the different forms of deployment chosen in each case, studies of the latter approach (i.e., gradual SG deployment) unequivocally suggest positive outcomes, where others find more harmful ones.[3]

Specific governance assumptions can also have a large effect on deployment outcomes: Concern about the potential for harm resulting from abrupt termination of SG deployment – known as *termination shock* – might best exemplify this point, insofar as the likelihood of termination shock rests heavily on the stability and effectiveness (or lack thereof) of SG governance arrangements (Parker and Irvine 2018).

The above observations point to a serious deficiency of studies or assessments that seek to characterize SG as possessing innate technology characteristics that would dominate all other considerations: Such characterizations fail to recognize the important influence of situational conditions, design and deployment choices, as well as governance arrangements.[4]

Answering the question, "what is SG deployment?" thus requires value-laden choices across a pyramid of possible assumptions (Figure 1). At its base, the pyramid requires the same kinds of assumptions regarding future states and impacts of the climate system that also underpin common mitigation pathway scenarios and climate impact assessments: assumptions about bio-physical parameters (e.g., climate sensitivity); choices of emissions pathways (and implicit policy choices such as carbon pricing); socio-economic parameters that relate physical impacts to economic costs and benefits; and social and ethical evaluations on issues such as equity, justice, and ecosystem impacts.

On top of these judgments, three additional types of SG-specific factors must be considered. These include SG technology design; the timing, scale and pace of SG deployment; and the governance arrangements and political conditions that will shape deployment actions. Each of these layers of assumptions interacts in important and rather complex ways with other layers, below and above.

3 See, for example, MacMartin *et al.* (2018).

4 This is exemplified in recent debates about whether SG may be characterized as inherently undemocratic; see Horton *et al.* (2018).

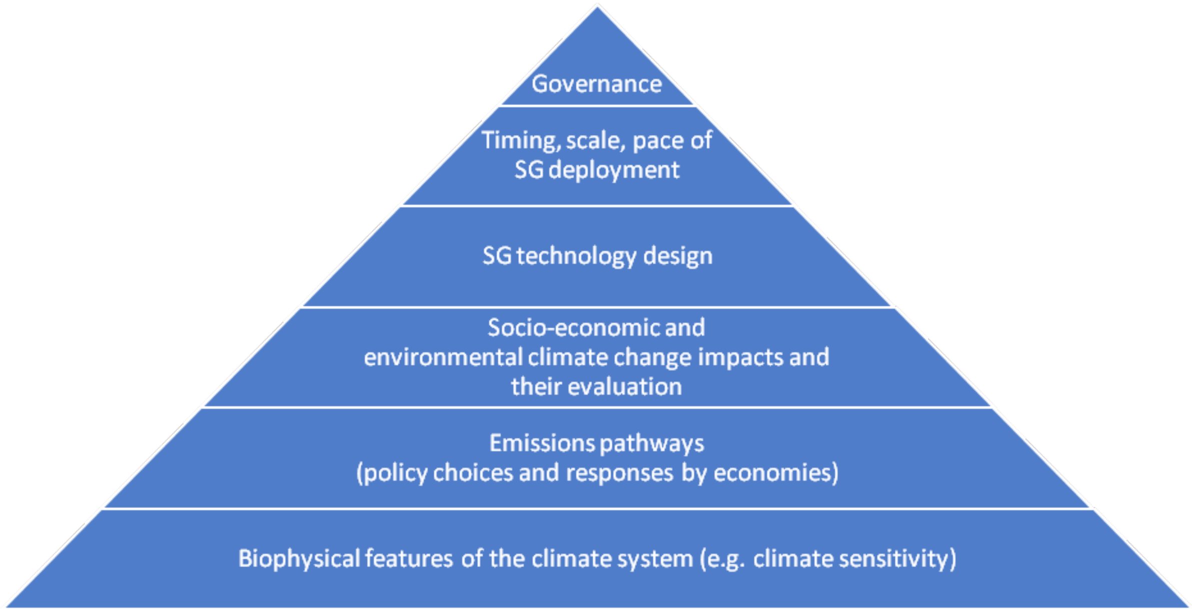

Figure 1. A pyramid of necessary assumptions for SG assessments; order does not imply importance.

Who may authoritatively assess solar geoengineering?

The value-laden schematic shown in Figure 1 is indicative of the stakes in assessing SG and provides a starting point for identifying the epistemic communities that might need to be involved. The bottom three layers likely require the same expertise for assessing climate impacts and mitigation pathways that is needed in other contexts. Additional layers (concerning technology design; deployment timing, scale, and pace; and governance conditions) may require new domains of expertise that span, but are not limited to, a wide range of earth system sciences, engineering, economics, ethics, ecology, public health, history, public policy, and governance.

It has even been argued that SG deployment would dramatically transform the meaning of climate action from eliminating and undoing the harmful activity of emitting greenhouse gases to including remedial measures. Insofar as SG deployment establishes a new relationship between human beings and their environment, it poses spiritual and cultural challenges that may require the voices of spiritual thought-leaders and non-experts to be added to previously enumerated perspectives.

How and by which criteria should solar engineering be assessed?

Finally, it will be crucial to decide how and by which criteria SG deployment will be assessed. In contrast to assessing emission reductions and removals, where the primary metric is tons CO_2-equivalent (co-benefits or sustainable development being important secondary considerations), there is currently no metric for SG that would enjoy similar levels of agreement. Global average temperature might seem a straightforward choice, but would fall short in many other dimensions. "Avoidance of dangerous climate change," measured as an ensemble of physical climate parameters, would seem more nuanced but requires substantial interpretation regarding other social goals. Whether sustainable development goals might fare better remains to be seen.[5] Criteria and metrics for SG assessment could therefore remain contested for some time. It is possible that various metrics will continue to co-exist side by side as an increasing number of institutions start to construct their own understanding of how SG deployment could potentially interact with their respective functions and roles.

Conclusion

With clarity concerning the "what, who, and how" of SG assessments emerging only gradually, such assessments and the knowledge they represent will likely be contested. Although some organizations – including several highly respected national and international institutions – have already conducted assessments, ongoing controversy regarding the potential role of SG in international climate policy suggests there may be room for improvement. To achieve greater recognition, future SG assessments could strengthen transparency and approach the pyramid of assumptions defining SG deployment (the "what") more systematically, strengthen the range of perspectives considered (the "who"), and identify widely recognized assessment metrics (the "how"). Greater clarity on these issues may be needed to develop a more widely accepted knowledge base for making SG deployment decisions.

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5 Thiele (2018) argues that considering geoengineering in the context of sustainability would provide "common ground in an otherwise polarized debate […] making a more productive dialogue possible."

Evaluating Solar Geoengineering Deployment Scenarios

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Key Points

- Scenarios of solar geoengineering deployment powerfully shape governance considerations and hence must be scrutinized.
- "Emergency" scenarios that envision rapid deployment are scientifically questionable and politically problematic for democratic countries.
- "Breakout" scenarios that imagine clandestine technology development are unrealistic.
- More conventional scenarios offer a more appropriate basis for thinking about possible future governance of solar geoengineering deployment.

When considering governance of solar geoengineering deployment, much depends on the specific deployment scenario that is envisioned. Scenarios are important because they establish the parameters of possible action, and contain assumptions about structures and behaviors. In this brief, I will comment on two deployment scenarios that often feature in discussions about solar geoengineering: "emergency" and "breakout." In both cases, closer inspection reveals that key scenario elements are either unwarranted, undesirable, or unrealistic, rendering any derivative analysis liable to lead to flawed, perhaps even dangerous, conclusions.

The emergency scenario imagines that accelerating climate change may result in a "climate emergency" necessitating rapid deployment of solar geoengineering to forestall catastrophe. In the literature, potential crises are frequently viewed in terms of climate tipping points, or thresholds beyond which abrupt, nonlinear effects take hold. Melting ice sheets and sea ice, and thawing permafrost are commonly offered as examples of climate tipping points. More recently, a group of scientists has advanced the "Hothouse Earth" hypothesis, according to which the cumulative effects of multiple positive feedbacks could push the Earth into a new, much less hospitable state (Steffen *et al.* 2018). Although the tipping point concept is entrenched in climate policy discourse, there is substantial disagreement within the scientific community about its theoretical soundness and considerable skepticism regarding storylines based on crossing tipping points (IPCC 2013).

Whether emergency deployment is justified in terms of tipping points or in reference to some other event such as a weather-related disaster, declaring a "state of exception" to ordinary politics in order to meet a (socially constructed) crisis risks a process of political degeneration in which rights are suspended, dissent is suppressed, power is concentrated, and decision-making is rushed and myopic. "Emergency" activities may have little or no connection to the precipitating event, and may evolve from temporary measures to standing policy. Framing deployment of solar geoengineering as a response to a "climate emergency" entails both questionable science and perilous politics, and should be approached with caution (Horton 2015).

The second, breakout scenario envisions a solar geoengineering capability developed in secret and subsequently deployed. Small-scale research and development activities such as computer modeling, laboratory experiments, and even limited field tests might conceivably be conducted in secret, but the larger scale trials that scientists regard as necessary before full deployment would be unlikely to go undetected. Multiple high-altitude aircraft operating from numerous, geographically restricted airfields would be readily observable through a variety of means, including remote sensing. Large amounts of material – perhaps millions of tons – would need to be obtained and stored prior to dispersal. Billions of dollars would likely be required to pay for such testing. And hundreds to thousands of individuals would probably be involved in such an endeavor, all of whom would need to maintain strict confidentiality if their activities were to remain undisclosed. It is highly unlikely (though not impossible) that field trials of such magnitude could be carried out covertly for any extended period of time, and hence unlikely (though again not impossible) that reliable, quickly deployable solar geoengineering technology could be developed in secret.

Other deployment scenarios common in the literature are equally unrealistic. Countries pondering deployment as an act of desperation might possess resources sufficient to develop the technology. But full deployment would require continuous stratospheric aerosol release for decades, at a minimum, and it is unlikely that such countries would be powerful enough to withstand the range of commercial, financial, diplomatic, and (in the extreme) military pressures that other states opposed to deployment could bring to bear to halt implementation. A "greenfinger" scenario (Victor 2008) in which a private actor sought to implement solar geoengineering would also likely fail: lacking even the rudimentary trappings of statehood, such as territorial sovereignty or a monopoly on the legitimate use of force, individuals or companies would likely face great difficulties mustering the infrastructural, political, and security capabilities necessary to carry out long-term deployment in the face of international opposition.

In contrast to emergency, breakout, and similar scenarios, more conventional scenarios such as "temporary, moderate, and responsive" deployment offer a superior basis on which to pursue governance research (Keith and MacMartin 2015). Such scenarios should be grounded in a vision of international relations dominated by states operating in a context of complex interdependence and responding to a multiplicity of positive and negative incentives. Far from overlooking the potential for rash actions, conflicting interests, and international tensions, this perspective *anticipates* such possibilities. Scenarios built on more typical understandings of world politics are more apt to generate useful insights about governance of solar geoengineering deployment than are storylines that rest on implausible assumptions or risky characterizations.

Unconventional scenarios, however, do point toward at least two avenues of constructive research. First, the enduring appeal of emergency framing, despite its weak empirical foundations and hazardous political implications, suggests that scholars should take seriously the possibility that actors may invoke a climate emergency as justification for deployment. The research community should actively consider governance architectures designed to guard against this possibility. And second, solar geoengineering researchers should more fully appreciate the need for robust monitoring, not only during deployment, but *prior to* deployment. Strong monitoring capabilities are important for ensuring both that any implementation would be adaptive and flexible, and that any large-scale field experiments are successful *and* observable; visibility is essential to building trust.

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Solar Geoengineering Deployment: Governance Criteria for a Distributed Technological System

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Key Points

- Solar geoengineering raises issues comparable to those involved in building, operating, and maintaining large technological systems, in particular, questions of institutional architecture, standards, and best operating practices. These questions have been considered more often at the national than the international level, but some useful international parallels can be cited.
- The unknowns surrounding solar geoengineering deployment demand a precautionary approach. Yet, nations and regions remain divided in their understanding of what "precaution" means, even when they agree in principle that this is a desirable basis for governance.
- The legitimacy of governance depends on the perceived neutrality of decision-making institutions. However, judgments as to what constitutes an unbiased process rest on culturally-specific civic epistemologies, or public understandings of the right ways to generate and evaluate policy-relevant knowledge. Those understandings differ from country to country.

Introduction

Climate change looms large in the world's consciousness as the epitome of a wicked problem: difficult to explain and difficult, if not impossible, to solve. It presents multiple faces – scientific, economic, political, ethical – each offering its own approach to a causal explanation. It resists any simple attempts to frame or box it into a semblance of tractability, with solutions that appear adequate for the purpose. The history of climate negotiations from Kyoto in 1992 to Paris in 2015 illustrates varied attempts to establish a problem frame that is robust enough to contain the essential parameters of causation and to offer a solution that will hold carbon emissions to levels the world can sustain.

Under these circumstances, the possibility of a technological solution that could be deployed if other interventions fail or prove insufficient is extremely appealing. Solar geoengineering offers just such a promise. On the plus side, it is considered cheap, accessible even to poorer countries, and relatively easy to deploy on a large scale. On the minus side, it presents significant scientific and technological unknowns, poses challenges to existing regulatory institutions, and confronts potentially crippling public rejection. How then should we approach the following questions: *who* should specify criteria for governance of solar geoengineering and determine when they are satisfied; *what* should those criteria be; and *how* should decisions be made? This brief addresses these who, what, and how questions.

Deployment of Solar Geoengineering: Finding the Right Analogy

As yet, solar geoengineering is an idea, not an actuality. To determine how it should be governed, we need first to agree what kind of project it is, and hence what analogies are most appropriate for governance purposes. Based on prior experience with transnational environmental problems, three plausible starting points come to mind, each offering a different set of tools for addressing the who, what, and how questions addressed in this brief. If one begins with economic models, the questions become largely ones of calculation: who determines, or should determine, and carry out the necessary calculations; who decides whether costs and benefits are correctly modeled and measured? If one begins instead with international relations, and asks why nations agree not to harm one another, attention turns toward historical explanations for norms of non-aggression that have proved relatively durable, such as the ban on chemical weapons or nuclear non-proliferation. Yet a third possibility, explored in this brief, is to begin with the second element in the term geo-*engineering*, considering it as an engineering project, hence analogous to the deployment of other large-scale technological systems.

Technological systems the world over provide some insights that bear on the who, what, and how questions of governance. Extrapolating from prior experience, we know that, with respect to "who governs," it matters whether authority is centrally organized or dispersed in accordance with some notion of subsidiarity, i.e., the principle that decisions should be devolved to the unit closest to the problem at hand. Put differently, the deployment of solar geoengineering calls for an institutional architecture that is at once coherent enough, flexible enough, and competent enough to bear the challenges of a global project whose resolution depends to some extent on highly variable, local technical and political circumstances. With respect to the content of the criteria, particularly important for geoengineering is the issue of uncertainty, or what principles should click into place if the consequences of deployment cannot be accurately predicted in advance. With respect to process, or the how question, a focal issue is to determine how global publics, whose consent is essential for legitimate governance, can be adequately involved in decision-making on solar geoengineering. At each step, there are problems to be resolved and pitfalls to be avoided.

Lessons from Prior Experience

What technological systems provide analogies relevant to the deployment of solar geoengineering? The most apposite cases involve a global (or translocal) problem frame addressed through linked but localized technological infrastructures subscribing to a set of common, agreed-upon standards. Standards might include those applicable to the physical components of such systems as well as to their human and organizational features. Examples of useful precedents include the International Atomic Energy Agency's standards for nuclear power plants to meet global energy needs; high dam projects for irrigation and electricity that have been subjected to scrutiny by the World Commission on Dams as well as national regulatory authorities; voluntary standards established by the International Standards Organization; and the sustainability principles and practices agreed to by participants in the United Nations Global Compact.

A general finding from the experiences of such bodies is that standard-setting is only one part of the process of responsible governance. Implementation of standards is often the place where breakdowns occur. These may result from something so basic as not having a common language for communicating technical information to cultural barriers against practices that cannot be generalized across geographic regions. Pesticide application standards, for example, have proved difficult to implement globally because usage labels are written in a foreign language, or because protective clothing required by the standard-setting body cannot be worn comfortably in the places where the chemicals are used. Too much centralization tends to exacerbate the problems of communication, deployment, and monitoring needed to ensure the safe functioning of dispersed technological systems.

Turning to the content of standards, expert judgments on what is the right standard often diverge because experts disagree about the probability of different kinds of harm and also about the degree of protection that should be afforded when science does not provide definite answers. The precautionary principle was developed to address these uncertainties. In brief, it demands that when facts are uncertain and grave or permanent harm could result, the regulatory body has a duty to explore alternatives that would minimize risk. Yet a 2017 report prepared for the European Commission concluded that "precaution" means very different things under the 1992 Rio Declaration, the 2000 European Commission communication on the precautionary principle, and the 1998 Wingspread Declaration (UWE 2017). These three texts differ on the severity of harm and the degree of epistemic uncertainty required to trigger a precautionary response, as well as on the measures taken and provisions for review.

Early attempts to develop criteria for solar geoengineering governance have all agreed on the need to involve publics in decision-making. The 2009 Oxford Principles, for example, list as Principle 2 "Wherever possible, those conducting geoengineering research should be required to notify, consult, and ideally obtain the prior informed consent of, those affected by the research activities."[1] If this principle applies to research, all the more it should apply in cases of deployment, to ensure that risky actions are taken with public consent. One attempt to consult the public on a nationwide scale took place in Britain in connection with the release of genetically modified organisms (GMOs). Ambitiously titled "GM Nation?" (Horlick-Jones et al. 2005), the effort drew criticism from all sides. Advocates of GMO release argued that the wrong people had turned up to the more than 600 events organized by the initiative. Opponents argued that the government had made up its mind to allow GMO release and was not responsive to the arguments brought forward by their representatives. Subsequently attention in British policy circles shifted to mechanisms for getting the "right" publics to respond to calls for deliberation.

In designing participatory processes, the main issue is not merely who participates but by what criteria participants evaluate the legitimacy of the exercise. There is considerable evidence from different national contexts that citizens approach the legitimacy of governance processes with different civic epistemologies, or ways of knowing, conditioned by their respective constitutional and administrative cultures. This diversity of public response means that a process judged

1 www.geoengineering.ox.ac.uk/oxford-principles/principles.

to be adequate in one political culture may well fall short of expectations in another. This is a serious and often under-recognized challenge for global governance.

Summing up, if we regard solar geoengineering as an engineering project first and foremost, then governance criteria can be extrapolated from historical experiences with building and operating other large technological systems. Important issues that will need resolution include the appropriate degree of centralization vs. subsidiarity, the adoption of precaution as a principle of governance, and the design of participatory processes that are sensitive to cross-cultural differences in the public uptake and evaluation of regulatory decisions.

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Building a Governance Foundation for Solar Geoengineering Deployment

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Key Points

- Governance mechanisms to guide decision-making on solar geoengineering will be highly dependent on both the type of technology that is being deployed and the conditions under which deployment unfolds.
- Discussions on solar-geoengineering governance should focus on norm development, through information sharing and public deliberation, rather than deployment as such – with a view to having in place a solid and politically legitimate foundation, if and when deployment-specific governance mechanisms must be developed.
- The Academic Working Group on Climate Engineering Governance recently released a report that presents a suite of concrete governance recommendations for moving us toward establishing such a foundation (Chhetri *et al*. 2018). These recommendations fall into three categories: create politically legitimate deliberative bodies, leverage existing institutions, and make research transparent and accountable.

It is premature to outline the specific governance mechanisms that will be needed for solar geoengineering deployment. Not only are state preferences underdeveloped in this area (Jinnah 2018), but, ultimately, governance mechanisms to guide decision-making on this topic will be highly dependent on both the type of technology that is being deployed, and the conditions under which deployment unfolds.

With regard to technology, governance mechanisms must respond to potential and perceived risks. These risks, such as those related to security concerns associated with rogue deployment, will be significantly different if we are considering deployment of stratospheric aerosol injection versus marine cloud brightening, for example.

With regard to the conditions under which deployment occurs, governance mechanisms must respond to particular deployment scenarios. As David Victor has noted elsewhere, whereas a deployment response to a global climate emergency may require cost sharing and the implementation of complementary projects, responding to an imagined local climate emergency may instead require dispute resolution mechanisms and risk assessment. The global governance community lacks the foresight capacity at this time to prepare for all possible outcomes across these metrics, particularly in light of the great scientific uncertainty surrounding the efficacy and potential impacts of many of these speculative approaches.

Nevertheless, as research continues to progress, governance discussions surrounding solar geoengineering must continue in parallel. However, these discussions should not be focused on deployment as such. Rather, the focus should be on norm development through information sharing and public deliberation, such that if and when deployment-specific governance mechanisms must be developed, a solid and politically legitimate foundation is in place from which to do so. Although some weak and informal "de facto" mechanisms (Gupta and Möller 2018) currently guide solar geoengineering governance, the governance space is largely vacant (Jinnah and Nicholson *forthcoming* 2019).

The Academic Working Group (AWG) on Climate Engineering Governance,[1] which was established and overseen by the Forum for Climate Engineering Assessment,[2] recently released a report that presents a suite of concrete governance recommendations for moving us toward this goal. The report was developed by an international team of fourteen global governance scholars, including this author, who came to the process with a wide range of views on the ultimate wisdom of solar geoengineering strategies as a possible climate response measure. Despite their normative divergences in this regard, the AWG was able to reach consensus on the need for twelve concrete governance mechanisms that should be implemented in the near term (i.e. before 2025) to govern early-stage research and ensure robust social consideration of that research, all with an eye to building a foundation for possible consideration of solar geoengineering deployment in future. These recommendations fall into three non-mutually exclusive categories: create politically legitimate deliberative bodies, leverage existing institutions, and make research transparent and accountable. The remainder of this brief pulls from the AWG report to summarize these recommendations (Chhetri *et al.* 2018).

Create politically legitimate deliberative bodies

1. **Establish a world commission on solar geoengineering.** Develop a high-level representative body to engage in a broad-based international dialogue on issues related to solar geoengineering governance. This body's mandate should include debating first-order questions about whether and to what end these technologies should be researched and developed, responsibilities to future generations (McKinnon 2018), and how solar geoengineering fits within a broader climate response plan.

2. **Establish a global forum for stakeholder dialogue.** Develop a forum to facilitate stakeholder deliberation among those who would likely otherwise be marginalized from international and possibly even established domestic decision-making processes. Importantly, the forum should include formalized mechanisms to allow for input and feedback into the world commission's ongoing work.

1 http://ceassessment.org/academic-working-group

2 https://ceassessment.org

Leverage existing institutions

3. **Strengthen cooperation between international organizations.** Recognizing that several international institutions have existing capacity and possibly even interest in engaging in solar geoengineering governance (Nicholson *et al*. 2018), mechanisms for coordinating across international organizations on this subject should be developed and enhanced. Secretariats of international institutions can potentially play an important role in facilitating this process (Jinnah 2014).

4. **Assess and improve capacities for regional coordination and conflict resolution.** Regional organizations should work to better understand potential positive and negative spillover effects, and link these effects to other forms of dialogue about regional environmental governance.

5. **Continue ongoing assessment roles for the IPCC and related processes.** The IPCC and other relevant assessment bodies, such as national academies, should assess the current state of knowledge on solar geoengineering technologies so as to ensure that any consideration of future deployment occurs in the context of current climate science.

6. **Develop foresight capabilities in decision-making systems.** National governments and appropriate coordinating United Nations bodies should work to develop and employ foresight practices to inform consideration and development of governance structures for the research and potential deployment of solar geoengineering technologies.

Make research transparent and accountable

7. **Report on solar geoengineering research and development activities in the global stocktake under the Paris Agreement.** Assuming the final form of the stocktake permits such inclusion, parties to the Paris Agreement should be encouraged to report on any ongoing or planned solar geoengineering research to ensure greater transparency concerning global technological development.

8. **Institutionalize codes of conduct for responsible solar geoengineering research.** Recognizing that there are existing and emerging codes of conduct for research, funding organizations should evaluate, adapt, and/or adopt codes of conduct as a condition of providing funding. The scientific community should aim to strengthen this process by coalescing around and supporting a specific and explicit code.

9. **Ensure that ongoing research includes international and interdisciplinary collaboration.** Given that most solar geoengineering research is currently located in North America and Europe, but potential impacts are global in scope, state and private funders of research should prioritize projects that feature substantial international and interdisciplinary collaboration.

10. **Clarify funding streams.** To enhance transparency, all sources and recipients of research funding should be a matter of public record, and there should be clarity that funding is specifically for solar geoengineering.

11. **Develop a publicly accessible clearinghouse.** National governments should develop publicly accessible clearinghouses of all publicly funded and, to the extent possible, privately funded solar geoengineering research (Craik and Moore 2014). Such national clearinghouses should, in turn, feed data into an international clearinghouse. The clearinghouses should be designed and developed by an existing authoritative body or ideally through a collaboration among a set of authoritative bodies.

12. **Develop best practices for risk and impact assessments.** National governments, risk assessment and environmental impact assessment (EIA) experts, and solar geoengineering researchers should work together to expand risk assessment and EIA procedures and protocols so that they can evaluate potential environmental and social harms while also enabling public notification and consultation for solar geoengineering experiments.

Taken together, these recommendations could form a solid foundation for near-term solar geoengineering governance. However, depending on political context, they could also be adopted independently. Crucially, given the lag between problem identification and the development of governance institutions, the time to develop anticipatory flexible mechanisms to ensure good governance of these emerging technologies in the future is now.

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The Relevance of the Climate Change Regime to Governance of Solar Geoengineering

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Key points

- The international climate change regime has yet to take a position on solar geoengineering (SG) but will eventually have to address it.
- Various elements of the climate change regime, including the global stocktake mechanism, are potentially relevant to SG governance.
- The regime's universal membership and perceived legitimacy on matters relating to the global climate could be of particular value to SG governance.
- Governance decisions that require relatively prompt action, such as responding to unilateral SG deployment, may be better addressed through other institutions.

The international climate change regime[1] has yet to take a position on – or explicitly acknowledge – the controversial subject of solar geoengineering (SG). However, interest in SG will likely increase as climate change impacts become more severe and mitigation efforts struggle to take hold. Eventually, the climate change regime will no longer be able to ignore SG and the governance issues surrounding it.

SG governance might fulfill various objectives. At a minimum, SG governance might focus on avoiding or minimizing physical risks associated with SG research or deployment. SG governance might also address systemic risks associated with SG technology development, such as technological lock-in or decreased mitigation. In response to worries that SG efforts are being stymied, SG governance might take on a rather different role of supporting research, coordinating development efforts, and providing a social license for SG activities. If a viable SG technology is developed, governance mechanisms will be needed to decide whether to deploy it – and if SG is deployed, to spell out deployment parameters and address the termination problem. Finally, governance might also deal with the concern that a nation or private actor might deploy SG unilaterally. The desired objectives of SG governance will have important implications for governance design.

Although the climate change regime has been silent on SG, various elements of that regime are potentially relevant to SG governance. Both the Framework Convention's declared objective of

1 I use this term to refer to the UN Framework Convention on Climate Change and other agreements entered into pursuant to that convention, as well as the Conference of the Parties (COP) and other institutions and implementation mechanisms established by those agreements.

avoiding dangerous anthropogenic interference with the climate system, and the Paris Agreement's elaboration of that objective in terms of holding the increase in global average temperature to 2°C or less, assume mitigation as the primary means of addressing climate change. Yet the Paris Agreement's choice of a temperature goal, as opposed to a target atmospheric carbon concentration or a carbon budget, leaves room for the possible use of SG. Indeed, the Framework Convention is a framework agreement that explicitly contemplates the subsequent adoption of protocols addressing matters relating to climate change. Moreover, the Paris Agreement provides a specific mechanism that could allow SG to be brought into the ambit of the climate change regime: the global stocktake. This mechanism is aimed at evaluating the implementation of the Paris Agreement by "assess[ing] the collective progress towards achieving the purpose of th[e] Agreement and its long-term goals." Assessments by the Intergovernmental Panel on Climate Change – including any potential assessment of SG – could be considered as part of the stocktake process.

The fact that the climate change regime *could* take on at least some aspects of SG governance does not necessarily imply that it *should*, as such governance might be better pursued through other institutions or mechanisms. Thus far, the climate change regime has not effectively responded to climate change, and its processes are unwieldy at best. But to be fair, climate change presents a collective action problem in the extreme, exacerbated by powerful interests with a vested stake in existing energy systems. Under these circumstances, it is unsurprising that the climate change regime has struggled to make progress, and not obvious that an alternative regime would have succeeded. The climate change regime nevertheless has certain strengths that could prove useful for some aspects of SG governance.

Most significantly, the climate change regime commands universal membership, and it is widely viewed as a legitimate policymaking authority on matters relating to the global climate. Providing legitimacy to decisions on SG – whether with respect to field experimentation, deployment, or prohibitions on specific types of SG – is a critical function of SG governance. Notably, the climate change regime is uniquely situated to offer legitimacy to SG decisions because it already requires members to undertake climate mitigation. SG decisions could be integrated into climate change policy, rather than potentially distracting from climate mitigation. In contrast, SG decisions made by a clique of powerful nations, or under a multilateral regime focused solely on SG, would more likely be perceived as an effort to shirk responsibility for climate change mitigation.

The climate change regime need not engage in every SG governance decision in order to confer legitimacy. Decisions regarding specific requirements for risk assessment, for example, could be delegated to a body that incorporates technical experts as well as political representatives. And decisions regarding coordination of research efforts might be left to a subset of nations interested in engaging in such research.

Indeed, the climate change regime would seem to be an unattractive venue for governance decisions that require relatively prompt action. While one might imagine a COP decision expressing opposition to unilateral SG deployment, the climate change regime lacks the decision making capacity and enforcement mechanisms to respond quickly and forcefully to such deployment if it actually were to occur. In such a scenario, the UN Security Council[2] or some other institution might be better equipped to respond.

Similarly, while the climate change regime has established universal commitments for each nation to undertake mitigation and to report on its progress in doing so, the regime is ill-suited to impose uniform requirements on member states. Over time, the regime has moved towards decentralization and differentiation, as the largely binary approach of the Kyoto Protocol (reflecting a divide between developed and developing countries) has given way to a differentiated approach in which individual nations enjoy broad discretion in spelling out their nationally determined contributions. Luckily, SG governance generally does not require uniform actions by states. However, it would ideally involve universal agreement – or at least consensus – on fundamental questions such as whether to proceed with large-scale field experimentation or deployment.

For now, the climate change regime might focus on the more straightforward task of promoting transparency by facilitating discussions on SG and SG governance. The Paris Agreement's pledge-and-review process offers an important precedent on transparency with respect to countries' mitigation actions. For SG, the global stocktake – as part of assessing the international community's progress towards the Paris Agreement's ultimate objective – could serve as a mechanism for gathering and disseminating information on SG research and activity and for fostering deliberations on SG and SG governance.[3]

Reference

Academic Working Group on Climate Engineering Governance. 2018. *Governing Solar Radiation Management*. Forum for Climate Engineering Assessment, American University. October. http://ceassessment.org/SRMreport.

2 See also brief by Pasztor in this volume.

3 For further discussion of this possibility, see Academic Working Group on Climate Engineering Governance (2018 38 – 39).

How Geoengineering Can Produce a "Tug-of-War" Over the Climate

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Key points

- Countries may modify global temperatures with solar geoengineering or counter-geoengineering.
- If countries hold different preferences about ideal global temperatures, geoengineering and counter-geoengineering could result in a "tug-of-war," wherein countries waste resources to counteract each other's interventions.
- Sufficiently high inefficiencies may even lead countries to engage in conflict to credibly prevent inefficient intervention.

Introduction

Over the next century, the effects of climate change and its political and economic impacts will be distributed unevenly. In some cases, warmer temperatures may confer geopolitical benefits. As the Arctic melts, proximate countries such as Russia may gain access to oil and natural gas reserves and strategically important shipping routes (NRC 2015). The development of solar geoengineering and counter-geoengineering, which allow countries to unilaterally alter global temperatures, then raises a salient question: how will countries' divergent preferences affect their climate and security policies in an environment where they can alter global temperatures?

Background

Solar geoengineering lowers temperatures by introducing sulfate aerosol particles into the atmosphere to scatter and reflect sunlight away from the planet (Crutzen 2006). While the technology has not yet been deployed or tested outdoors, it has generated interest and raised concerns among journalists, governments, international organizations, and researchers in the natural and social sciences. The technology's low price and immediate effectiveness have generated concern about *free-driving*, in which a country with extreme preferences acts unilaterally to cool the entire planet (Weitzman 2015). Given these concerns, journalists and academics are now considering the possibility that countries that prefer warmer temperatures may employ counter-geoengineering responses to disable or *neutralize* geoengineering or to *counter* its effects with short-lived warming agents. Beyond effects on global temperature, solar geoengineering generates two additional externalities. First, it may disrupt hydrological cycles, precipitating famine in African and Asian countries that grow monsoon crops. Second, because solar geoengineering masks the temperature effects of climate change, it may prompt some countries to reduce emissions-mitigation efforts, imposing further damages on countries that are vulnerable to the non-temperature effects of climate change (e.g., ocean acidification).

Counter-geoengineering and security

Concern about potential externalities has prompted political economists to write extensively about governing solar geoengineering. In a working paper (Bas and Mahajan 2018), we extend existing work by studying foreign policy in an environment where states can deploy counter-geoengineering and engage in conflict, and where states are unable to perfectly monitor whether others have altered global temperatures. Our efforts to extensively model interactions between states and test them empirically lead to three key insights.

Counter-geoengineering may produce highly inefficient outcomes

We rely on a game-theoretical model with two countries. Both countries have an ideal temperature point which may be less than, equal to, or greater than the status-quo (current) temperature before geoengineering or counter-geoengineering. Each country simultaneously chooses how much to geoengineer or counter-geoengineer the status-quo temperature. Such climate interventions are, of course, beneficial for a country, insofar as they bring temperatures closer to its ideal point, but they also entail political and economic cost. We assume that each country's marginal cost of changing global temperatures increases as they continue to intervene. Moreover, one country's temperature modification affects the other, insofar as it moves global temperatures toward (or away from) its ideal temperature point and produces damaging side effects, such as hydrological disruptions and ocean acidification. Countries simultaneously choose how much to deploy geoengineering or counter-geoengineering measures. For simplicity, we first consider deployment in a single period.

If both countries' temperature targets are sufficiently close and fall on the same side of the status quo, then they intervene in the same direction. Because neither country captures the entire benefit of its intervention, each undersupplies its intervention relative to the social optimum. If countries' ideal temperature points are far apart, then countries deploy in opposite directions, engaging in an inefficient "tug-of-war" in which each expends resources to cancel out part (or all) of the other's intervention. It is easy to imagine this behavior when countries' ideal points fall on opposite sides of the status-quo. But a tug-of-war can also occur when both countries' ideal temperatures fall on the same side of the status quo but are far apart from one another. Returning to the *free-driver* problem, countries that prefer moderate cooling may warm the planet to offset geoengineering actions by a country with extreme cooling preferences. Deployment in opposite directions is inefficient, as countries could achieve the same temperature by reducing their interventions. However, neither country can credibly commit to such reductions.

Inefficiencies from the tug-of-war may generate conflict

Next, suppose that countries can engage in conflict prior to deployment. If neither country chooses to fight, then both intervene (as described above). However, if a single country chooses to fight, then conflict ensues. Each country has a given probability of winning the conflict, and the victor single-handedly intervenes while the defeated country loses its capability to do so. Fighting, however, is also costly and inefficient for both countries, as each would prefer to reach the same outcome without fighting. Nonetheless, countries may choose to fight if doing so is *less* inefficient than engaging in a tug-of-war by intervening in opposite directions.

Cooperation and imperfect monitoring

So far, we have considered only interactions in a single period. When countries engage in repeated interactions over an infinite horizon, they may reach cooperative outcomes that avoid inefficient intervention and conflict. Recall that the potential for inefficient outcomes arises because countries may be unable to commit to limited interventions. Over an infinite horizon, however, countries may sustain cooperation by using the threat of inefficient intervention or conflict as a punishment for violating cooperative agreements. Facing the shadow of future punishments, each country may choose to abide by a cooperative agreement. In an environment with naturally fluctuating temperatures, where neither country can perfectly detect whether the other deployed geoengineering or counter-geoengineering measures, the benefits of abiding by agreements and the costs of failing to do so decrease. As states recognize the potential to flout cooperative agreements with impunity, or if states face reprisals despite adhering to such agreements, sustaining cooperation becomes more challenging.

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Notes on Insights from Other Regimes: Cyber

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Key Points

- With growing attention on solar geoengineering (SG), and growing concern about the collective risks of unilateral SG action, it is important to begin thinking through problems of SG governance, including applying lessons from efforts to establish international regimes in other areas such as nuclear arms control and cyber security.
- The process of establishing inter-state norms for SG can be expected to take decades, and is likely to involve multiple institutions, negotiating arenas, and "norm entrepreneurs."
- A loosely linked set of norms developed within a "regime complex" may offer less coherence than a hierarchical regime (such as an over-arching UN treaty), but could have important advantages in terms of flexibility and adaptability. Groups of states could develop such norms to guide and constrain research or deployment.

The latest report of the Intergovernmental Panel on Climate Change (IPCC) makes clear that we are falling behind the goals established at Paris in 2015 to manage international climate change (IPCC 2018). While not a substitute for mitigation and adaptation, solar geoengineering (SG) will be increasingly on the agenda. Unlike many collective action problems among sovereign states, SG involves risks related to "free drivers" rather than free riders (Weitzman 2015),[1] and that has made many observers wary of collective risks imposed by unilateral actions of states with advanced capabilities. The free driver problem has led to calls for restraint on unilateral actions, but the current path of inadequate action also poses major risks. It is important to think through problems of governance before deploying SG; to that end, some lessons can be learned from efforts to establish regimes in other areas.

In the area of nuclear energy and weapons, for example, early efforts, such as the Baruch Plan for international control, focused on UN treaties, but that approach was a dead end. In 1957, the International Atomic Energy Agency was created to promote the use of nuclear energy, while keeping it separate from military uses. The first nuclear arms control agreement, the Limited Test Ban Treaty, was not concluded until 1963, and the Non-Proliferation Treaty (NPT), which consolidated the unequal position of the five declared nuclear weapons states, dates to 1968. The NPT was reinforced by an informal nuclear suppliers' group that "interpreted" the treaty in 1978. Bilateral arms control in the form of the SALT treaty did not occur until 1972. In short, the international nuclear non-proliferation regime took more than two decades to develop after

1 See also Weitzman's brief in this volume.

Hiroshima and consisted of a mosaic of normative pieces and practices rather than a single clear treaty (Nye 2011).

Cyber security is another example worth noting (Nye 2018). Security was not a major concern among the small community of researchers and programmers who developed the Internet in the 1970s and 1980s. In 1996, only 36 million people – about one per cent of the world's population – used the Internet. Within two decades, at the beginning of 2017, 3.7 billion people, or nearly half the world's population, used the Internet. As the number of users grew after the late 1990s, the Internet became a vital substrate for economic, social, and political interactions. However, along with rising interdependence came not just economic opportunity, but also vulnerability and insecurity.

Russia first proposed a UN treaty to ban electronic and information weapons in 1998. With China and other members of the Shanghai Cooperation Organization,[2] Russia has continued to push for a broad UN-based treaty. The United States resisted what it saw as an effort to limit American capabilities and continues to view a broad treaty as unverifiable and deceptive. Instead, fifteen states agreed to a Russian proposal that the UN Secretary General should appoint a group of governmental experts (GGE).[3] Initially the GGE, which first met in 2004, produced meager results, but gradually its members agreed to support a wider process of defining norms for state behavior, while also embarking on concrete discussions about confidence-building measures. GGE-issued reports in 2010, 2013, and 2015 helped set the negotiating agenda for cyber security. In July 2015, the GGE proposed a set of norms that was later endorsed by the G20 (GGE 2015). Expert committees are not uncommon in the UN process, but only rarely does their work rise from the basement of the UN to being recognized at a summit of the world's twenty most powerful states. The success of the GGE was unusual, but the group failed to agree on a new report in 2017.

Despite its initial success, the GGE had inherent limitations. Its participants were technically advisers to the UN Secretary General rather than fully empowered national negotiators, and although their number increased from the original 15 to 20 and then to 25, most nations did not have a voice. By 2017, some 70 countries had expressed interest in participating. But as the group expanded, it had more trouble reaching agreement, and extraneous political considerations weighed more heavily in its deliberations.

One can draw a few modest conclusions and projections from these early efforts to develop a regime of normative constraints on cyber conflict:

Time – The process of developing inter-state norms for cyber security is consistent with the time (two decades) that it took for states to develop norms and cooperation in dealing with the disruptive technology of nuclear weapons. While we should think in terms of decades, we

2 http://eng.sectsco.org

3 The full name of the group is the United Nations Group of Governmental Experts on Developments in the Field of Information and Telecommunications in the Context of International Security; www.un.org/disarmament/topics/informationsecurity.

should be alert to events, social processes, and technological surprises that could speed up the process – as a hypothetical example, growing popular opposition to SG (in this case). Moreover, the involvement of multiple stakeholders in negotiations, in addition to governments, may broaden public interest and help to accelerate the process, at least in non-authoritarian states.

Norm entrepreneurship – Norms can be suggested and developed by a variety of entrepreneurs. For instance, a new norm entrepreneur, the non-governmental Global Commission on Stability in Cyberspace[4] was announced by the Dutch foreign minister at the 2017 Munich Security Conference; it is chaired by former Estonian foreign minister Marina Kaljurand. The Chinese government, using its Wuzhen World Internet Conference series, has issued principles endorsed by the Shanghai Cooperation Organization that call for recognizing the rights of sovereign states to control content on the Internet in their territory. Brazil has established the NETmundial process[5] to promote multi-stakeholder approaches. Other norm entrepreneurs include Microsoft Corporation, which has called for a new Geneva Convention on the Internet. The answer may be to avoid putting too much of a burden on any one institution, such as the GGE. Norms are affected by their institutional homes and, at this stage, many homes may be better than one or none. Progress in some areas need not wait for others.

Coherence – Multiple norm entrepreneurs and multiple negotiating arenas raise questions about the consistency and coherence of the norms that are developed to restrain cyber conflict, but trying to develop a treaty for the broad range of cyberspace issues might turn out to be counter-productive. A loose coupling of issues, such as now exists, permits cooperation among actors in some areas, even as disagreements persist in others. For example, China and the United States can use the Internet for economic cooperation even as they differ on human rights and content control. Countries could cooperate on cybercrime, even while they differ on laws of war or espionage.

The current, loosely linked set of cyber security norms should be seen as a regime complex rather than a coherent hierarchical regime (Nye 2014). What regime complexes lack in coherence, they make up in flexibility and adaptability. Particularly in a domain with extremely volatile technological change, these characteristics help both states and non-state actors adjust to uncertainty. Moreover, they permit the formation of clubs or smaller groupings of like-minded states that can pioneer the development of norms that may be extended to larger groups at a later time. As Keohane and Victor (2011) have noted of the regime complex for climate change, adaptability and flexibility are particularly important in a setting where the most demanding international commitments are interdependent, yet governments vary widely in their interest and ability to implement them.

Some have suggested that the 1967 Outer Space treaty, which reserves the use of outer space for peaceful purposes, could provide a model for a cyber treaty. But technological change has

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4 https://cyberstability.org

5 http://netmundial.org

introduced ambiguities in the outer space domain, and cyberspace (which is anchored in sovereign states) fits poorly with models designed to govern a global commons, such as space or the oceans.

The development of a regime complex may be more robust when linkages are not too tight. Such flexibility would be incompatible with an over-arching UN treaty at this point; there may be more coherent ways to develop linkages among issues and actors. For example, Kleinwächter (2018) has suggested the 1970s Conference on Security and Cooperation in Europe as a model. He proposes a Conference on Security and Cooperation in Cyberspace that would have four different negotiation arenas ("baskets") that could provide a loose coherence.

Of course, the governance of SG will be very different from the governance of nuclear energy or cyber space. The technologies are vastly different, and the political problems almost equally so. The American-University-based Academic Working Group (AWG) on Climate Engineering Governance[6] argues that the current problem of SG governance is to avoid overly-tight shackling of research while simultaneously protecting against recklessly conducted research or deployment. At the research workshop hosted by the Harvard Project on Climate Agreements in September 2018, on which this volume is largely based, Scott Barrett argued for an "SG Club" to create norms rather than negotiate a treaty. Such a group (perhaps not a "club" in the strict sense) would need to include the most capable states, enough additional states for legitimacy, and mutual restraint as a prime motive. At the same meeting, Sikina Jinnah – who has been active in the AWG – emphasized a world commission and a global forum for stakeholder dialogue, as well as linkage to existing institutions, such as the IPCC and regional organizations.[7] Many models can be proposed, but examining different models and lessons from other issue areas is increasingly important as the need for SG governance grows more urgent.

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The Road to Solar Geoengineering Governance

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Key Points

- Perhaps the most important up-front solar-geoengineering (SG) governance issues relate to how decisions on SG deployment might be made, or whether to even consider SG as a potential tool. There need to be incentives for research looking into risks, potential benefits, and governance requirements of SG.
- Other key challenges include issues around liability and compensation in case of unequal outcomes, and long-term institutional guarantees against premature termination.
- The Carnegie Climate Geoengineering Governance Initiative (C2G2) has adopted a three-step approach to fostering consideration of SG: 1. highlighting the urgency of these issues to major players 2. learning more about the risks and potential benefits, and how to govern them, and 3. encouraging national and international fora to set rules on how to proceed in a safe and considered manner.
- The goal is to catalyze a global learning process, to enable intergovernmental decision making on whether or not to make use of these technologies, and if so, how. Ultimately, it is likely the UN General Assembly will need to be involved in this process.

In October 2018, the Intergovernmental Panel on Climate Change issued its Special Report on Global Warming (SR15) with a dramatic headline: limiting temperature rise to 1.5°C "would require rapid, far-reaching and unprecedented changes in all aspects of society." This stark message has prompted growing questions about what approaches – in addition to massive emission cuts and carbon dioxide removal – might be available to avert crisis: including the possibility of solar geoengineering (SG).

Over the past two years, my colleagues and I at the Carnegie Climate Geoengineering Governance Initiative (C2G2) have traveled the world alerting policymakers that the conversation may start to shift in this direction, and that if it does, governance must take center stage. A growing number now feel the time for this discussion has arrived. When I mentioned our work to the ambassador for climate change at the Global Climate Action Summit in San Francisco in September 2018, she said: "Finally somebody is dealing with this issue." But many of our interlocutors have been reluctant to say this in the open. One senior EU country official – while agreeing with our approach – told me that talking about geoengineering outside the room would amount to career suicide.

In the wake of SR15, we at C2G2 expect that increasing numbers of practitioners will consider these ideas. But currently, the international community does not know nearly enough about the risks, costs, and potential benefits of proposed SG methods, or their governance requirements, to understand if they could be effective, and – if so – whether, when, or how to deploy them.

One immediate challenge is the governance of *research* on SG, which is already taking place. Research governance could include codes of conduct, and safeguards to ensure research does not automatically head down a slippery slope towards testing and deployment. In the longer term, if SG technologies were ever deployed, they could create large and potentially long-term transboundary risks and challenges, which would need to be addressed in multiple existing international fora, and potentially new ones.

Perhaps the most important up-front governance issues relate to how decisions about deployment might be made, or whether to even consider SG as a potential tool. There need to be incentives for research looking into risks, potential benefits, and governance requirements of SG.

Other key challenges include issues around liability and compensation in case of unequal outcomes, and long-term institutional guarantees against premature termination. These are dramatically difficult tasks, not made easier by multiplying challenges to the multilateral rules-based order.

We at C2G2 have adopted a three-step approach to fostering consideration of SG: 1. highlighting the urgency of these issues to major players 2. learning more about the risks and potential benefits, and how to govern them, and 3. encouraging national and international fora to set rules on how to proceed in a safe and considered manner.

CATALYZE

- Bring issue to governments, international organizations, civil society
- Highlight urgency and risks

LEARN

- Understand better the risks and potential benefits
- Develop governance and monitoring frameworks

DECIDE

- National, international fora agree to rules and guardrails to prevent hasty, unilateral, ungoverned deployment
- Decide whether to deploy or not

So far, we see significant progress in raising the issue up the agenda and growing momentum towards learning more about governance, but limited progress in terms of specific decisions. This is about as much as we might have expected at this stage.

C2G2 has engaged extensively with national governments and international organisations, and find many doors opening to us at department-head or ministerial levels. We have also briefed many leading civil society and faith groups, some of whom see this as one of the great emerging challenges of our time.

SR15 itself contained more on SG governance than we had expected. The UN Environment Programme (UNEP) will now include a chapter on SG in its annual Frontiers Report,[1] which we are helping to prepare. We are working with the Convention on Biological Diversity to develop a research agenda to inform future decisions. We were invited to the inaugural meeting of the Paris Peace Forum,[2] a major new initiative by the French government to defend the multilateral order.

Perhaps most encouragingly, following considerable country-level engagement by C2G2, several governments – led by Switzerland – have decided to promote a resolution at the fourth session of the UN Environment Assembly in Nairobi in March 2019, which, if adopted, would mandate UNEP to undertake a major state-of-play assessment of large-scale carbon removal and SG, for consideration in the subsequent session.

We have also been active in China – a highly significant country when it comes to addressing climate change. Our meeting with a senior government official responsible for climate change has led to the consideration of this issue by senior officials in a number of departments, and I was invited in October to present at a session on ecological civilization at the Taihu World Cultural Forum[3] in Beijing.

In the United States, we played a behind the scenes role ahead of the Global Climate Action Summit[4] in California, by engaging with the Governor of California on the possibilities for state-level action on governance. When I briefed him on the stated need to remove excess carbon dioxide already in the atmosphere, he responded: "Why isn't anybody talking about this?"

On an individual level, we have been engaging with several selected global leaders, who have agreed to use their influence to promote a society-wide conversation. Meanwhile, our Advisory Group[5] has continued to grow in diversity and stature.

None of these developments on their own mark a breakthrough, but in aggregate we can see the beginnings of a global policy conversation start to take shape. Compared to even one year ago, we have seen geoengineering governance broadening out from a relatively niche academic debate to an issue that could soon emerge on the agenda of several intergovernmental processes and international organisations. In the coming years, we plan to raise its profile even higher, and bring it to the agendas of many other organisations, following their respective mandates and areas of work.

1 The 2017 Report is at: http://wedocs.unep.org/handle/20.500.11822/22255.

2 https://parispeaceforum.org

3 http://www.thffc.com

4 https://www.globalclimateactionsummit.org

5 https://www.c2g2.net/c2g2-advisory-group

The goal is to catalyze a global learning process, to enable intergovernmental decision making on whether or not to make use of these technologies, and if so, how. Ultimately – and this is key for the governance of SG – we assume that some level of consideration will need to take place at the UN General Assembly (UNGA). UNGA is the global body with the most legitimacy to address these issues, and our goal is to catalyze UNGA consideration by 2022. Is this too ambitious? Perhaps, but judging by the events of the past year, this conversation may advance more rapidly than we now imagine.

Monitoring and Verifying the Deployment of Solar Geoengineering

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Key Points

- Architectures for collecting and sharing information that enable states to monitor each other's solar geoengineering (SG) activities are crucial to address concerns about SG governance and to promote cooperative approaches to SG deployment.

- One model for such an architecture might be the Comprehensive Nuclear-Test-Ban Treaty, which relies on a well-developed network of monitoring stations that can detect and attribute responsibility for nuclear tests all over the world.

- Public confidence in the integrity and validity of the data collected by an SG monitoring and detection system will be critical; in addition, a trusted-third-party authority or new decentralized information-sharing protocols will be needed to collect, certify, and disseminate these data to stakeholders.

The governance challenges of solar geoengineering (SG) deployment raise important questions about what architectures of information collection and sharing would be necessary for states to address the legitimacy, efficiency, and security concerns associated with large-scale alterations of the earth's radiative balance.

Bas and Mahajan (2018) recently argued that cooperation in SG deployment strongly depends on states' ability to monitor each other's deployment. The absence of monitoring capabilities would therefore be a major barrier to cooperation, and lack of cooperation would result in inefficient deployment and possible undesirable consequences.[1] It would be preferable if states interested in SG deployment sought to develop means of timely detection and observation of SG actions by other states well before deployment begins. This would increase the chances of reaching a cooperative outcome, and avoid potentially dangerous conflict. The same is true for states that would consider SG undesirable, and therefore favor enforcing a moratorium on deployment.

Measurements of global average temperature alone would not satisfy the need for timely detection and monitoring of deployment actions, because it would take years to detect the effects of SG with high confidence (Lo *et. al*, 2016). Therefore the development of new *in-situ*, ground-based, and possibly space-based observation and measurement assets would be required in the years preceding deployment (Smith *et al*. 2010).

1 See brief by Scott Barrett in this volume.

This brief discusses a possible architecture of information collection and sharing for governing SG deployment, based on an existing model used in the governance of nuclear weapons testing. Such an architecture could help address three fundamental governance challenges: (1) the ability to observe and monitor local densities of aerosols in regions of interest, possibly covering the whole atmosphere, to facilitate cooperative action; (2) the ability to quickly detect and attribute unilateral SG actions; and (3) the ability to detect and deter the use of harmful or proscribed SG methods.

Designing an architecture for monitoring and verifying SG deployment

An architecture for monitoring SG deployment could be based on models from regimes that require the use of wide-area environmental detection methods to verify state compliance. A particularly relevant example is the Comprehensive Nuclear-Test-Ban Treaty (CTBT), which seeks to establish a global prohibition on nuclear weapons testing in the atmosphere, underwater, and underground.

The CTBT has a particularly well-developed information collection and sharing structure. It is supported by the International Monitoring System (IMS), a network of seismic, infrasound, hydroacoustic, and radionuclide monitoring stations run by member states that provides capability for detecting and attributing nuclear tests all over the world (Preparatory Commission for the CTBTO 2018). In cases where the data indicate a possible nuclear explosion but are inconclusive, the treaty provides for an on-site inspection mechanism: a defined area is searched and additional evidence is gathered to rule on whether or not a nuclear explosion has taken place. Surprisingly, the IMS is functional even though the CTBT has not yet entered into force.

In practice, data acquired by IMS stations are transferred continuously to the CTBT organization's International Data Center in Vienna for storage and analysis, and are openly shared with member states. These data are not directly available to the public, however. The overlapping coverage of stations operated by different states allows for cross-correlation and independent verification of the information collected. This architecture is also robust in the sense that states that have not joined or that decide to leave the treaty in the future would still be monitored. For example, IMS data have been used to assess all North Korean nuclear tests, despite the fact that North Korea is not a party to the CTBT.

In addition to this multilateral detection capability, some countries also deploy so-called national technical means of detection. For example, the United States operates space-based sensors placed on U.S. Global Positioning Systems (GPS) satellites that can detect optical, electromagnetic, and x-ray signals from nuclear explosions in space, as well as special-purpose aircraft to collect samples from the atmosphere to detect and identify nuclear explosions. This dual architecture of national and international technical means of detection could also emerge for SG governance. The states that may be most interested in SG deployment are likely to seek national means of observing aerosol concentrations in the atmosphere, not only to guide their own deployment actions but also to respond to other states' possible deployment activities. Implementing these monitoring capabilities could require significant financial resources and access to technologies, and it is not clear that global coverage could be achieved by a single state.

The detection and attribution of unilateral action will require a monitoring system that is capable of locating injection points, perhaps by using a combination of aerosol concentration measurements and atmospheric transport modeling. Assuming that the cheapest and easiest mode of injection is via direct releases to the atmosphere from airplanes (Smith *et al*. 2018), techniques for attribution could be based on correlating the location of injection points (if they can be determined) with radar and transponder information about the past positions of identified or unidentified aircraft. One interesting question is whether particular environmental conditions at the time of injection, combined with knowledge of the different injection processes involved, could constitute a unique forensic signature for attribution. If so, an inspection mechanism may be required to compare samples taken *in-situ* in the atmosphere to samples retrieved from incriminated airplanes, if they can be detected and accessed.

Conclusion

The sharing of monitoring and verification capabilities could provide important benefits for SG governance: it could reduce costs associated with data acquisition, and it could provide public and trusted information for coordinating deployment, or for enforcing a moratorium. One can imagine a state having sufficient resources to deploy SG but no access to space for deploying monitoring equipment with sufficient coverage. Because the atmosphere is a global public good, it also seems fundamental that any information related to large-scale alterations of the atmosphere should be made public.

An important attribute for transnational information acquisition and sharing systems is the ability to demonstrate that the data collected by various sensors or sources are genuine and can be trusted by all participating states. For sensors, existing tamper-resistant hardware and public-key cryptographic protocols, such as those used, for example, by the CTBT-IMS stations, are sufficient if a recognized centralized body can establish secure communications with all sensors in the network. Absent a trusted third party – or central authority – to certify information, however, new, decentralized information-sharing protocols would need to be developed to efficiently collect, record, and share data that can be trusted by all relevant stakeholders.

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Is There Nothing New Under the Sun? Analogs for the Governance of Solar Geoengineering

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Key Points:

- Although solar geoengineering is sometimes characterized as unprecedented in ways that would cause its governance to be very difficult, if not impossible, it is not *sui generis* in its core challenging aspects.
- Humanity has governed technologies and socio-economic phenomena – such as international monetary policy, nuclear technologies, activities in outer space, and food, energy, and water systems – that have similar characteristics.
- These imply that governance of solar geoengineering deployment is feasible; that facilitative international institutions, limited international cooperation, side payments, coercion, and norms could achieve modest aims; and that participation of key states will be essential.
- After a decade of much talk yet little research, belated and suboptimal solar geoengineering is an increasingly salient hazard.

Solar geoengineering is sometimes characterized as unprecedented in ways that would cause its governance to be very difficult, if not impossible. For example, geographer Mike Hulme writes that "world agreement on the desirable temperature setting is unattainable, and the mere attempt to reach such agreement is likely to unsettle international relations" and from this concludes that it would be "ungovernable." (Hulme 2014, p. xiii) These observers often point further to solar geoengineering's unduly technocratic character, possible premature or excessive deployment, and the need to maintain it for long time scales to prevent a "termination shock" caused by sudden and sustained cessation.

In some ways, solar geoengineering would indeed be novel. It could give states or – in principle – even nonstate actors the power to dramatically affect environmental conditions across the entire globe. However, in its core aspects that critics cite – international (dis)agreement, technocratic complexity, possible premature or excessive implementation, and long-term maintenance – solar geoengineering is not *sui generis*. Humanity has governed technologies and socio-economic phenomena with similar characteristics with some degrees of success. Here, I briefly describe four examples and offer lessons that can be drawn from them.

States' leaders regularly act in ways that they know will have substantial impacts on other states. In general, such actions are not prohibited but instead managed through diverse governance arrangements. This is evident in the case of *international monetary policy*. Like climate, countries' economies are complex, imperfectly understood, and important to their citizens' well-being. Typically, political leaders set low-resolution objectives – such as maximum sustainable employment and stable prices – toward which appointed experts strive via various technical tools. These measures affect other states' economies in fairly predictable ways, sometimes negatively so. States are highly asymmetrical in their capacities for international economic influence, and one of them could use monetary policy as a means to intentionally harm another, at least hypothetically. But this appears to not occur, probably because such efforts would be poorly targeted and have unacceptable collateral impacts. Furthermore, the lack of centralized international decision-making in monetary policy is notable. The most important institution – the International Monetary Fund (IMF) – neither sets global monetary policy nor constrains that of its members (apart from conditions on loans). Instead, it monitors economic conditions, conducts research, provides a forum for sharing information, offers advice, helps build capacity, and responds to crises.

Nuclear technologies constitute perhaps the most frequently suggested analogy for solar geoengineering. This is understandable. Some applications of each (nuclear power and solar geoengineering research) should arguably be promoted, while others (nuclear weapons and solar geoengineering deployment) might be warranted in *extremis* but could be harmfully used prematurely or in ways contrary to global norms. Nonproliferation of nuclear weapons has been reasonably effective, in large part through a facilitative international organization, the International Atomic Energy Agency (IAEA); side payments of assistance in developing nuclear power; the emergence, socialization, and internalization of norms; an acceptance of some states' weapon capacities; and coercion by great powers of weaker states. Liability for transboundary harm from nuclear power accidents has also furthered its responsible development. Yet four states have acquired nuclear weapons outside the Nonproliferation Treaty's bounds, indicating limits to what international cooperation, side payments, coercion, and norms can accomplish when essential security interests are at stake.

Another domain in which a select set of powerful countries could use high-leverage technologies to affect others is *activities in outer space*. When these began in the 1960s, some observers expressed fears that the superpowers would use space as a platform to reinforce their supremacy. Multilateral agreements with modest aims were able to prevent weapons of mass destruction in space, establish liability for harm, and coordinate satellite-based radionavigation systems. Furthermore, joint activities regarding the International Space Station contributed to the thawing of the Cold War. However, a treaty that prohibits the exploration and use of the moon and other celestial bodies without the international community's approval failed to attract the participation of the key countries with space programs.

Although the need to maintain solar geoengineering post-deployment is a serious concern, modern societies rely on the continued operation of multiple complex systems, most obviously those of *food, energy, and* – in some locations – *water*. If one of these systems were to become and remain inoperative, the consequences would be grave. Nevertheless, both lay and elite observers seem confident that these systems are sufficiently maintained, secure, redundant, and resilient.

This is not to belittle possible vulnerabilities, which have become evident in the past and should be expeditiously identified and addressed. Instead, my purpose is to highlight that long-term maintenance of complex international systems is not qualitatively new and has been successful.

Such technologies and socio-economic phenomena offer some guidance for solar geoengineering deployment. First, its governance – including maintaining it for long time scales – is not as unprecedented as it might seem and is arguably feasible. Second, governance's objectives should be modest. It could include an international institution that is widely perceived as legitimate with functions like those of the IMF and the IAEA as well as a (likely informal) mechanism through which norms of restraint and nonpractice could develop.

Third, participation of key states is essential. A proposed agreement to prohibit solar geoengineering deployment in the absence of international consensus would probably be rejected by the very states most likely to implement it. Instead, an effort to prevent premature and excessive deployment would need to count as participants the most powerful states, which might need to be explicitly granted more authority than others in order to attract them. Additional states with the capacity to deploy – and interest in doing so – might need substantial side payments – such as participation in research, assurances of notification and consultation, and perhaps compensation for demonstrable harm – to bring them into the cooperative fold.

Finally, climate change poses substantial risks, but there is no indication that emissions cuts and adaptation will sufficiently control them. Solar geoengineering has the potential to greatly reduce climate change and does not face the same global collective action problems. Although concerns of premature and excessive deployment have lingered, after a decade of much talk yet little research, belated and suboptimal solar geoengineering is an increasingly salient hazard. Governance should therefore aim to not only reduce risks and manage challenges, but also facilitate solar geoengineering's responsible research, development, and – if appropriate – use.

This essay draws in part from the presentations of Scott Barrett and David Victor at the research workshop on the governance of solar geoengineering deployment at Harvard University in September 2018, on which this volume is partly based.[1] *The author thanks them.*

Reference

Hulme, Mike. 2014. *Can Science Fix Climate Change? A Case against Climate Engineering.* Polity Press. Available in part online: www.researchgate.net/publication/262603723_Can_Science_Fix_Climate_Change_A_Case_Against_Climate_Engineering.

1 These and other presentations may be downloaded here: www.belfercenter.org/publication/harvard-project-conducts-research-workshop-governance-solar-geoengineering. See also briefs by Barrett and Victor in this volume.

Solar Geoengineering and Compensation for Harms

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Key Points

- The recognition that interventions to cool the climate could raise issues of harm and compensation appeared as early as 1974, in a *Science* article by Kellogg and Schneider.
- The concept of a "no-fault climate disaster insurance policy" or "general climate compensation fund" has been put forward as a way to address the uneven distribution of adverse effects from geoengineering, and from climate change more broadly.
- Establishing such a compensation system, however, would raise difficult practical and moral questions: How do we place a value on human life and suffering? And should every person's life (or suffering), everywhere in the world, be valued the same?
- "Using" solar geoengineering as a springboard to establish a general climate compensation fund exacerbates these difficulties because the lines of human agency are much clearer in the case of a deliberate geoengineering intervention.

This brief focuses on a recurring theme in discussions of solar geoengineering: The question of compensation for harms. In a 1974 article in the journal *Science*, William Kellogg and Stephen Schneider contend that "we understand enough about the earth-atmosphere system to recognize that humans can affect it, and surely have already, by pushing on certain 'leverage points' that control the heat balance of the system" (Kellogg and Schneider 1974, p. 1163). Kellogg and Schneider proceed to describe in some detail the possibilities they see for "climate stabilization" and the "hazards" such stabilization measures might pose. They do not use the term geoengineering (which was introduced in 1977), and while some of the ideas they discuss are no longer in circulation, others have stuck – including the idea of creating a "stratospheric dust layer," which is termed solar geoengineering in this volume.

This early contribution foresaw many of the concerns that would come to dominate geoengineering discussions in the scientific community decades later. Kellogg and Schneider discuss potential military applications, the socio-political implications of unevenly distributed effects, the difficulty of determining "[w]ho would decide and who would implement climate modification and control schemes," and the possibility that "perceived climatic cause and effect linkages […] could be used as an excuse for hostility" (p. 1171). In the context of this last concern, they point out that such linkages could never be determined with certainty. But they also offer a possible solution (p. 1170):

"[…] we […] wish to offer one 'modest' proposal, for 'no fault climate disaster insurance.' If a large segment of the world thinks the benefits of a proposed climate modification scheme outweigh the risks, they should be willing to compensate those (possibly even a few of themselves) who lose their favored climate (as defined by past statistics), without much debate as to whether the losers were negatively affected by the scheme or by the natural course of the climate. After all, experts could argue both sides of cause and effect questions and would probably leave reasonable doubts in the public's mind."

This is, to my knowledge, the first time that the question of compensation for harms from geoengineering was raised. Such "no-fault climate disaster insurance" might appear a worthwhile cause, independent of whether or not solar geoengineering enters the equation. A group of ethicists from the University of Oxford seem to take this position, arguing in a 2014 paper that "if compensation is to be provided for [climate-related] harms, it should not be dependent on whether the harms were due to geoengineering, anthropogenic climate change, or other natural climatic events" (Wong *et al*. 2014, p. 19); the authors go on to propose setting up a "general climate compensation fund" to this end. From this perspective, solar geoengineering could be viewed as a welcome opportunity to achieve an outcome that many would consider desirable in any case, albeit difficult to achieve on its own. Leveraging concerns about geoengineering to address climate compensation issues more broadly amounts to asking, "what can solar geoengineering do for us?"

On first encounter, one might consider the concept of such a "general climate compensation fund" to be similar to the idea of distributing adaptation assistance based on development needs and adaptive capacity, rather than basing such assistance on the attribution of extreme weather events to climate change (Hulme 2011). But this overlooks an important difference: Providing adaptation assistance based on needs and capacity is an approach that focuses on building resilience, as opposed to compensating for loss. A solar geoengineering intervention that is built around a system of compensating for loss would send the highly ambiguous signal that such losses are, in principle, accepted by the international community; much like the controversial loss and damage agenda that is emerging in climate politics today.

Compensating for loss also raises questions that are extremely difficult to resolve as practical matters. For example – and this applies to compensation schemes more generally – there are losses for which conventional understanding holds that no monetary value can be given. Of course, there are often situations in practice where precisely this is done. Even human lives are routinely valued in financial terms by the insurance industry. But on a global scale, questions that are difficult to resolve within a single political culture would be intensified: Would all human lives be valued the same? If not, on what basis would differentiation occur and how would this sit with our convictions about what is just? Developing such a system would test not just international diplomacy, but moral commitments to concepts of equality and the value of human life. These debates would raise questions about what are the right forms of solidarity and compassion for our global era.

"Using" solar geoengineering as a springboard to establish a general climate compensation fund would further exacerbate these difficulties. While climate change itself is human-caused, a deliberate solar geoengineering intervention would bear an even greater weight of human agency. Destruction and suffering from an extreme weather event following a solar geoengineering intervention would inevitably raise questions about whether or not such an event would have occurred in a world that had not been "geoengineered" (as Kellogg and Schneider point out: "After all, experts could argue both sides of cause and effect questions…"). And in any case, those who find themselves to be "negatively affected" would, in all likelihood, not simply accept that their suffering was the necessary price to pay for a greater good, even if they are compensated. I do not have a solution to these difficulties; a solution might not exist, and some might not consider these issues to be that problematic in the first place. But reflecting on how some of the courses of action on offer today might strain widely held moral and social values seems a worthwhile enterprise.

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Some Distinctions for Thinking About the Governance of Solar Geoengineering

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Key Points

- When we ask how the deployment of solar geoengineering *should* be governed, what we are doing is attempting to identify a process for deployment that would be *politically legitimate* and expected to lead to *morally acceptable outcomes*.
- Several distinctions are useful in considering legitimacy and the nature of acceptable outcomes:
  - » Both sociological and normative legitimacy might be considered in assessing deployment. The former refers to the degree to which citizens *feel* that a decision-making process has been legitimate; the latter to the inclusiveness of the political process along several dimensions.
  - » Outcome-oriented criteria should go far beyond the criterion of Pareto optimality or model-based social-welfare optimization; they should incorporate various dimensions of justice.
- A final distinction concerns that between ideal and non-ideal (political) theory. This refers to whether all relevant actors are motivated to pursue the ideal approach to – in this case – governance of solar geoengineering deployment. They are, in fact, not so motivated, hence the need for a non-ideal-theory framework.

Looking at the limited range of options available to mitigate the coming climate crisis, it is difficult to escape the conclusion that some form of solar geoengineering will be deployed on a global scale this century. What would an acceptable framework for the governance of the deployment of solar geoengineering look like? What purposes would it serve and what structure would it have? My aim in this brief is to introduce several distinctions that I believe will be essential in framing plausible answers to these questions.

I begin with a familiar picture of the scholarly exercise. On this picture, when we ask how the deployment of solar geoengineering *should* be governed, what we are doing is attempting to identify a process for deployment that would be *politically legitimate* and expected to lead to *morally acceptable outcomes*. If this is our aim, then we need to think carefully about the most appropriate criteria for both of these concepts.

The first step is to remember the limited significance of bare *sociological legitimacy*. This is the degree to which citizens *feel* that a decision-making process has been legitimate. This notion of legitimacy is far from the only one that is of interest. After all, people can feel that a process has been (il)legitimate only because they have been systematically misled, or for other questionable reasons. For example, many Americans believe that the legitimacy of the 2016 U.S. presidential election was tainted because millions of unauthorized immigrants voted illegally. Yet these Americans are simply mistaken. The 2016 election was not illegitimate, at least not for this reason. This example shows that there is an important distinction between bare sociological legitimacy and properly *normative legitimacy*.

Normative legitimacy, in turn, is a function of the inclusiveness of the political process along several dimensions. One dimension is how open the political process is to dissenting voices, the presentation of counter-evidence, attempts to change the agenda, and so on. However, another dimension of inclusiveness is whether the decision-making process at some stage includes everyone who will be affected by the decisions it issues. Once again, this second dimension of inclusiveness is not reducible to the first. Just as one can have an impeccably democratic decision to launch a war on another country that is itself given no say in the matter, so, too, there could be an impeccably democratic decision by a single country to deploy solar geoengineering on a global scale unilaterally. However, other things equal, such a decision would be politically illegitimate in a strong moral sense. This shows that the *multiple dimensions of inclusiveness* internal to the normative concept of political legitimacy are not reducible to one another.

Now, if what we want to know is how the deployment of solar geoengineering ideally should be governed, then we will want to draw parallel distinctions about the moral criteria for evaluating the potential outcomes that a process of deployment could lead to. These *outcome-oriented criteria* should go far beyond the criterion of Pareto optimality, and beyond even the sort of optimality that is at work in climate models that try to optimize a utilitarian social welfare function. In addition, the justifiability of any given framework of environmental policy turns on how the framework takes into account considerations of *social justice, international justice,* and *intergenerational justice*. None of these sets of considerations, moreover, are reducible to the others. As a result, there are real trade-offs to be faced between, for example, the interests in food and energy security of the domestic and the global poor today and the diverse risks to future generations from deploying solar geoengineering. Thinking about the purposes that a governance framework for deployment ideally should advance thus requires thinking about what the relevant outcome-oriented moral criteria are.

However, there is more to the governance challenge than simply reaching clarity on the applicable normative standards. Indeed, a sober look at the political landscape throws into question the practical relevance of the ideal-theoretical exercise. For it is not clear that the public has any well-formed beliefs about the desirability of solar geoengineering. And even if it did, there is no guarantee that the public's preferences would come to be reflected in national laws and policies. In the United States, public policy can remain opposed to the preferences of the large majority of citizens for decades, as the absence of reasonable gun regulations indicates. And of course, elsewhere a third of the world's population continues to live under repressive and often resource-dependent dictatorships. These facts put pressure on the implicit aim of the ideal-theoretic normative exercise: to identify the shape of a legitimate global governance framework, so that "we" can put it in place later.

A sober look at the political landscape suggests that the options for "us" – scholars, scientists, and even most domestic policymakers – are much more limited. To introduce a distinction from political theory, the most urgent questions for us today are ones in so-called *non-ideal theory*. The distinction between ideal and non-ideal theory overlaps with but is distinct from the economist's idea that we need a separate theory of the second-best. The distinction turns instead on whether every relevant actor is *motivated* to pursue what would (then) be the ideal. Thus, we are operating in ideal theory whenever we ask ourselves questions of the following kind: what sort of rules for solar geoengineering should we put in place, assuming every powerful actor in the world is motivated to put in place whatever governance framework all of us together should?

By contrast, we have shifted to non-ideal theory once we recognize that *not* everyone in the world is motivated to do what would (then) be best, and that some recalcitrant actors have the economic and political power to block desirable reform efforts. Once we are operating in this mode, we face an altogether different set of worries, distinct from collective action problems that can arise even on the assumption that everyone is morally well-motivated. To my mind, the most important background fact in this regard is that the global energy transition – no matter how it happens – will represent a massive expropriation of fossil fuel interests. Understandably, the fossil fuel interests have been attempting to stall this transition through massive lobbying and propaganda for decades, with astonishing success. There is no reason to expect these efforts to stop when frameworks for governing the deployment of solar geoengineering are put on the table for discussion.

On the contrary, just as the existing infrastructure for directly capturing carbon dioxide from the air overwhelmingly reflects the commercial interests of the natural gas producers, so, too, we can expect that fossil fuel interests will use their considerable resources to shape any future framework for deploying solar geoengineering in their image. What will that image be? And what ought to be the countervailing political strategy of people who are well-meaning? These are the central questions of non-ideal theory.

Public Perceptions of Solar Geoengineering with Implications for Governance

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Key Points

- Solar geoengineering is relatively unfamiliar to members of the public. Generally there is support for research on this technology.
- Low familiarity and lack of clear guidance from academic or political actors opens up room for conspiratorial messages. This can have substantial consequences for governance.
- Preferences over modes of governance (e.g., unilateral versus multilateral) are likely to parallel preferences for modes of governance in other issue areas (e.g., foreign aid).
- "Bottom up" approaches to solar geoengineering (e.g., designing cities to reflect more sunlight) may help to tether discourse around other solar geoengineering technologies.

In considering public perceptions of solar geoengineering, it is helpful to start with some fundamentals. First, very few people know about solar geoengineering and related technologies to begin with. A nationally representative survey in the United States in 2016 had approximately 20% saying they were somewhat or very familiar with geoengineering (Mahajan, Tingley, and Wagner, forthcoming). In 2018 this was around 30%. Both numbers are probably biased up slightly in that people will often say they are more familiar with something than they actually are. This unfamiliarity leaves open the possibility that various elites – in and out of government – will be able to drive the narrative around the topic.

Second, it is important to think about what types of public perceptions could be consequential for solar geoengineering governance. In the short term, views about doing basic research will be important. The polling I have done shows substantial support for research. But at some point there might be field experiments that will attract some degree of public attention that would lead to demands for various governance configurations. Public perceptions around the use of geoengineering, and implications for governance, are a bit harder to probe, as the exact conditions around usage (did it work? what were the side effects? who did it? etc.) are so multidimensional that it is hard gauge how such perceptions will have implications for governance. Intellectual property considerations will be an interesting area to track. An easy question for the public to ask is whether individuals and firms should be able to patent technologies for the modification of the global climate. I suspect there will be some debate about this issue as the technology matures.

In light of low familiarity by members of the public and clear social and political questions, a natural question then is: who will fill the void? Groups of academics and non-governmental organizations will be one source of information about the topic. Indeed, contributors to this volume speak to this approach. And various advisory bodies, such as the National Academies, have started to explore the issue. Formal political actors may step in, though it is not at all clear why elected officials would want to take on the topic in the foreseeable future.

Unfortunately, a more conspiratorial community has emerged that threatens to fill the void. On social media, such as Twitter, the large majority of discussions about geoengineering relates to "Chemtrails" (Tingley and Wagner 2017). This conspiracy theory posits that governments and other actors are actively spraying chemicals into the atmosphere for a variety of purposes, including weather modification – the provided evidence being the "contrails" (white streaks of water vapor) left behind airplanes. "Just look up!" – leading academics exploring solar geoengineering have been harassed online by those promulgating this conspiracy theory. The implications for governance should not be underestimated. Conspiracy theories like this one have the ability to distort otherwise rational conversations and debates about complicated topics such as solar geoengineering. This could have implications for governance. Indeed, I and some students have explored alternative platforms for debating the topic that avoid the many limitations of platforms such as Twitter (Bose, Ojo, Tingley 2018).

Taking a step back, I think it useful to surface what we know about public preferences around governance in other issue areas. For example, in the study of foreign aid there are clear divisions between liberals and conservatives on whether foreign aid should be delivered through multilateral or bilateral institutions. Conservatives tend to prefer bilateral aid, in large part because it gives them greater control over the aid. Liberals prefer multilateral institutions. The same patterns exist when members of the U.S. public are asked about governance of solar geoengineering. In light of the low familiarity people have with the topic, it is likely that heuristics drawn from other issue areas will be applied. This highlights the potential politics of "who governs".

Unpacking the question of "who governs" also highlights the role of sub-national actors. I predict the role of sub-national actors, including cities, will be very important. Just as we are seeing around climate change, sub-national actors may take up work on solar geoengineering for more local purposes. While solar geoengineering using airborne deployment will be difficult to work for localized areas – and maybe something to be avoided anyway, due to this making weaponization possible – other forms are already being explored. Such "bottom up" solar geoengineering (Harrison 2018) focuses on reflecting sunlight directly at the surface level. While these approaches have been around for a while – "white tops rather than black tops" – it highlights a more important point: If members of the public come to understand solar geoengineering via a range of technologies, including innocuous ones to reduce urban heat traps, then this type of issue linkage could help foster reasonable conversations about other forms of solar geoengineering. This is because "reflection" from white-topped buildings is easy to understand – "accessible." Without these more accessible notions of solar geoengineering, public perceptions of the technology could be more untethered and easy to manipulate, which has implications for the demand for regulation and governance more generally.

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Governing the Deployment of Geoengineering: Institutions, Preparedness, and the Problem of Rogue Actors

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Key Points

- The probability of deployment of solar geoengineering systems is rising.
- The most practical and effective governance systems will depend on the scenario for deployment. The greatest difficulties for governance will arise if countries attempt to deploy a globally coordinated geoengineering system, because it is highly likely that countries will not agree on the best goals and strategies for deployment.
- Unilateral deployment is much more likely than coordinated deployment, with the greatest likelihood of unilateral deployment from governments whose leaders have a fragile hold on power and face public demands to address perceived climate emergencies.
- International cooperation in response to unilateral action is likely to emerge quickly, because non-deploying countries will be exposed to harmful side-effects from poorly deployed geoengineering systems or abrupt termination of those systems.

For too long, discussions about how to govern geoengineering have remained a few steps removed from what most people think is the real governing need: deployment. Instead, a great deal has been written about governing research, partly in the hope that good governance of research will create norms that will spill over into good governance of deployment. And while a great deal has been written about the *need* to govern deployment, most discussion of this issue has been quite abstract, as the technologies and scenarios for deployment remain unknown.

It is time to become more specific and to grapple with how deployment might be governed. I do not advocate deployment, and I do advocate a research-driven effort to create norms and standards for good behavior. But when planning for governance, it is important to recognize that the world might not wait for a thoughtful, norm-driven process of geoengineering research that carefully lays the foundation for governing deployment. Indeed, the more that western countries insist that governance be in place before deployment occurs, the higher the odds that deployment will occur without a system of governance to deal with the consequences.

The kind of governance needed for deployment depends on the scenario for deployment. As figure 1 shows, in stylized terms, it is possible to imagine three broad kinds of deployment:

One, shown at the top, involves some kind of widely recognized climate "emergency," in which countries agree that extreme responses (including geoengineering) are needed. In that scenario, governance is needed for purposes such as agreeing that geoengineering should be launched, deciding how to share costs, and managing possible side-effects.

In the middle is a weaker variant of the same motivating force: for example, a regional climate emergency (e.g., the Himalayan monsoons fail, affecting the welfare of the whole of southeast Asia and western China). That scenario may give rise to similar governance needs, along with the extra task of managing conflicts between countries that wish to deploy geoengineering and those who oppose action – a task that might require demonstrating that a regional scheme has few risks for others and will be constrained, if possible, to generating regional benefits.

Finally, at the bottom, is the scenario of unilateral action. In that case, governance issues may be largely moot, because the geoengineering country (or individual "greenfinger") is governing itself – without international cost sharing or oversight. A country that undertakes deployment may need to convince others that this unilateral action is less harmful than imagined, while countries opposed to geoengineering might have governance needs of their own: to launch disputes or other more aggressive actions against the deploying country, to manage side-effects, and to avoid even worse outcomes, such as the climate shock if geoengineering operations are suddenly terminated.

My point is that the institution(s) that would be mobilized for governance and the functions they perform will vary enormously depending on the scenario in which deployment occurs.[1] The global social value of deploying geoengineering is highest for the scenario at the top of Figure 1. And when most scholars and policy makers advocate for establishing a governance scheme before deployment is contemplated, this is the kind of scenario they envision. The problem is that the need for widespread agreement in this scenario almost guarantees that efforts to create effective institutions in the first place will fail. Thus the need for deployment governance must be analyzed alongside the likelihood that the first-best scenario for governance is the least likely to occur.

1 Many other factors probably also create variation in institutional needs – for example, the geoengineering technology being deployed. A governing regime for stratospheric aerosol injection is probably different from one that relies on marine cloud brightening, in part because costs, side-effects, and vehicles for deployment will vary. For example, countries opposed to geoengineering will have many more options for halting deployment operations when these operations involve ships using the high seas, which can be interdicted, and when the ships must travel through territorial waters between deployments.

At least four implications follow from this logic:

First, it is important to understand the likelihood and character of unilateral deployment. This kind of deployment may be coupled with what arms-control experts call breakout – the development, in stealth, of capabilities that can be sprung on the world with little notice, making them hard to reverse. I think the probability of the other scenarios in the figure – an acute regional emergency or an imagined local emergency – is much higher than widely appreciated. Indeed, the basic science of climate impacts is increasingly focused on risks of extreme impacts – outcomes that, real or perceived, may be seen politically as catastrophes that demand prompt response.

That is a world in which publics will demand action, and leaders will want to show they are responsive. A leader with fragile public support and few restraints on power may look to the short-term gains from unilateral deployment: being seen as taking action, and possibly even succeeding in ameliorating climate-change impacts. Leaders who are more secure in power – or political systems that have strong parties and other institutions – may be less likely to undertake unilateral actions because they are more concerned with long-term impacts and with protecting their relations with other countries. More analytical work is needed to explore how the logic of political survival intersects with the logic of unilateral geoengineering.

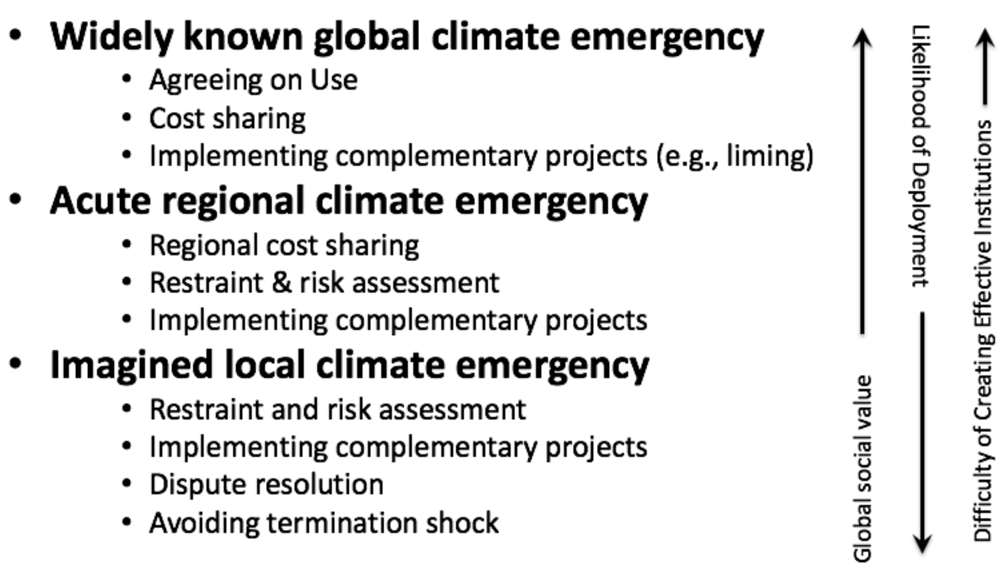
Second, because unilateral action is more likely than imagined, I suspect that "greenfinger" scenarios – that is, scenarios where wealthy, capable, do-gooder actors pursue deployment – are also more likely. As wealth accumulates in highly concentrated ways, and the super-wealthy come to imagine that they are super-intelligent, it seems more likely that rich people who think they know best will find governments that would welcome a political boost from rich friends. Historically, governments have often turned conspicuously to outsiders for intellectual and financial help (and turned to other outsiders for conspicuous enemies). The greenfinger scenario is simply a modern variant of that age-old logic.

Third, we in the analyst community should look more closely at the tradeoffs between the first-best scenarios, which involve global, multilateral action (the top of figure 1), and the more probable but much less ideal scenarios for unilateral regional or local action. We should articulate the relationship between the political difficulties of achieving first-best outcomes and the probability (and relative welfare loss) of worse outcomes. This exercise could help inform the kinds of voting rules, and the need to avoid deadlock, that should be considered in setting up first-best institutions. Martin Weitzman's brief in this volume discusses possible voting rules, and his analysis, while stylized, could readily be extended to incorporate the common interest in avoiding worst-case outcomes. All else equal, such rules will lead to institutions that are more prone toward agreement. Whether those institutions can be established in the real world is also a subject that needs some attention.

Fourth, if unilateral action on geoengineering is more likely, then countries that are highly unlikely to take such action – i.e., the consolidated democracies of the west – should look at the institutions they might create to get ready. The role of these institutions might be to share information on possible breakouts and wargame those options. Most intriguing and valuable for this group of countries could be to develop counter-geoengineering technologies. Some countermeasures might be simple (e.g., injecting potent short-lived greenhouse gases into the atmosphere). More valuable and probably less risky would be options that directly counter a unilateral geoengineering action—for example, catalysts that could scrub aerosols from the stratosphere or bots that could destroy geoengineering delivery vehicles.

For too long, the discussion of geoengineering governance has involved too much imagination about governing institutions and not enough attention to the incentives for countries to build such institutions. A focus on incentives may suggest that it will be impossible to gain truly global support for institutions that can effectively restrain unilateral geoengineering. But it also suggests that there could be very powerful incentives for countries to create something different: a club that prepares responses to unilateral geoengineering. An ideal world institution for global governance of geoengineering may be tempting to envision, but this outcome is unlikely. A "blade runner" world of countries working together to counter rogue geoengineers presents a darker picture, but is perhaps more probable and therefore a more useful basis for practical discussions of governance.

Figure 1: Stylized Deployment Scenarios for Solar Geoengineering



Moral Hazard and Solar Geoengineering

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Key points

- Moral hazard is typically defined as the lack of incentive to guard against risk when one is protected from its consequences.
- In the context of solar geoengineering (SG), "moral hazard" is often discussed as the risk that mere mention of SG might detract from efforts to mitigate greenhouse-gas emissions in the first place. Technically, that is not moral hazard *per se* but rather a version of crowding out.
- Fear of this type of crowding out may be the single most important reason for the long-standing taboo – prior to about a dozen years ago – against SG research.
- Concerns about crowding out must be taken seriously, since vested interests will surely use SG as yet another excuse to delay necessary mitigation action.
- But these concerns must not be an excuse to avoid or limit SG research. The stakes are too high.

> Moral hazard [ˈmôrəl ˈhazərd, *noun*]
> The lack of incentive to guard against risk when one is protected from its consequences.

The first thing to know about "moral hazard" in the context of solar geoengineering (SG) is that it is a misnomer. The possibility that merely discussing SG could weaken efforts to mitigate greenhouse-gas emissions is not a case of moral hazard as much as it is a simple case of SG "crowding out" mitigation.

The second thing to know is that whatever we call this crowding-out phenomenon, it is clearly real. And well beyond crowding out emissions abatement, vested interests will surely exploit the availability of SG as yet another reason to do too little to reduce greenhouse-gas emissions in the first place.

The third thing to know is that none of this should be an excuse not to consider – or not to conduct research into – SG. The remainder of this brief discusses each of these points in turn.[1]

1 This essay, to a large extent, is based on Wagner and Merk (forthcoming). For a longer prior exploration of "moral hazard" in the context of SG, see, e.g., Lin (2013).

"Moral hazard" it is not

The term "moral hazard" has been a core part of SG discourse long before the recent resurgence in SG research.[2] Strictly speaking, the concern about SG is not, in fact, moral hazard, as the term is typically defined in economics where it usually refers to adverse incentives between two parties (for example, in the context of one party providing insurance to the other). Here the problem is more akin to a "lack of self-control"[3] or an escape from "moral responsibility."[4]

Perhaps the main consequence of using the term "moral hazard" is that any tradeoff between SG and greenhouse-gas mitigation comes to be seen as a moral failing of sorts. That connotation is unfortunate.

In fact, it is highly unclear whether mere talk of SG poses a moral problem of sorts, or whether the greater moral problem is not talking about SG. In fact, Paul Crutzen, who jump-started the broader SG discussion in his taboo-breaking 2006 essay in *Climatic Change*, zeroed in on a key moral quandary of SG: the tradeoffs inherent in using tropospheric air pollution to cool the planet.[5] In an essay introducing a special issue of *Earth's Future* on "Crutzen + 10," he revisited the issue in a co-authored essay, asking in the title: "Was breaking the taboo on research on climate engineering via albedo modification a moral hazard, or a moral imperative?"[6] This essay concludes "that the overall verdict is still out" and calls for further SG research.

"Moral hazard" is real

"Moral hazard" is a misnomer. Yet the phenomenon itself is real. It is also ever present. There are indeed tradeoffs between SG and cutting greenhouse-gas emissions, akin to there being tradeoffs between taking a pill of statins each day on the one hand and diet and exercise on the other. Those exercising the rational amount each day might scale back their exercise ever so slightly, once their physician introduces them to statins to help control their blood pressure.

More important than the real, rational tradeoffs, however, are those linked to the fact that the world is far from a rational climate policy in the first place. Few exercise the "optimal" amount. In fact, most don't at all. The big question, hence, is what introducing an "easier" choice – statins, in the case of high blood pressure, and SG, in the case of climate change –does to those who are not exercising (or cutting emissions) nearly enough. On an individual level, some might

2 Keith (2000) first introduced the term to geoengineering discussions.

3 See Wagner and Weitzman (2015, p. 197).

4 Winickoff *et al.* (2015) argues that SG research might be seen as "an intervention in the ongoing ethical debate about proper remedies for climate change" (p. 631). See also Burns *et al.* (2016) for a further parsing of the definition of "moral hazard" in the context of SG.

5 See Crutzen (2006).

6 Lawrence and Crutzen (2017) explore this question in depth. The question, in turn, already mixes up the moral responsibility of researchers with actual crowding-out effects. A more accurate phrasing of the question might be: "Even with crowding out, might breaking the taboo on SG research still have been a moral imperative?"

use the potential availability of SG as yet another reason to avoid the harder task of cutting emissions. However, the opposite might hold true, too: introducing SG could serve as a wake-up call of sorts, much like a first-time prescription for statins might jolt a patient to start dieting and exercising. The question of whether "crowding out" or "crowding in" dominates – and under what circumstances – is indeed important.[7]

At least as important is the question of how political interests vested in the fossil-fueled status quo would misuse the possibility of SG and underplay its side effects. Fossil fuel interests would surely use SG as yet another excuse to lobby against necessary greenhouse-gas emissions reductions. That goes for fossil-fuel-exporting states as much as for fossil fuel companies, and for politicians beholden to them.[8]

"Moral hazard" should not be a distraction

"Moral hazard" and its variants are ever present. Whether attention to SG crowds out emissions abatement, or whether – under certain circumstances – it has the inverse effect, the (policy) interaction between SG and emissions abatement matters. It matters because of the real tradeoffs involved. It matters because of politics, in particular because those already opposed to emissions reductions will use SG as yet another excuse not to act.

The flipside is that "moral hazard" concerns *should not* distract from SG research.

Health insurance, condoms, seat belts, and even Ben Franklin's Philadelphia fire brigade – all these innovations were met with cries of "moral hazard": What if the existence of a fire brigade discouraged citizens from taking precautionary measures to avoid fires? "Moral hazard," or a version of it, plays a role in each of these examples.[9] But in each case, it is clear that opposing the policy intervention on moral hazard grounds would be counterproductive. All four interventions have reduced unnecessary deaths and suffering. SG research could do the same.

By the same token, however, SG research should not distract from sensible emissions-abatement policies either. That points to the importance of accounting for – and controlling – vested interests and adverse incentives that stand in the way of a more rational climate policy portfolio.

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7 See, e.g., Merk *et al.* (2016, 2015) for further exploration, especially Merk *et al.* (2016) for the first revealed-preference study, which finds weak crowding in. See also Burns *et al.* (2016) for a review of the literature, as well as ongoing research (see: geoengineering.environment.harvard.edu/moral-hazard). Mahajan *et al.* (2018) points to the possibility that acquiescence bias is responsible for much of the weakly positive support for the "moral hazard" argument in prior stated-preference surveys of first-order beliefs about moral hazard.

8 See, e.g., Gingrich (2008).

9 For discussions of moral hazard in relation to health insurance, condoms, seat belts, and Ben Franklin's fire brigade see, respectively, Finkelstein (2014), Cassell *et al.* (2006), Cohen and Einav (2003), and Grinols and Henderson (2009, p. 113).

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Thinking About SG – An Economic Perspective

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Key Points

- Solar geoengineering (SG) is relatively cheap (with potentially powerful impacts). As such, the incentive structure associated with SG is the inverse of that associated with policy to reduce greenhouse-gas emissions – yielding a *free rider*, rather than a *free driver* problem.
- SG entails novel ethical and governance challenges, especially around balancing errors of doing too much, and of too little.
- One possible theoretical approach to addressing this "balancing act" involves a highly stylized voting rule, where the relative fraction of the population required to vote for a change ought to be exactly proportional to the relative cost of an error (of doing too much or too little).
- A hypothetical "World Climate Assembly" voting on optimal SG deployment might be a good starting point to think through optimal governance scenarios.

Solar geoengineering (hereafter SG) is so relatively cheap to enact that it might effectively be undertaken unilaterally by one nation feeling itself under climate siege, to the detriment of other nations.[1] This SG externality is what I have called a *free-driver* problem because, without some form of international restraint, the country most in favor of SG can drive the SG outcome to the detriment of other countries. Essentially any determined country with even a medium-sized economy could, if unopposed, put up a geoengineered sunshade on its own, in answer to its own perceived need to lower global temperatures and change its own climate quickly. There are thus two serious public-goods problems involved in the economics of climate change: a free-rider problem with relatively expensive carbon emissions abatement and a free-driver problem with relatively inexpensive SG.

The setting for this paper's problem of SG is a future world that has accumulated high enough greenhouse gas (GHG) concentrations for a long enough time that some countries are feeling under severe threat from climate changes. Perhaps Bangladesh is threatened by inundation and mass migration due to severely melting ice sheets. Or maybe Indian agriculture is collapsing from high temperatures and serious monsoon alterations. Or other countries like China or the United States are concerned with damaging climate change for other reasons. Suppose that the governments of one or more such concerned countries feel themselves under such intense domestic political pressure to *do something* that they cannot wait for gradual diminishment of

1 Ballpark estimates of annual geoengineering costs of offsetting projected heating in this century might be in the neighborhood of around eight billion dollars or so.

GHG emissions, but must come out in favor of geoengineering lower temperatures immediately (at very little direct deployment cost to them). Suppose that much of the rest of the world does not want the high level of SG that a free-driver solution implies. What is the outcome?

For concreteness here, I quantify the level of SG by the annual injection flow of stratospheric sulfur dioxide (SO_2). In essence, the world wants or needs a social choice mechanism to reconcile different preferences about where to dial the knob of SO_2 flow injections. Maybe it is worthwhile to set aside some space here to think more abstractly about social-choice rules concerning where to dial the knob of SG flow levels that differentially impact parties having different interests.

What might economic theory contribute to an understanding of the governance problem of SG? I have a big-picture big-think message that some might view less charitably as a form of science fiction. I ask the reader here to entertain a willing suspension of disbelief while I try to set out, as a thought experiment, a possible theoretical resolution of the SG knob-setting problem in the form of a particular social choice mechanism. I am asking: Is there any recognizable decision mechanism, however hypothetical, abstract, and seemingly unrealistic, that economic theory might suggest? At the very least I hope that this theoretical exercise is thought provoking and might stimulate other new ideas, perhaps along vaguely similar lines.

Imagine a hypothetical "World Climate Assembly" (WCA), which acts like a legislative general assembly. Each country is represented with voting weight perhaps, say, proportional to its population. The world starts off with some given flow-level of annual stratospheric SO_2 injection, which might be zero at the beginning. Consider an asymmetric supermajority voting system. I will use 3/4 as a numerical example, but the idea is more general. Any proposal to *increase* the level of geoengineering by dialing up the knob requires at least a 3/4 supermajority of the general assembly. Any proposal to *decrease* the level of geoengineering by dialing down the knob requires at least a 1/4 "superminority" of the WCA. (A perhaps related application is that a 3/4 supermajority is required in the United States for states voting on a constitutional amendment, because the framers of the constitution purposely wanted to keep down the number of amendments by a high but attainable hurdle.)

This asymmetric supermajority voting system has (for me, at least) a certain intuitive appeal. Overdoing SG seems much more dangerous than underdoing SG because it represents a relatively much riskier strategy with a much more heavily weighted potential downside, so it should require a larger fraction of the vote to increase SG than to decrease SG. To up-dial SG is to move in the direction of an unknown and riskier strategy. To down-dial SG is to move in the direction of the known and less-risky strategy.

Now comes a question that economists love to pose and answer in applying economic theory to policy. Is there any coherent welfare story, which is not completely ridiculous, that could be used to justify the proposed policy? If we cannot find any such welfare story, then the proposed policy seems somewhat more suspect, because it is based on heuristics alone. If we can find such a welfare story, then the proposed policy at least passes a minimal internal consistency check and could be used as a point of departure, although it may be legitimately criticized on many other grounds. (An example of this methodology is the idea that "free trade is a good policy," where economists since the time of Adam Smith can come up with a justifying welfare story that is not completely ridiculous, although it can be negated, for example, by declining-cost infant-industry arguments.)

For the WCA 3/4 voting rule, here is a sketch of an underlying welfare story. Each nation has a *different* most-preferred value of SG. The loss function for each nation is kinked at its most-preferred value of SG, with an increased unit of SG incurring *three* times as much loss for each nation as a unit of decreased SG, for reasons having to do with the idea that overdone geoengineering is riskier and more horrifying, whereas underdone geoengineering is merely undesirable. Thus, each nation faces the same kinked shape of a loss function, but different most-preferred SG levels. Under these circumstances, the minimum total global welfare loss (or, equivalently, the maximum total global welfare gain) is realized by the above asymmetric WCA 3/4 supermajority voting rule. This is not a trivial result. Under certain non-ridiculous assumptions about each country's welfare function for SG, we can assert that a WCA supermajority voting rule maximizes total welfare.

I have used the example of a WCA 3/4 supermajority voting rule, but the number 3/4 generalizes.[2] A *less* stringent WCA supermajority 2/3 voting rule (such as what is required in the U.S. Congress to override a presidential veto) is welfare maximizing when increased SG incurs *two* times as much loss as decreased SG. A *more* stringent WCA supermajority 4/5 voting rule is welfare maximizing when increased SG incurs *four* times as much loss as decreased SG. And so forth.

Is this WCA proposal naïve? Yes, absolutely. To begin with, there are very few precedents of international voting outcomes applying with binding force. More generally, I am simplistically brushing aside a great many truly important aspects of the real world of international agreements. More specifically, why would a country voluntarily accede to a voting limitation on their SG sovereignty along the lines of the WCA proposal? I do not have a good answer to this question, except to ask another question. What are the alternatives for SG governance and on what alternative theory are they based? Remember, a strict rules-based social-choice governance mechanism for dialing the knob on SG flows may look more appealing in a future world edging toward catastrophic climate extremes.

In conclusion, I hope that this theoretical WCA supermajority exercise is thought provoking and might stimulate other new ideas, perhaps along similar lines, but maybe even something altogether different.

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2 A full theoretical treatment is available in Weitzman (2015).

The Implications of Uncertainty and Ignorance for Solar Geoengineering

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Key points

- Both unchecked climate change and any potential deployment of solar geoengineering (SG) are governed by processes that are currently unknowable; i.e., either is afflicted with *ignorance*.
- Risk, uncertainty, and ignorance are often greeted with the precautionary principle: "do not proceed." Such inertia helps politicians and bureaucrats avoid blame. However, the future of the planet is too important a consequence to leave to knee-jerk caution and strategic blame avoidance. Rational decision requires the equal weighting of errors of commission and omission.
- Significant temperature increase, at least to the 2°C level, is almost certainly in our planet's future. This makes research on SG a prudent priority, with experimentation to follow, barring red-light findings.
- On an expected-value basis, greater SG uncertainties make SG itself more attractive. That is because the uncertainties of unchecked climate change and SG are highly correlated. The uncertainties of climate change are likely far more consequential.

What's known about climate change provides a lower bound on its cost.[1] What's unknown makes it possibly much costlier. And then there are climatic unknowables, consequences that we can't even conjecture. These unknowns and unknowables, which we label UUs, make the expected costs of climate change greater than calculations employing known factors would indicate. It is hard to imagine pleasant surprises about climate effects.

It is against this backdrop of UU-afflicted climatic consequences that solar geoengineering (SG) must be evaluated.

1 The official U.S. social cost of carbon dioxide (SC-CO_2) under the Obama Administration was around $40/ton (U.S. Government Interagency Working Group on Social Cost of Carbon 2010, 2015). Climate sensitivity tail uncertainty points to that quantification as a lower bound (Wagner and Weitzman 2015; Weitzman 2009, 2011). The latest attempts at estimating the SC-CO_2, for example, point to values possibly ten times higher than the $40 figure, with large uncertainty ranges (Ricke *et al.*, 2018).

Risk, uncertainty, and ignorance

Risk arises when the probabilities of all possible states of the world are known, as say securing a "7" with the roll of two dice. Uncertainty arises when the states of the world are known, but not their probabilities – for example, the chance that a particular politician will win re-election. Virtually nothing about climate change merely involves risk, but it is a hot bed of uncertainties.[2]

When considering a cloudy future, and notably a climate future, there is a third, critical concept: ignorance. Given ignorance, even the identities of important states of the world are not known.[3] Neither 9/11 nor the Arab Spring was seriously contemplated. Although some climate outcomes, like climate sensitivity, can be neatly captured by assumed probability distributions, hence are merely uncertain, other important climate-related outcomes reside in the realm of ignorance.[4] Consider for example how societies will respond to massive in-migrations.

SG, if implemented, would also usher in ignorance. A case in point here is a recent *Nature* cover article analyzing the effects of volcanic eruptions, chiefly Mt. Pinatubo, on crop yields.[5] Its main conclusion: Volcanic eruptions had no statistically significant effect on global crop yields, as the temperature effects from reduced heat stress on plants were counterbalanced by an "insolation effect" due to more scattered sunlight. The study's headline-grabbing conclusion then extrapolates this finding to SG. Without going into the science itself, the mere date of the study demonstrates that SG brings with it UUs: Mt. Pinatubo erupted in 1991. Most of its effects were felt in 1992. Yet the *Nature* study was not published until a quarter century later, in 2018. And it, too, is far from perfect, having likely missed important aspects of SG, such as the CO_2 fertilization effect. Many of nature's deeply buried secrets have yet to be uncovered.

How then should we think about policy decisions in the climate change context, where uncertainty and ignorance prevail, and where human life is threatened? Some critics urge a departure from the prescriptions of rational decision theory and its guiding principle that expected utility be maximized. Such departures – the precautionary principle would be a salient example – usually place a much greater emphasis on avoiding actions that might introduce unexpected undesired consequences,[6] as would the use of SG. We observe that when the stakes are enormous, as they are when the Earth is on track for 2°C warming or much worse, it is too expensive to take refuge in the blame-avoidance methods of the precautionary principle and its non-rational cousins.

Errors of commission versus omission

Decision-making around SG – both about research but especially around deployment – shows that individuals, including many scholars in the area, often treat errors of commission as being

2 Knight (1921) offers the seminal introduction to the topic, distinguishing between risk and uncertainty.

3 See Zeckhauser (2006), which expands on Knightian risk and uncertainty to include "ignorance."

4 See, e.g., Kopp *et al.* (2016) for a recent assessment.

5 See Proctor *et al.* (2018).

6 See Heal and Millner (2014) for a survey of alternative decision criteria in the context of climate policy.

significantly more serious than errors of omission. Psychologically such an imbalance is understandable.[7] However, from the perspective of a rational decision theory, or as best assuring the future of the planet, the two should indeed be weighted equally.

Consider the decision of whether to enroll in a high-risk medical trial. Faced with a bad case of cancer, the standard treatment is high-dose chemotherapy. Now consider as an alternative treatment an experimental bone-marrow transplant. The additional treatment mortality of the trial, of say 4 percentage points, is surely an important aspect of the decision – but so should be the gain in long-run survival probability. If that estimated gain is greater than 4 percentage points, say 10 or even "only" 6 percentage points, a decision maker with the rational goal of maximizing the likelihood of survival should opt for the experimental treatment.[8]

All too often, however, psychology intervenes, including that of doctors. Errors of commission get weighted more heavily; expected lives are sacrificed. The Hippocratic Oath bans the intention of harm, not its possibility. Its common misinterpretation of "first do no harm" enshrines the bias of overweighing errors of commission.

To be sure, errors of commission incur greater blame or self-blame than those of omission when something bad happens, a major source of their greater weight. But blame is surely small potatoes relative to survival, whether of a patient or of the Earth. Hence, we assert once again, *italics* and all: *Where climate change and solar geoengineering are concerned, errors of commission and omission should be weighted equally.*

That also implies that the dangers of SG – and they are real – should be weighed objectively and dispassionately on an equal basis against the dangers of an unmitigated climate path for planet Earth.[9]

The precautionary principle, however tempting to invoke, makes little sense in this context. It would be akin to suffering chronic kidney disease, and being on the path to renal failure, yet refusing a new treatment that has had short-run success, because it could have long-term serious side effects that tests to date have been unable to discover. Failure to assiduously research geoengineering and, positing no red-light findings, to experiment with it would be to allow rising temperatures to go unchecked, despite great uncertainties about their destinations and dangers. That is hardly a path of caution.

7 Wagner and Weitzman (2015) explore it in the context of SG. Wagner and Zeckhauser (2012) survey biases in climate policy decision-making more broadly.

8 We are simplifying by positing that survival and non-survival are the two possible outcomes. See Schneider and Lane (2005) for decision-making in medicine.

9 While the SG deployment decision itself might influence decisions around cutting CO_2 emissions in the first place, a concept often (falsely) called "moral hazard," we will not discuss this phenomenon further. See Wagner's brief in this volume.

A model of optimal learning

We are developing a simple model to illustrate potential decision-making about the use of SG in the context of UUs. SG's key characteristics can perhaps best be described as *fast*, *cheap*, and *imperfect*: SG is *fast* in the sense that its effects are felt within months of deployment, within one model period; it is *cheap* in that its direct costs are low, orders of magnitude below both the costs of unmitigated climate damages and also of cutting CO_2 dramatically in the first place; and is clearly *imperfect*. It neither destroys nor removes CO_2, and it could possibly produce large damages. Other key model assumptions include incomplete learning, and that feedback, albeit swift, is also imperfect.

The objective in our model is to pick the level of learning – through the use of experimental (partial) deployment of SG – as a complement to scientific study, to determine to what extent, if any, SG should be deployed. The optimal level would minimize the sum total of expected damages from both climate change and SG. The goal of the exercise is to straighten one's thinking about optimal testing in a highly simplified context where there is a period of testing and a period of implementation. In the testing period, one learns imperfectly about both the unfolding consequences of climate change, and both the positive and adverse effects of SG.

While the model itself is too technical to describe here, one conclusion is already evident: the greater are the uncertainties about SG damages, the more appealing, on an expected value basis, is SG. One reason for this perhaps counterintuitive result is simply the strongly positive correlation between SG uncertainty on the one hand and climate change uncertainty on the other. We would also hasten to add our speculation that, in the end, climate change uncertainty is likely to be dramatically more consequential.

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GOVERNANCE OF THE DEPLOYMENT OF SOLAR GEOENGINEERING

Agenda

Thursday, September 27

Harvard Kennedy School, Taubman Building, Fifth Floor, Nye Conference Room

8:00 – 9:00 am **Breakfast**

9:00 – 9:30 am **Welcome, framing, and self-introductions**

Robert Stavins

Director, Harvard Project on Climate Agreements

David Keith

Faculty Director, Harvard's Solar Geoengineering Research Program

9:30 – 9:50 am **Status update on – and insights from – research in the social sciences on the governance of SG deployment**

Scott Barrett

9:50 – 10:10 am **Responses**

Stefan Schäfer, Gernot Wagner

10:10 – 10:40 am **Discussion**

10:40 – 11:00 am **Break**

11:00 – 11:20 am **Status update on – and insights from – research in law on the governance of SG deployment**

Daniel Bodansky

11:20 – 11:30 am **Response**

Albert Lin

11:30 am – 12:00 pm **Discussion**

12:00 – 1:15 pm **Lunch**

Speaker: John Holdren

1:15 – 1:35 pm **Thinking about SG – an economic perspective**

Martin Weitzman

1:35 – 1:45 pm **Response**

James Stock

1:45 – 2:10 pm **Discussion**

2:10 – 2:30 pm **Criteria for decision making on deployment (Questions 1 – 3)**

Sheila Jasanoff

2:30 – 2:50 pm **Public perceptions of SG deployment and implications for governance**

Dustin Tingley

2:50 – 3:00 pm **Response**

Lucas Stanczyk

3:00 – 3:30 pm **Discussion**

3:30 – 3:50 pm **Break**

3:50 – 4:10 pm **Institutional venues for governance of SG deployment (Questions 4 – 5)**

David Victor

4:10 – 4:30 pm **Responses**

Joshua Horton, Sikina Jinnah

4:30 – 5:00 pm **Discussion**

5:00 – 5:15 pm **Closing observations for day 1**

Daniel Schrag

6:30 – 8:00 pm **Reception and dinner**

Harvard Kennedy School, Taubman Building, Fifth Floor, Allison Dining Room

Speaker: Janos Pasztor

Friday, September 28

Harvard Kennedy School, Taubman Building, Fifth Floor, Nye Conference Room

8:00 – 8:30 am	**Breakfast**
8:30 – 8:50 am	**Governance of SG deployment under conditions of uncertainty (Ques. 6)** Richard Zeckhauser
8:50 – 9:10 am	**Responses** Daniel Heyen, Kate Ricke
9:10 – 9:30 am	**Discussion**
9:30 – 10:15 am	**Insights from other international regimes into the governance of SG deployment** Matthew Bunn, Joseph Nye, Meghan O'Sullivan
10:15 – 11:00 am	**Discussion**
11:00 – 11:20 am	**Break**
11:20 – 11:50 am	**A research program for the governance of solar-geoengineering deployment (Question 7)** David Keith, Jesse Reynolds
11:50 am – 12:15 pm	**Closing observations, discussion, and next steps** Robert Stavins

GOVERNANCE OF THE DEPLOYMENT OF SOLAR GEOENGINEERING

Participants

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Scott Barrett is the Lenfest-Earth Institute Professor of Natural Resource Economics at Columbia University. He was a lead author of the second assessment report by the Intergovernmental Panel on Climate Change and was previously a member of the Academic Panel of Environmental Economists to the U.K.'s Department of Environment. Barrett is the author of *Environment and Statecraft: The Strategy of Environmental Treaty-Making*, published in 2005. His most recent book, *Why Cooperate? The Incentive to Supply Global Public Goods*, was published in September 2007. Barrett received his Ph.D. in economics from the London School of Economics (1989); an M.A. in economics from the University of British Columbia, Vancouver; and a B.S., *summa cum laude*, in resource economics from the University of Massachusetts, Amherst (1979).

Muhammet A. Bas (PhD, University of Rochester, 2007), is an Associate Professor of Political Science at New York University, Abu Dhabi. He was previously an Associate Professor of Government at Harvard University. His research is broadly motivated by an interest in factors affecting the likelihood of international conflict. He studies (1) various sources of uncertainty in crisis interactions; (2) emergence and spread of new military technologies, and in particular, nuclear weapons; and (3) changes in the natural environment such as climate change, or natural disasters. In order to address these substantive questions appropriately, Bas develops a number of new statistical methods on strategic interaction, some of which can be fruitfully utilized in other areas of international relations and political science. Bas's work has been published in a number of peer-reviewed journals including *International Organization, International Studies Quarterly, Journal of Conflict Resolution,* and *Political Analysis*.

Daniel Bodansky is Foundation Professor of Law in the Sandra Day O'Connor College of Law. He is also the faculty co-director for the Center for Law and Global Affairs. In addition, he is an affiliate faculty member with the Center for Law, Science and Innovation and the Julie Ann Wrigley Global Institute of Sustainability's School of Sustainability at ASU. Bodansky is a leading authority on international environmental law generally, and global climate change law in particular. He teaches courses in public international law and sustainability and is a key player in the college's Program on Law and Sustainability.

Matthew Bunn is Professor of Practice at the Harvard Kennedy School. His research interests include nuclear theft and terrorism; nuclear proliferation and measures to control it; the future of nuclear energy and its fuel cycle; and policies to promote innovation in energy technologies. Before coming to Harvard, Bunn served as an adviser to the White House Office of Science and Technology Policy, as a study director at the National Academy of Sciences, and as editor of *Arms Control Today*. Bunn is the author or co-author of more than twenty-five books and book-length technical reports (most recently *Insider Threats*), and over 150 articles in publications ranging from *Science* and *Nuclear Technology* to *Foreign Policy* and T*he Washington Post*.

Daniel Heyen recently joined ETH Zurich as a postdoctoral researcher after a postdoctoral appointment at the Grantham Research Institute on Climate Change and the Environment at the London School of Economics. He is an applied theorist working at the interface of decision theory and environmental economics. His main research interest is in societal decision-making under uncertainty and learning. Key topics are the description of scientific uncertainty, the value of information and forecasts, and the design of risk regulation and the precautionary principle. A second line of his research focuses on strategic aspects of environmental technologies with geoengineering as an important area of application. Heyen holds a Ph.D. in economics from Heidelberg University.

John P. Holdren is the Teresa and John Heinz Professor of Environmental Policy at the Harvard Kennedy School (HKS); Co-Director of the Program on Science, Technology, and Public Policy in HKS's Belfer Center for Science and International Affairs; and Professor of Environmental Science and Policy in the Department of Earth and Planetary Sciences at Harvard University. He is also Senior Advisor to the Director at the independent, nonprofit Woods Hole Research Center. From January 2009–January 2017, he was President Obama's Science Advisor and the Senate confirmed Director of the White House Office of Science and Technology Policy (OSTP), becoming the longest-serving Science Advisor to the President in the history of the position (dating back to World War II). Holdren earned S.B. and S.M. degrees from M.I.T. and a Ph.D. from Stanford in aerospace engineering and theoretical plasma physics.

Matthias Honegger is a research associate with the Institute for Advanced Sustainability Studies, consultant with Perspectives Climate Research, PhD candidate at Utrecht University and currently visiting fellow at the Solar Geoengineering Research Program (SGRP). He holds a master's degree in environmental sciences from the Swiss Federal Institute of Technology (ETH) and has worked as climate policy consultant on sectoral mitigation policies, national mitigation targets and UNFCCC negotiations in particular with government agencies in the MENA region and occasionally southeast Asia, including advising the Presidency of COP 18 in 2012. In his research, Matthias explores whether differences in climate policy negotiators' and observers' views of solar geoengineering and carbon removal can be explained by diverging values and worldviews and how these differences result in discrepancies between popular expectations, economic models and actual policy planning. He has recently co-authored the first encompassing assessment of potential effects that deployment of Solar Geoengineering or Carbon Removal could have on the pursuit of the Sustainable Development Goals.

Joshua B. Horton is Research Director, Geoengineering at the Harvard John A. Paulson School of Engineering and Applied Sciences and also manages the Weatherhead Center for International Affairs Initiative on Climate Engineering. His research encompasses the politics, policy, and governance of solar geoengineering, with a current focus on compensation for harms arising from possible future deployment of the technology. From 2013–2016, Horton was a Postdoctoral Research Fellow in the Belfer Center's Science, Technology, and Public Policy Program. Horton obtained a Ph.D. in political science from Johns Hopkins University in 2007, where he specialized in international relations.

Pete Irvine is a Postdoctoral Research Fellow at the Harvard School of Engineering and Applied Sciences working in Prof. David Keith's group. Dr. Irvine conducts research on the climate and broader impacts of solar geoengineering and works to put those findings into perspective with the risks posed by climate change. Dr. Irvine was awarded his PhD on the climate response to solar geoengineering in 2012 and worked after this as a post-doc at the Institute for Advanced Sustainability Studies, Potsdam. In recent work, Dr. Irvine has worked on novel analyses for evaluating solar geoengineering's performance at offsetting climate change and is currently working to evaluate the effects of solar geoengineering on drought and aridity. Beyond this, Dr. Irvine has published on the sea-level rise response to solar geoengineering, produced reviews of its climate impacts, and collaborated to produce several interdisciplinary pieces addressing the broader socio-political implications of solar geoengineering.

Sheila Jasanoff is Pforzheimer Professor of Science and Technology Studies at the Harvard Kennedy School, where she founded and directs the Program on Science, Technology and Society; she also founded and coordinates the Science and Democracy Network. Previously, she was founding chair of Cornell University's Department of Science and Technology Studies. Jasanoff's research centers on the interactions of law, science, and politics in democratic societies. Jasanoff holds an A.B. in mathematics from Harvard College, a Ph.D. in linguistics from Harvard University, and a J.D. from Harvard Law School.

Sikina Jinnah is an associate professor of politics at University of California, Santa Cruz, and a 2017 Andrew Carnegie Fellow. Her research focuses on the shifting locations of power and influence in global environmental governance, in particular in the areas of climate change, climate engineering, and the nexus between international trade and environmental politics. Jinnah is Co-Editor of the journal *Environmental Politics*, is on the editorial board for the journal *Global Environmental Politics*, is a Senior Research Fellow with the Earth System Governance project, and is a member of the Academic Working Group on International Governance of Climate Engineering at the Forum for Climate Engineering Assessment, and serves on that organization's Advisory Board.

David Keith is a professor at the Harvard School of Engineering and Applied Sciences and Harvard Kennedy School, and founder of Carbon Engineering, a company developing technology to capture CO_2 from ambient air. He has worked near the interface between climate science, energy technology, and public policy for twenty-five years. Best known for his work on the science, technology, and public policy of solar geoengineering, he led the development of the Solar Geoengineering Research Program. Keith took first prize in Canada's national physics prize exam, won MIT's prize for excellence in experimental physics, and was one of *TIME* magazine's Heroes of the Environment.

Albert Lin is a professor of law at the University of California, Davis School of Law. His research interests include the relationship between technology, the environment, and law. His writings on geoengineering include: Carbon Dioxide Removal After Paris, __ *Ecology Law Quarterly* __ (2018 forthcoming); The Missing Pieces of Geoengineering Research Governance, 100 *Minnesota Law Review* 2509 (2016); and Does Geoengineering Present a Moral Hazard?, 40 *Ecology Law Quarterly* 673 (2013). Lin received his J.D. from the University of California, Berkeley School of Law and an M.P.P. from the Harvard Kennedy School.

Aseem Mahajan is a PhD student in Harvard's Department of Government. His research focuses on energy and environmental politics, with recent work exploring the effectiveness and impacts of India's *Saubhagya* scheme to provide electricity access to the entire country; public opinion toward geoengineering and counter-geoengineering; perceptions of equity in climate bargaining; and the politics of climate resilience. Previously, he worked at the IFF, a community development financial institutions in Chicago, and PricewaterhouseCooper's Global Transfer Pricing division in New York. He holds an A.B. in politics with a focus on political economy and finance from Princeton University.

Christine Merk works as a postdoctoral researcher at the Kiel Institute for the World Economy (Kiel, Germany). One of her main research interests are individuals' trade-offs between mitigation and climate engineering technologies. She conducts economic experiments integrating concepts from the psychology of risk perception to learn more about individuals' perceptions of and reactions to climate engineering. Furthermore, she researches the effects of nudging interventions on sustainable consumption in field experiments. Her background is in political and administration science, and she holds a PhD in Economics from Kiel University.

Joseph S. Nye, Jr. is University Distinguished Service Professor, *Emeritus*, and former Dean of the Harvard Kennedy School. He has served as Assistant Secretary of Defense for International Security Affairs, Chair of the National Intelligence Council and a Deputy Under Secretary of State. He is a fellow of the American Academy of Arts and Sciences, the British Academy, and the American Academy of Diplomacy. In a recent survey of international relations scholars, he was rated the fifth most influential over the past 20 years; ranked as the most influential scholar on American foreign policy, and in 2011, *Foreign Policy* named him one of the top 100 Global Thinkers. He is co-chair of the Aspen Strategy Group. Nye received his bachelor's degree, *summa cum laude*, from Princeton University, won a Rhodes Scholarship to Oxford University, and earned a Ph.D. in political science from Harvard University.

Meghan L. O'Sullivan is the Jeane Kirkpatrick Professor of the Practice of International Affairs at the Harvard Kennedy School and the Director of the Belfer Center for Science and International Affairs' Geopolitics of Energy Project. The project brings together experts from the realms of academia, industry, and government to explore the complex interactions between energy markets and international affairs. O'Sullivan's third book, *Windfall: How the New Energy Abundance Upends Global Politics and Strengthens America's Power*, was published by Simon & Schuster in September 2017.

Janos Pasztor is currently Senior Fellow and Executive Director of the Carnegie Climate Geoengineering Governance Initiative (C2G2) at the Carnegie Council for Ethics in International Affairs. He has over thirty-five years of work experience in the areas of energy, environment, climate change, and sustainable development. Before taking up his current assignment, he was UN Assistant Secretary-General for Climate Change in New York under Secretary-General Ban Ki-moon. Pasztor has B.Sc. and M.Sc. degrees from MIT.

Sébastien Philippe is a Stanton Nuclear Security Postdoctoral Fellow at Harvard Kennedy School's Belfer Center for Science and International Affairs. His research aims to develop new monitoring and verification technologies and approaches to support global governance challenges, with a focus on nuclear non-proliferation, arms-control and disarmament. Before his Stanton fellowship, Philippe was with Princeton University's Program on Science and Global Security. He earned his PhD in Mechanical and Aerospace Engineering from Princeton University in June 2018.

Jesse Reynolds is an Emmett/Frankel Fellow in Environmental Law and Policy at the University of California, Los Angeles School of Law. He draws from international law, international relations, and economics to research how society can develop norms, rules, and institutions to manage transboundary environmental problems, particularly those involving new technologies. His book *The Governance of Solar Geoengineering: Managing Climate Change in the Anthropocene* is forthcoming on Cambridge University Press. Reynold's obtained his B.A. in environmental science and chemistry from Hampshire College; his M.S. in environmental science, policy, and management from the University of California, Berkeley (as a Science-to-Achieve-Results Graduate Fellow through the U.S. Environmental Protection Agency); and his Ph.D. in international law from Tilburg University (in part as a Fulbright Fellow through the U.S. Department of State).

Kate Ricke is an Assistant Professor at UC San Diego with joint appointment between the Scripps Institution of Oceanography and the School of Global Policy and Strategy. She is a climate change scientist who combines quantitative modeling and large data set analysis techniques applied to physical and social systems. Her research focuses on how uncertainty and heterogeneity, both in the projected impacts of climate change and in preferences for how to address them, influence strategic incentives in climate policy problems. She has worked on topics ranging from the regional climate effects and international relations implications of solar geo-engineering, to decadal climate variability's influence on international climate agreements to the effect of heterogeneous national climate change impacts on efficient coalition building. She has conducted uncertainty assessments of ocean acidification's effects on coral reefs, marginal carbon dioxide emissions' effects of global and regional warming, and temperature target overshoot scenarios. Prior to UCSD, Ricke was a research associate in the Sibley School of Mechanical and Aerospace Engineering at the Cornell University and a Fellow at the Carnegie Institution for Science. She received her PhD in Engineering & Public Policy at Carnegie Mellon University and her BS in Earth Atmospheric and Planetary Sciences at MIT.

Stefan Schäfer leads a research group at the Institute for Advanced Sustainability Studies in Potsdam, Germany and is a Visiting Fellow in the Science, Technology and Society Program at Harvard University. His research draws on approaches from Science and Technology Studies to examine questions at the intersection of science, technology, democracy, and sustainability, with a focus on the global governance of climate change. He is also an associate fellow of the Institute for Science, Innovation and Society at the University of Oxford, where he was an Oxford Martin Visiting Fellow in 2017.

Daniel Schrag is the Sturgis Hooper Professor of Geology, Professor of Environmental Science and Engineering at Harvard University, and Director of the Harvard University Center for the Environment. His primary appointment is in the Department of Earth and Planetary Sciences in the Faculty of Arts and Sciences. He serves as Area Dean for Environmental Science and Engineering in the Harvard John A. Paulson School of Engineering and Applied Sciences and also co-directs the Program on Science, Technology and Public Policy at the Harvard Kennedy School.

Lucas Stanczyk is an assistant professor of political science and affiliated faculty of philosophy at MIT. In 2017, he joined the philosophy department at Harvard. He works on topics at the intersection of political philosophy and political economy. His current book manuscript develops a theory of justice in production. His other research and teaching is focused on ethical problems in global energy policy and the ethics of growing inequality.

Robert Stavins is the A. J. Meyer Professor of Energy & Economic Development, Harvard Kennedy School; Director, Harvard Environmental Economics Program; and Director, Harvard Project on Climate Agreements. He is a University Fellow, Resources for the Future; Research Associate, National Bureau of Economic Research; elected Fellow, Association of Environmental and Resource Economics; Member, Board of Directors, Resources for the Future; and Editor, Journal of Wine Economics. He was Chairman, Environmental Economics Advisory Board, U.S. Environmental Protection Agency. He was a Lead Author, Second and Third Assessment Reports, Intergovernmental Panel on Climate Change; and Coordinating Lead Author, Fifth Assessment Report. His research has examined diverse areas of environmental economics and policy, and appeared in more than a hundred articles in academic journals and popular periodicals, plus a dozen books. He holds a B.A. in philosophy from Northwestern University, an M.S. in agricultural economics from Cornell, and a Ph.D. in economics from Harvard.

James Stock is the Harold Hitchings Burbank Professor of Political Economy in the Faculty of Arts and Sciences and also a member of the faculty at the Harvard Kennedy School. His research includes energy and environmental economics with a focus on biofuels and on U.S. climate-change policy. He currently is Faculty Associate at the Harvard University Consortium on the Environment, Faculty Fellow with the Harvard Environmental Economics Program, Nonresident Fellow at the Columbia Center for Global Energy Policy, and a member of the scientific advisory board for the Resources for the Future Social Cost of Carbon Initiative. Stock received a M.S. in statistics and a Ph.D. in economics from the University of California, Berkeley.

Robert Stowe is Executive Director of the Harvard Environmental Economics Program and Co-Director of the Harvard Project on Climate Agreements – both University-wide programs based in the Harvard Kennedy School (HKS). He was also an Adjunct Lecturer in Public Policy at HKS, teaching a course on international climate-change policy (2016 – 18). Stowe has been engaged through the Harvard Project in the annual Conferences of the Parties of the U.N. Framework Convention on Climate Change since 2007. He was a Contributing Author to a chapter on international cooperation in the Intergovernmental Panel on Climate Change's Fifth Assessment Report. Stowe has worked in non-profit, academic, and business organizations, including as Vice President of Programs of the Citizens Network for Foreign Affairs, which provides assistance in agriculture and agribusiness to developing countries, and as a consultant to the World Bank and other organizations on agricultural management projects. Stowe holds a Ph.D. in political science from the Massachusetts Institute of Technology and an A.B. in physics from Harvard College.

Dustin Tingley is Professor of Government at Harvard University. His research interests include international relations, international political economy, statistical methodology, and experimental approaches to political science. Recent projects include attitudes towards global climate technologies and policies and the intersection of causal inference and machine learning methods for the social sciences. Tingley received a Ph.D. in Politics from Princeton in 2010 and B.A. from the University of Rochester in 2001.

David Victor is an internationally recognized leader in research on energy and climate change policy, as well as energy markets. His research focuses on regulated industries and how regulation affects the operation of major energy markets. He has a dual understanding of the science behind climate change and how international and domestic public policy work. Victor authored *Global Warming Gridlock*, which explains why the world has not made much diplomatic progress on the problem of climate change, while also exploring new strategies that would be more effective. Victor is a leading contributor to the Intergovernmental Panel on Climate Change (IPCC), a United Nations-sanctioned international body with 195 country members.

Gernot Wagner is a research associate at the Harvard John A. Paulson School of Engineering and Applied Sciences, a lecturer on Environmental Science and Public Policy, the executive director of the Solar Geoengineering Research Program, an associate of the Science, Technology, and Public Policy Program at Harvard Kennedy School's Belfer Center for Science and International Affairs, and an associate at the Harvard University Center for the Environment. Wagner co-authored *Climate Shock* with Professor Martin Weitzman of Harvard University and published by Princeton University Press (2015).

Martin L. Weitzman is a professor of economics at Harvard University. Previously he was on the faculties of MIT and Yale. He has been elected as a fellow of the Econometric Society and the American Academy of Arts and Sciences. He has published widely in many leading economic journals and written three books. His current research is focused on environmental economics, including climate change, the economics of catastrophes, cost-benefit analysis, long-run discounting, green accounting, biodiversity, and comparison of alternative instruments for controlling pollution.

Richard Zeckhauser is the Frank P. Ramsey Professor of Political Economy at the Harvard Kennedy School. He is an elected fellow of the Econometric Society, the Institute of Medicine (National Academy of Sciences), and the American Academy of Arts and Sciences. In 2014, he was named a Distinguished Fellow of the American Economic Association. His contributions to decision theory and behavioral economics include the concepts of quality-adjusted life years (QALYs), status quo bias, betrayal aversion, and ignorance (states of the world unknown) as a complement to the categories of risk and uncertainty. Many of his policy investigations explore ways to promote the health of human beings, to help markets work more effectively, and to foster informed and appropriate choices by individuals and government agencies. He graduated from Harvard College, *summa cum laude*, and also received his Ph.D. from Harvard University.

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