On the Design of an International Governance Framework for Geoengineering*

Ian D. Lloyd[1,2]
Michael Oppenheimer[2,3]

1. Program in Atmospheric and Oceanic Sciences, Princeton University, NJ, USA
2. Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ, USA
3. Department of Geosciences, Princeton University, Princeton, NJ, USA

For submission to *Global Environmental Politics*

Word count: 8,869

May 11, 2011

Corresponding Author:
Ian D. Lloyd
Geophysical Fluid Dynamics Laboratory / NOAA
US Route 1, Forrestal Campus
Princeton, NJ 08542
Tel: (609) 452-5341, email: illoyd@princeton.edu

* For invaluable comments during the preparation of this manuscript we would like to thank Robert O. Keohane, Scott Barrett, Helen Milner, Christian Grobe, Thomas N. Hale, Alex Ovodenko, and Alex Whitworth.

Abstract (149 words):
This paper explores the governance options surrounding the deliberate, large-scale manipulation of the Earth's climate system to counteract climate change known as geoengineering. For focus we only consider methods that affect the incoming solar radiation into the atmosphere, referred to as Solar Radiation Management (SRM). We examine whether an international governance framework for SRM is needed, how it should be designed, and whether it is feasible. We propose a governance regime that initially has small membership and weak legalization, and is flexible in that future institutional reforms allow for broader membership and deeper commitments. The regime is supported positively by case studies from arms control and environmental protection, including Antarctica, Outer Space, and the Montreal Protocol. For these latter cases, acting early and treating the problem as part of the "common heritage of mankind" has produced more effective outcomes compared to the "national appropriation" approach with arms control.

Introduction

This paper explores the global governance options surrounding the deliberate, large-scale manipulation of the Earth's climate system to counteract climate change, known as geoengineering. The term geoengineering encompasses a broad range of techniques with different governance considerations, and in the interest of focus we only consider those methods that affect the net incoming solar radiation into the atmosphere, often referred to as Solar Radiation Management (SRM). We pose three questions: *i) Will an international framework on SRM be needed? ii) What are the main characteristics that should be included in the design of a governance regime? And, iii) is the proposed governance regime feasible?*

At this writing, exploration of the scientific and political implications of geoengineering is in its early stages with information gathering efforts and interest in the topic expanding beyond a small core in the scientific community. The literature to date on SRM governance has focused on ad-hoc approaches[1] and formal governance options through the United Nations[2], with a report by the House of Commons for the joint US-UK hearings on geoengineering supporting formal governance through the UN system[3]. In terms of research, the European Union has initiated a program to study scientific and political issues surrounding geoengineering, and a report by the US Government Accountability Office has recommended the initiation of a coherent research program in the context of the federal response to climate change[4].

On the first question we argue that an international framework will be needed because of the nature of the problem. There will be growing incentives for states to act unilaterally

[1] Victor 2008.
[2] Virgoe 2009.
[3] Science and Technology Committee, H.C. 221., 2010.
[4] US GAO Report, October 2010.

to benefit themselves, but these actions carry significant uncertainty and could have both positive and negative consequences for others. Thus, geoengineering can be viewed as a collective "non-action" problem that is opposite in nature to climate change. A formal governance regime for both experimentation and deployment would stand a better chance than ad-hoc governance approaches of upholding a number of widely agreed upon normative principles, such as regulation of the terms for SRM usage by public entities, broad public participation, and providing informed consent of affected populations. The regime would also reduce the risk posed by unilateral action, remove decision making ability from nonstate actors, encourage greater transparency of SRM activities within the public domain, and minimize the risk that SRM would divert from mitigation and adaptation efforts.

On the second question we focus on designing a regime that would be effective; where in the context of this paper we refer to effectiveness as the ability of an institution to induce cooperation through mutual policy adjustment[5] and create positive outcomes that would not otherwise have occurred. The initial goal of the regime would be to uphold a temporary moratorium on SRM deployment, and encourage collaboration on scientific research. We argue that restricted membership will be more effective – smaller groups will have a reduced heterogeneity of preferences compared to larger groups, and are more likely to reach collective goals[6]. States are typically unwilling to agree to a highly legalized regime with strong enforcement procedures. A legalized regime, therefore, would not be politically feasible as a first step, especially under conditions of high uncertainty. Thus a small body with weak legalization is more feasible initially. The fair, default solution is that members should have equal votes and veto powers, although power constraints may affect the outcome[7]. Finally, the regime should be flexible in that subsequent institutional reforms are possible, allowing for the regime to proceed as a series of steps that expand membership and deepen legal commitments.

The proposed regime design is supported positively by case studies with similar problem structures, including arms control, stratospheric ozone depletion, and treaties that regulate unexplored territory, such as the Outer Space Treaty and the Antarctica Treaty. For Antarctica, Outer Space, and Ozone, potential environmental problems were averted through international cooperation, and states only had to make relatively small adjustments to their status quo. The case studies suggest two pathways for SRM. The first route would be "national appropriation" as with arms control, whereby some states have strongly invested interests in SRM, and an NPT-type structure could emerge with states divided into two annexes. Alternatively, SRM could become taboo or subject to tightly controlled implementation in order to preserve the "common heritage of mankind", much like the mineral exploitation of Antarctica or the military use of outer space.

[5] Keohane 1984, 51–55.
[6] See Olson 1965; Downs, Rocke, and Barsoom 1996.
[7] "Power" is defined as the ability of A to cause B to act in a way it would not otherwise do; Dahl 1957. "Power constraints" refers to the ability of states to impose their power on others in order to influence institutional design; Moe 2005.

The final question addresses feasibility: even if there are strong normative reasons for an SRM regime, is the proposed SRM regime likely to occur? Will states be better off joining an SRM regime or staying with the status quo and utilizing existing institutions? To answer this question we examine the incentives for actors to join, the benefits of cooperation, and the heterogeneity of preferences. We argue that states will have incentive to join the regime to have a voice on the SRM issue and 'lock-in' their power to influence collective decisions in the long-term, reduce the likelihood of a unilateral intervention, and satisfy the "demand for information" through collaborative scientific research. However, power constraints may lead to a sub-optimal regime, and the question of legitimacy is discussed.

Geoengineering defined and the nature of the problem

In a comprehensive report on the science of geoengineering, the Royal Society[8] defines geoengineering as "the deliberate, large-scale manipulation of the Earth's climate system in order to counteract climate change." Geoengineering techniques are divided into two categories: Carbon Dioxide Removal (CDR), referring to the removal of carbon dioxide from the atmosphere, and Solar Radiation Management (SRM), concerning the intentional manipulation of incoming solar radiation in the atmosphere. SRM techniques include, as one of many examples, the injection of sulphur particles into the stratosphere to replicate the global cooling effect of a large volcanic eruption, such as the 1991 eruption of Mount Pinatubo.

The challenges in developing SRM technology are expected to be far less demanding than the production of nuclear weapons or the creation of vessels for space exploration. For instance, one proposed method is to add devices onto commercial airplanes that would emit reflective particles[9]. Determining the cost, feasibility, and timescale of specific SRM methods will require coordinated research efforts. The general discussion of SRM governance in this paper specifically concerns SRM techniques that include the following options:

i) Injection of particles (sulpher or otherwise) into the stratosphere, above approximately 10km altitude where particles have a lifetime of several years, to reflect incoming solar radiation and replicate the global cooling effect from volcanic activity.

ii) Cloud whitening techniques, whereby aerosols or water vapor would be sprayed into the atmosphere, creating increased low-level cloud cover to reflect incoming solar radiation.

iii) Placing a large mirror in space, at a Lagrangian point where its position is fixed relative to the Earth, or placing a plethora of small mirrors high in the atmosphere.

iv) Any other current or future technology which could significantly alter the net incoming solar radiation in the Earth's atmosphere, and which would constitute a

---

[8] Shepherd et al. 2009.

[9] Aurora Flight Services 2010.

deliberate human attempt to alter the Earth's climate.

In terms of governance, provisions for managing CDR are moving forward under existing international treaties such as the UN Convention on Biodiversity (UNCBD) and the London Convention/London Protocol under the International Maritime Organization. At this writing there is no clear international treaty to control a deliberate, large-scale intervention using SRM techniques. In the interest of focus we limit the scope of this paper to the medium to long-term governance of large-scale climate interventions using SRM techniques that would affect the global commons of the atmosphere, for which currently there is the largest gap in international regulation and greatest potential for fast and uncertain impact on global climate. We only briefly consider here the development of principles and norms for short-term SRM experiments, which has been discussed from the perspective of ad-hoc governance approaches[10].

What is the scientific understanding of the impacts of SRM implementation?
Implementation of SRM would create a net global cooling effect that would offset global temperature rise from climate change. But the impacts of SRM contain great uncertainty. If it were possible to deploy SRM today, it would cause unpredictable and potentially unwanted regional impacts that would create winners and losers[11]. For instance, US temperature and rainfall patterns and the Asian Monsoon system would be affected. If the uncertainty of impacts were to be reduced in future, it is possible that SRM could provide a collective good in the case of a "climate emergency." Once started, however, any SRM intervention would have to continue either indefinitely or until GHG emissions were reduced, because sudden cessation of SRM activities would create rapid climate warming.

There are two scenarios in which SRM might be used. In the first scenario, climate change impacts are largely addressed by conventional mitigation strategies, and SRM is used as a 'peak-shaving' device whereby SRM implementation is employed for a period of at least 50-100 years in order to counter the worst of global temperature rise[12]. The second scenario for the use of SRM is in a world where greenhouse gas emissions continue unchecked or not effectively limited. To compensate for climate change, SRM would have to be used for an indefinite period in increasingly large measure, and the regional temperature and rainfall changes due to SRM would become more pronounced. From the perspective of anticipating a "climate emergency", the risk of adverse impacts in this second business-as-usual scenario would be much greater because of the scale of the intervention required.

SRM invokes broader questions relating to environmental institutional design under conditions of scientific uncertainty. SRM governance is not purely a collective "non-action" problem where the purpose is prevention. As scientific uncertainty is reduced in future, it is possible that SRM could provide a public good in terms of a controlled,

[10] For example, see Victor 2008; Morrow, Kopp, and Oppenheimer 2009.
[11] Robock 2009; Ricke et. al. 2010.
[12] Wigley 2006; Rasch et. al. 2008.

'peak-shaving' solution. Just as likely, SRM may become less favorable as negative climate impacts are realized.

On the interests, preferences, and resources of states
As the uncertainty and consequences of regional-scale climate change unfold, the incentives for states to act unilaterally may grow. Under an interest based approach to international relations, states that stand to suffer from the adverse consequences of climate change would have structural reasons to use SRM unilaterally and oppose those who try to prevent them.

Which states are most likely to be adversely affected by climate change? The most comprehensive assessment of climate change impacts and vulnerability is contained in Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)[13]. Despite the uncertainty from climate model projections under the current IPCC scenarios, a few broad features can be deduced. In particular, sea level rise will impact low-lying states with coastal development and affect Small Island Nations; changing monsoon patterns in Asia could cause catastrophic crop failure; the drying of the Sahel may cause widespread drought in Africa; changes in hurricane activity and extreme weather patterns may affect the US.

Who has the technical capability to conduct SRM? At this writing, the US and the UK have been the primary standard bearers for scientific, technological, and policy-oriented research on geoengineering. Generally, states with nuclear weapon or space exploration capabilities would most likely be among the first to develop the capability for SRM deployment. Estimated costs for global SRM deployment are in the range of $1-10 billion per year[14], and any state or nonstate actor could potentially wield SRM technology. The short time required to create global impact and the low cost of injecting reflective particles into the stratosphere could produce economic incentives that are irresistible[15].

Which states are likely candidates for use of SRM? Small Island nations which might lose viability as sea-level rises and would certainly have incentives to intervene on climate, but may lack technical capacity. Even if they could use SRM, coercive action from other states through persuasion, threats, sanctions, or brute force could quash any attempted SRM intervention. Larger developing states such as Brazil, China, India, or South Africa could place economic development first and foremost and favor SRM. Russia may also acquire SRM capabilities, but is one of a few nations that could potentially benefit from the impacts of climate change in the medium-term (20-40 years). Coercion through economic sanctions would be less effective against these states. The US may also consider SRM as an option if confronted by extreme climate impacts such as drought or severe hurricanes damage. Barrett[16] suggests that one could imagine a scenario where winners and losers from climate change engage in "geoengineering wars."

---

[13] International Panel on Climate Change 2007.
[14] Keith 2000; Nordhaus 2000; Aurora Flight Services 2010.
[15] Barrett 2008.
[16] Barrett 2008.

Figure 1 shows a first cut that divides states according to projected climate change vulnerability and potential capacity to produce and use SRM technology unilaterally. Although vulnerability to climate change is widespread, not all states will have the technical capacity to implement SRM. The actions of one state, however, will affect all other states, and any institution formed by a group of nations in the "Yes-Yes" box would create externalities to nations in all other categories by conducting SRM activities.

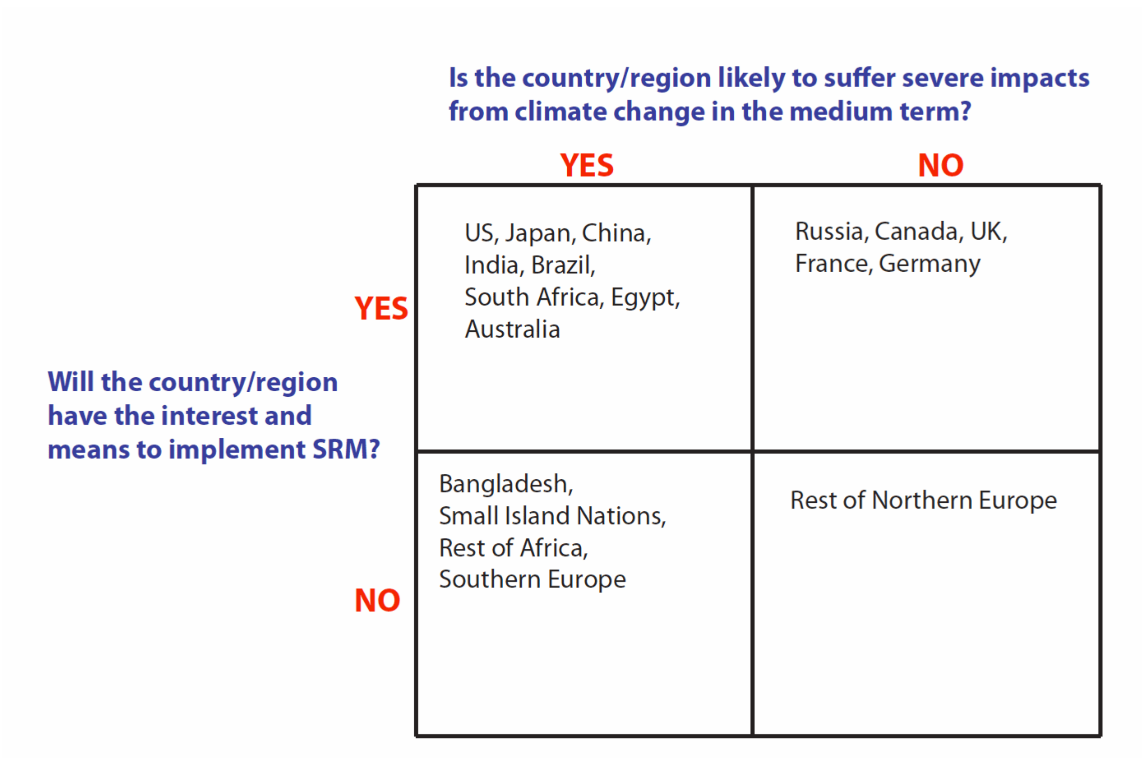

Figure 1

This "first-cut" is very approximate. The intention is to illustrate how, given suitable criteria, states can be split into a 2X2 matrix asking: "Is the country/region likely to suffer severe impacts from climate change in the medium term (20-40 years)?" and "Will the country/region have the interest and means to implement SRM?" Vulnerability to climate change is estimated from the IPCC report on "Impacts, Adaptation, and Vulnerability"[17], and the ability to implement SRM is judged based on nuclear and space capabilities, GDP, and general activity and interest on SRM. Due to the difficulty in making distinctions between states, only select cases are highlighted.

[17] Intergovernmental Panel on Climate Change, Fourth Assessment Report. 2007.

Geoengineering and the risk of diverting resources from adaptation/mitigation
A number of statements by scientific societies[18] agree that the impacts of SRM are uncertain, and that the best method of stabilizing the Earth's climate is to reduce greenhouse gas emissions[19]. But in future, states *could* decide that SRM is the best course of action to manage the risk of climate change. An international agreement should be flexible in that it can take account of both these factors: to not divert from mitigation and adaptation, and to allow for the possibility that one day SRM may be publicly and politically desirable.

Central to the discussion of SRM is the "moral hazard" problem, which in the context of the geoengineering literature poses that the actions of state and nonstate actors in even thinking about SRM would divert time, resources, and political will from domestic mitigation efforts and international climate change negotiations.

The threat of SRM detracting from carbon mitigation efforts is a legitimate concern, but it is not possible to predict whether this risk will come to fruition. The reverse moral hazard argument could also apply, whereby the prospect of using SRM will become so repulsive that efforts to reduce GHG emissions will be redoubled. The reverse moral hazard is more challenging, however, because of the strong economic incentives that may arise to employ SRM rather than pursuing GHG mitigation options. The economic incentives in favor of SRM would have to be overcome by shifts in perception and ideology of not just one state, but all states that would be capable of using SRM.

Regardless of whether the moral hazard argument for SRM will be realized, governance of SRM should be considered from a risk management approach. The design of SRM governance should take into account the *risk* that SRM could derail mitigation efforts. An SRM governance regime, then, should seek to reduce the risk that the availability of SRM would decrease attention to emissions abatement.

Geoengineering and climate change: Inherent ties and fundamental differences
The question of SRM governance is implicitly connected with efforts to mitigate carbon emissions and adapt to climate change. Climate change is a collective action problem, and the success of any global climate agreement will depend on the mitigation efforts of a select few large emitters. The actions of states with low emissions, while politically meaningful, will not have significant impact on the outcome of mitigation efforts. Attempts by states to negotiate a consensus agreement on binding emissions limits with widespread participation have to date been unsuccessful, and a regime complex of loosely coupled institutions for climate change has emerged[20].

SRM, however, poses an entirely different governance problem to that of climate change. While there are no clear international regulations to govern SRM, any state, private organization, or potentially an individual could unilaterally intervene on climate and

[18] National Academy of Sciences; Royal Society; American Geophysical Union; American Meteorological Society.
[19] Shepherd et. al. 2009.
[20] Keohane and Victor 2011.

create global impacts on the climate system. Keohane and Victor[21] outline these differences:

"With geoengineering, action by one or a few actors may be too tempting and need to be prevented, which makes the cooperation challenge the opposite of collective action to control emissions. That is, the challenge in geoengineering is how to make it more difficult rather than easier to act."

On the need for an SRM governance regime

A critical question is whether an international treaty is needed and could be both effective and feasible. On the *need* for an SRM regime we argue in this section that a regime would meet a number of normative governance principles for SRM. In subsequent sections we address the questions of *effectiveness* and *feasibility* from a positive state-centric perspective by evaluating the problem structure of SRM and relevant case studies.

A number of normative governance principles have been discussed for the regulation of SRM[22]. These principles include the regulation of SRM activities by public entities (rather than private-sector or military); broad public participation in SRM; a specialized body to conduct independent assessment of SRM impacts; notification, consultation and informed consent from the affected population as prerequisite to experimentation and deployment; and the principle that SRM activities should not endanger or violate basic human rights irrespective of potential gains. There are four reasons why an effective SRM regime is desirable for meeting these criteria when compared to the unilateral governance case:

i) *Removal of decision-making ability from nonstate actors*. International regulations on SRM would remove decisions of SRM deployment away from an epistemic community of scientists, policy experts, and other nonstate actors. Deployment by nonstate actors would violate most of the governance principles listed above, including regulation by public entities, broad public participation, and informed consent of affected populations.

ii) *Transparency.* SRM activities should be conducted in a transparent fashion in order to build trust, and avoid the possibility of SRM activities being conducted in a non-public manner by private or military interests. Transparency through an SRM regime would support the principles of public regulation, broad public participation, evaluation of SRM impacts, and informed consent.

iii) *Regime compliance.* The incentives to comply with an international framework and the punishments for non-compliance could reduce the likelihood of unilateral action, which in turn would give a better chance of meeting the normative criteria of global public consent for any decision on SRM, if and when needed.

[21] Keohane and Victor 2011.
[22] Rayner et. al., 2009; Morrow et. al. 2009; Schneider 2009; and Jamieson 1996.

iv) *Diversion of resources from mitigation/adaptation.* Designed correctly, a governance regime could reduce the risk of a "moral hazard" dilemma, whereby efforts for mitigation and adaptation are further weakened by the prospect of SRM. That is, by imposing suitable decision-making procedures, a successful regime would make it difficult to invoke the use of SRM.

Ad-hoc versus formal governance
Victor[23] argues that norms to govern SRM, along with efforts to expand research, will soon be vital. Victor's ad-hoc ("bottom-up") approach to building principles and norms for SRM research and deployment may be needed in the short-term at both the domestic and international level. For medium to long-term SRM governance, however, we argue that a formal ("top-down") coordinated approach will be needed in order to meet the proposed normative criteria. The need for formal SRM governance is taken as a premise for the remainder of this paper.

The top-down governance approach has been supported in recent reports and hearings within the US and UK governments. During the joint US-UK hearings on geoengineering[24], Phil Willis MP testified "there are good reasons for developing international regulatory framework on geoengineering, whether through existing regimes, or new designs for SRM outside of current frameworks." The House of Commons report on geoengineering[25] supports the eventual adoption of SRM governance through the United Nations, for the following reasons:

"First, in the future some geoengineering techniques may allow a single country unilaterally to affect the climate. Second, some – albeit very small scale – geoengineering testing is already underway. Third, we may need geoengineering as a 'Plan B' if, in the event of the failure of 'Plan A' – the reduction of greenhouse gases – we are faced with highly disruptive climate change."

Design of an international regime for SRM

In this section we outline the desirable features of an effective SRM regime, conditional on the preferences of states before participation and ratification, and the incentives of states to comply with the rules after ratification. Under a rationalist framework of world politics it is important to acknowledge that any state may choose to protect their sovereign interests and international institutions may not be adequate to prevent unilateral action. Notwithstanding this possibility, neoliberals argue that multilateral institutions can enhance the likelihood of cooperation by reducing transaction costs, enhancing the shadow of the future, and building trust through repeat interactions[26].

The SRM regime design is first described under a general analytical framework. It is then supported by case studies with similar problem structures that are broadly

[23] Victor 2008.
[24] US House Committee on Science and Technology, 2010.
[25] House of Commons report, HC221 2010.
[26] Axelrod and Keohane 1985.

preventative in nature and require collective "non-action." Variation across state preferences and problem structure in the case studies is shown to support the proposed SRM regime design. Briefly, the initial goal of the regime is to hold a temporary moratorium on SRM deployment, and allow for collaborative scientific research. To begin with the SRM regime should have small membership, weak legalization, equal voting powers for members, and the flexibility to allow for future institutional reforms. This flexibility would enable the regime to proceed as a series of steps that allow for broader membership and deeper commitments with time.

The proposed SRM regime is based on positive arguments relating to the effectiveness of institutional arrangements. We draw on existing theories because they provide useful criteria for classifying different features of our regime design, but we do not use theoretical conjectures about regime design as justification. In particular, the Rational Design (RD) framework, which considers states as self-interested rational actors that design institutions to advance their joint self-interest, is used to separate regime design into the criteria of Membership, Scope, and Flexibility[27]. However, the RD criteria of Centralization and Control are not addressed in full here, as they may be subject to political process and given high uncertainty it is not clear what the positive implications are[28]. The RD framework does not address legitimacy[29], which we consider in part through a scientific body to provide accountability. For example, the conjecture "larger uncertainty leads to greater centralization" is not empirically proven – and the opposite may be true in the case of climate change. We also note that some of the SRM design features are consistent with Principal-Agent theory[30], which is concerned with why states choose to delegate responsibility to international organizations for certain types of problem, such as the "demand for information", monitoring and compliance, and credibility of commitments. Finally, we acknowledge that power constraints may make regime design sub-optimal, and any SRM regime may ultimately reflect the interests of a few powerful states[31].

i) A small membership is needed initially for an effective regime

This statement is intuitive: smaller groups are more coherent and effective, and do not rely on coercion or positive inducements apart from the collective good itself. As group size increases, the provision of the common good becomes less optimal[32]. The initial inclusion of states that are not capable of performing SRM would inhibit cooperation.

The case for small membership is supported by, for instance, institutions with small membership such as the Group of Eight (G-8), the International Monetary Fund (IMF) or World Bank boards, compared to multilateral organizations such as the UN General Assembly (UNGA) or UN Framework Convention on Climate Change (UNFCCC). The

---

[27] Koremenos, Lipson, and Snidal 2001.
[28] Under the RD framework, Centralization refers to the degree of delegation among institutions (e.g., the centralized Antartica Treaty, versus the decentralized WTO dispute-resolution panels); while Control refers to the rules and procedures for making collective decisions.
[29] Wendt 2001.
[30] Hawkins et. al. 2006.
[31] Moe 2005.
[32] Olson 1965; Snidal 1985.

IMF and World Bank have weighted voting system based on the relative contribution of states; for the IMF, the US has 17% of the vote, which effectively provides veto power on decision requiring 85% majority. The G-8 consists of members representing the world's eight largest economies, who are able to set agendas that reflect their common interests. Conversely, the UN General Assembly or the UNEP/FCCC are large and unwieldy, containing states with a large heterogeneity of preferences leading in general to weaker effectiveness. The SRM regime should initially hold membership to 30 states or less.

For a state to gain membership in the SRM regime it will most likely meet three criteria: *vulnerability*, *technical capacity*, and *affordability*. First, the state will desire to seek membership if they have a high vulnerability to climate change or the potential effects of SRM. Second, the state should have the technical capacity to develop and implement SRM within a relatively fast time frame compared to other states. Finally, the state should find SRM deployment affordable. SRM implementation would cost approximately $1-10 billion per year to offset global temperature rise[33], and states for which this cost would be less than 1% of GDP would likely be more suitable for membership.

At the 2010 Asilomar Conference on Climate Intervention Technologies, Richard Benedick proposed an outline for SRM membership that would approximately fit these three criteria. Benedick recommends an SRM governance framework initially including under 20 states: Australia, Brazil, Canada, China, Egypt, Germany, India, Japan, Russia, South Africa, Spain, Sweden, and United Kingdom. Benedick puts forward in his memo[34] that the "proposed list is not immutable; it represents a consideration of scientific infrastructure, geographical balance and record of climate mitigation efforts" and that "the objective is not to negotiate a formal treaty, but rather to forge a community of mutual trust and commitment" towards a "generally agreed set of guidelines."

The proposed criteria for membership with a 30-state limit would act as an initial protocol subject to future review. Because the actions of a few states would cause global climate impacts, and because more states will eventually gain the technical capacity to implement SRM, membership should be open to future expansion.

ii) A regime with weak legalization is needed to engage participation

States are typically unwilling to agree to highly legalized commitments, especially under conditions of high uncertainty[35]. Ideally, an SRM regime with precise rules and extensive legalization would be more effective; such a legalized regime would place a moratorium on SRM deployment, with strict enforcement consequences for non-compliance. The regime could include a clause to allow for SRM deployment after a difficult voting process (for example double or super-majority), ensuring wide participation and approval in the event that mitigation efforts are deemed inadequate.

---

[33] Keith 2000; Nordhaus 2000; Aurora Flight Services 2010.
[34] Benedick 2010.
[35] For example, see Thompson 2009.

But while a legalized regime may be a desirable end goal, it may not be politically feasible as an initial regime, as economically developing states such as China, Brazil, India, and South Africa would be wary of forfeiting their ability to implement SRM. The regime design for SRM must account for the political capacity of states to collectively build international institutions, and address the key political tradeoff between participation and depth of cooperation[36]. Thus, when first designed, the SRM regime should have limited legal power, and a small body with weak legalization is needed. With future reforms and reduced scientific uncertainty, deeper commitments may be possible.

This approach will help to confine the scope of the regime to SRM only, since mitigation and adaptation efforts proceed through the broader UNEP/FCCC framework. By creating an SRM regime with small membership and weak legalization, concerns over the "moral hazard" problem are reduced, which would be more prevalent if SRM were to be subsumed into the UNEP/FCCC process.

iii) Voting powers

The default solution in a small, weakly legalized regime is that members should have equal votes and veto powers. This solution would be fair in that SRM deployment would create similar global impact when performed by any state. However, the distribution of voting power may be skewed during the bargaining stage through alteration of state preferences by argumentative persuasion[37], and the outcome of such a political process is unpredictable.

iv) The SRM regime should be flexible

The SRM regime should be flexible in that multiple institutional reforms are possible. With subsequent reforms the regime could be strengthened as the uncertainty in SRM decreases, and membership could be expanded.

Thompson found that for the case of UN climate negotiations, increased uncertainty leads to greater flexibility of institutions[38]. This finding is in support of the conjecture posed by the RD framework that increased uncertainty leads to greater flexibility of institutions. Thompson distinguishes between general flexibility, where actors have equal impact on a global public good (the atmosphere) and particularistic flexibility, where actors can have unequal impact. Climate change exhibits particularistic flexibility, in that a few large emitters can have a much greater impact on the overall success of the treaty, and the transformative regime design has proven problematic. Thompson finds that "actors faced with general uncertainty have incentives to create institutions with transformative flexibility." The SRM problem also exhibits general flexibility, whereby actors within the regime membership will have an approximately equal capacity to use SRM and impact global climate. Despite the differences in problem structure between climate change and SRM (collective action versus collective "non-action"), Thompson's observation is useful

---

[36] Downs, Rocke, and Barsoom 1996.
[37] Grobe 2010.
[38] Thompson 2009.

for regime design, and is also supported by the development and strengthening commitments in the Montreal Protocol and Antarctica. Given conditions of uncertainty, a flexible regime design is useful in that institutional reforms can be made as actors gain understanding.

v) Accountability through collaborative scientific research

The SRM regime should contain a subsidiary scientific body that would allow for greater accountability and the coordination of scientific research. Buchanan and Keohane propose a Complex Standard for the legitimacy for Global Governance Institutions that puts forward three criteria: the consent of democratic states, minimal moral acceptability, and epistemic virtues[39]. A scientific body would help in meeting these criteria at least partially, by providing epistemic qualities and introducing accountability *ex post* and *ex ante* that would act to reduce abuses of power[40].

The following example illustrates how the scientific body could act to evaluate proposals for SRM. The example is a simple template for an accountability scheme and in practice many further layers of detail could be added[41]. If a state wishes to conduct any SRM activity, they would be required to submit a proposal to the scientific body, which would be classified according to three types of SRM:

Class I) *Low risk:* Small-scale non-invasive SRM experiments, without trans-boundary effects[42]
Class II) *Medium Risk:* Large-scale SRM experiments with *de minimis* impact, and potential trans-boundary effects
Class III) *High Risk:* Large-scale SRM deployment with global impact

The three classes of SRM activity would then be subject to decisions by the governing body. Class I experiments would be most frequently permitted; class II cases might be banned initially but occasionally permitted at a later time as knowledge from less invasive methods increased; and class III experiments only permitted with consensus from all members after a difficult voting process. Of course, several subclasses and further adjurations could be added to the classification. The scheme serves as an illustration and the precise details do not affect the arguments in this paper.

After SRM activities are conducted, *ex post* reviews should take place, in which the scientific body would judge whether the SRM intervention carried out corresponds to the original classification. If the SRM activity by a state exceeds its original classification, the state incurs reputational costs and will be less likely to be given consensus approval for future SRM activities. Thus, there is a built in mechanism to improve compliance.

---

[39] Buchanan and Keohane 2005.
[40] Grant and Keohane 2005.
[41] The Royal Society is developing guidelines for the different degrees of SRM activities (SRM Governance Initiative, 2011). Procedures similar to Institutional Review Boards and other scientific bodies are suggested for SRM experiments in Morrow et. al. 2009.
[42] On conducting low-risk SRM experiments, see Morrow, Kopp, and Oppenheimer, forthcoming.

Case studies supporting SRM regime design

To support the proposed analytic framework for SRM regime design, case studies with similar problem structure to SRM are examined. The selection of case studies is based on the criteria that the treaties are preventative in nature and require collective "non-action." We consider treaties in arms control, including the Partial Test Ban Treaty, Comprehensive Test Ban Treaty, and the Non-Proliferation Treaty, and treaties involving the regulation of unexplored territory, including the Antarctica and Outer Space treaties. We also consider the Montreal Protocol on Ozone Depleting Substances in the context of developing countries. For these case studies, we examine how variations in state preferences and problem structure affect regime design. Problem structure is considered in terms of incentives, capacity, information, and norms, and because problem structure may not be entirely endogenous to regime design, we also consider state preferences[43].

T*he 1963 Partial Test Ban Treaty and the 1996 Comprehensive Test Ban treaty*

Background and state preferences. The 1963 Partial Test Ban Treaty (PTBT) and the 1996 Comprehensive Test Ban treaty (CTBT) were designed to encourage non-proliferation by limiting technology development through nuclear testing. The PTBT was led by US, UK, and USSR, was eventually signed and ratified by 108 states. The PTBT has not been successful in ensuring compliance from all states; notable exceptions included France and China, who conducted tests through the 1960's–80's. The PTBT is legally binding, quite precise, but delegates almost no legal authority[44]. The CTBT has not at this writing been ratified by the US and has not entered into force. The PTBT requires parties "prohibit, to prevent, and not to carry out any nuclear weapon test explosion, or any other nuclear explosion" in the atmosphere, outer space, and under water. The CTBT was able to include underground testing due to improvements in technology.

Problem structure. The PTBT and CTBT have similar problem structures to SRM in that they both require collective "non-action"; namely that nuclear testing be prohibited. However, the PTBT/CTBT call for a ban on weapons testing, while for SRM a total ban may not be desirable, in the event that mitigation options fail and "Plan B" is needed in a climate emergency. In terms of incentives to form the PTBT/CTBT, active nuclear tests by several states galvanized the epistemic community and governments into gathering political will to create a treaty. Considering the capacity of states for nuclear testing, states capable of testing are also likely to be capable of performing SRM interventions, which are expected to be technically less demanding. With regard to information, the PTBT/CTBT highlight that verification of nuclear testing is crucial to the success of the treaties. By the time SRM technology becomes ready for large-scale deployment, verification technology may be available, for instance through remote sensing. Norms for the PTBT follow "national appropriation" – involving strongly invested interests in nuclear capabilities and linkages between states – and the treaty was formed in reaction to

[43] That is, regime design can be affected by state preferences and problem structure for a given issue area; Mitchell 2006.
[44] Abbott et. al. 2001.

nuclear testing by several states. SRM experiments have not, as yet, been conducted on this scale.

The 1968 Non-Proliferation Treaty

Background and state preferences. The central provisions of the Nuclear-Proliferation Treaty (NPT) requires that five Nuclear Weapons States (US, UK, Russia, France, China) must not transfer weapons to non-weapon states (art. I), and that non-weapon states must not receive any transfer of weapons (art. II). States have the right to withdraw from the treaty "if it decides that extraordinary events, related to the subject matter of this Treaty, have jeopardized the supreme interests of its country" (art. X). One of the contentious points (art. 3.3) is the avoidance of economic and technological development of some peaceful uses of nuclear materials, especially with regard to reprocessing and enrichment.

To date, the NPT has been signed by 190 states with the notable exceptions of India, Israel, and Pakistan. In the case of extreme national interest a state is under no obligation through international law. The NPT calls for safeguards to enable verification by the International Atomic Energy Agency (IAEA; art. III) and North Korea, for example, failed to accommodate for NPT safeguards allowing the IAEA to verify nuclear testing, and subsequently withdrew from the treaty. Although the NPT is in crisis today it has had some successes, for example with the policies of South Africa, Brazil, and Argentina.

Problem structure. The NPT has elements of both collective "non-action" and collective action problems: on the one hand the NPT sets out to reduce the number of nuclear weapons and allow for peaceful use of nuclear power (collective action) while on the other hand it requires cessation of weapons development (non-action). Regarding the incentives to join the NPT, nuclear deterrence provides a strong incentive for joining. Unlike nuclear weapons, An SRM intervention is "reversible" in the sense that if it is 'switched off' after a short time, no long-term damage will result and in this regard nuclear weapons carry a larger perceived threat. Annex I states have the capacity to use nuclear weapons. States have not developed SRM technologies as yet. Thus the division of states into two annexes, based on whether states have conducted large-scale testing, is not yet relevant to SRM. However, SRM technology is likely to be more affordable and much less technically demanding than nuclear weapons, and issues of technology transfer will be less important. The number of actors could therefore be larger, and provisions in Articles I and II would be less meaningful to states interested in capacity building for SRM. Similarly to the PTBT/CTBT, verification is a key component of the NPT, and information concerns are focused on the interests and resources of states, rather than scientific uncertainty. Like the PTBT/CTBT, the NPT also follows the norm of "national appropriation", in that states had strongly vested interests and linkages.

The Antarctic Treaty

Background and state preferences. From 1908 to 1940, seven states had territorial claims over Antarctica: Argentina, Australia, Chile, France, New Zealand, Norway, and the UK Three states, Argentina, Chile, and the UK, had overlapping claims. Cooperation on scientific activity in Antarctica during the International Geophysical Year (1957-1959) led to the signing of the Antarctica Treaty in 1959 by 12 states, including the seven claimants and Belgium, Japan, South Africa, the Soviet Union, and the US The availability of resources in Antarctica was unknown during the negotiations in 1958-1959, and in December 1958 the US convened a conference to determine a legal regime for Antarctica[45]. The treaty included the bargain that territorial claims would be "ignored for purposes of cooperation, but would not be ignored in principle" (art. IV), and declared the landmass of Antarctica to be used for peaceful purposes, promoting scientific research and cooperation.

The treaty grew in legal authority through subsequent reforms. Article IX establishes what is referred to as the "Antarctic Treaty Consultative Meeting" where states that have established a threshold level of interest in Antarctica periodically meet to formulate and recommend measures to further the objectives of the Treaty. The availability of mineral resources in Antarctica attracted further international attention in the 1970-80's[46], leading to the development of the 1991 Protocol on Environmental Protection (Madrid Protocol) to the Antarctic Treaty, which bans extraction of natural resources and contains a liability provision. The Treaty was eventually signed by 47 states. The participating states enter negotiations to resolve disputes through peaceful means, and unresolved disputes are referred to the International Court of Justice (art. XI).

Problem structure. Antarctica is similar to SRM in that it requires collective "non-action" over the regulation of unexplored territory. Considering the incentives to ratify, the treaty was agreed in 1959 by a small number of states to resolve territorial disputes over claims of sovereignty[47]. The bargains made by these states did not have direct externalities to others. SRM is different in that deployment would create externalities through global climate impact. Even if the Madrid Protocol reflected the economic interests of the Parties regarding mineral resources, as opposed to a successful process of international cooperation, the Protocol was not possible when the treaty was first signed. For Antarctica, states had the capacity to comply, as they did not have to significantly change their status quo to ratify the treaty. But there were still costs incurred in the maintenance of the treaty and support for monitoring and compliance procedures[48]. In terms of information, Antarctica contained large scientific uncertainty and the treaty was created in the spirit of scientific cooperation. Antarctica followed the norm of the "common heritage of mankind", and was developed out of the desire to preserve Antarctica for peaceful purposes and reduce rivalry over resources.

The Outer Space Treaty

Background and state preferences. The Outer Space treaty states that the "exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries" (art. I). The motivation for the Outer

[45] Peterson 1998.
[46] Peterson 1980.
[47] Peterson 1988.
[48] Sands 2003.

Space Treaty was to ensure that the new realm of outer space could not be exploited for military purposes, with the preamble declaring outer space as the "province of all mankind" that "should be to the benefit of all nations." Unlike Antarctica, the treaty is a one-off agreement and has not undergone institutional reforms. Article IV calls for arms control provisions: nuclear or any other weapons of mass destruction may not be placed in orbit around the Earth or any other celestial body, and the moon and other celestial bodies are limited exclusively to peaceful purposes, with military use being expressly prohibited.

States which launch objects into space are also liable for damage, but the treaty lacks compensation or dispute mechanisms. The treaty has an extensive liability scheme: "Each State Party to the Treaty that launches or procures the launching of an object into outer space, … is internationally liable for damage to another State Party to the Treaty … by such object or its component parts on the Earth, in air space or in outer space, including the Moon and other celestial bodies" (art. VII). With regard to state preferences, nuclear states used Outer Space to regulate nuclear testing in a "new" territory and prevent the creation of another problematic issue for arms control.

Problem Structure. The problem structure of Outer Space requires collective "non-action." Regarding incentives, the treaty was the second "non-armament" treaty to follow after the Antarctic Treaty, with states seeking to avoid "a new form of colonial competition" in which nuclear testing would be conducted in outer space. Similarly to Antarctica, states had the capacity to comply, as they did not have to change their status quo apart from membership costs. In terms of information, Outer Space could be observed and monitored with high scientific certainty, and extensive liability schemes were developed. In contrast SRM has high scientific uncertainty, although it is possible that SRM could develop a liability regime for negative impacts of SRM that are traceable. Like Antarctica, outer space followed the norm of the "common heritage of mankind."

<u>The Montreal Protocol on Substances that Deplete the Ozone Layer</u>

Background and state preferences. The 1987 Montreal Protocol (MP) is often held up as an exemplar of a successful environmental agreement, controlling the phase-out for the production and use of Ozone-Depleting Substances (ODS). The negotiation process was initiated by UNEP in the early 1980's, leading to the 1985 Vienna Convention, which set out general obligations and procedures including a provision to "take appropriate measures" to protect the environment against human activities that are likely to modify the ozone layer. As scientific and economic uncertainty were reduced, the MP underwent several reforms to implement stricter controls on ODS.

Benedick attributes the success of the MP to a number of factors: the role of science; changes in public opinion; national leadership and policies; involvement of private-sector organizations; and choices in the procedures of the negotiation process[49]. The MP was

[49] Benedick 1998.

designed as a flexible and dynamic instrument, and included a clause that authorized UNEP to reopen diplomatic negotiations after the Vienna Convention.

Problem Structure. For developing states, for which per capita consumption of CFCs was only a small fraction of industrialized nations, the MP represents a collective "non-action" problem in that they were required to not develop CFCs. Developing states were given incentives to comply with MP through financial and technical assistance from the Multilateral Fund and a 10-year grace period allowing for an increase in per capita CFC consumption (art. V). In terms of capacities, CFC technologies were readily available and affordable (particularly given the existence of the Fund). With regard to information, there was significant scientific uncertainty surrounding the CFCs and the ozone hole when the protocol was first signed. As uncertainty reduced, the protocol strengthened. Finally, In terms of norms, solutions to the ozone problem were viewed as environmental protection for humans and ecosystems.

Inferences for SRM regime design: Explaining institutional outcomes through variations in problem structure

Variations in problem structure and state preferences lead to different institutional outcomes across the case studies examined, and lend support to the proposed SRM regime design. The normative characteristics of the case studies hold a key distinction: the PTBT/CTBT and the NPT follow "national appropriation", while Antarctica, Outer Space, and the MP follow environmental protection as the "common heritage of mankind." For the latter cases, negotiations came early in the life-cycle of the environmental problems, and the issues of concern became taboo. States had the capacity, incentives, and information to cooperate. In contrast for the arms control cases, states had strongly vested interests and linkages, and complex treaties with mixed success emerged like the two-tier annex structure of the NPT.

Problem structure and state preferences thus influence regime design from a dynamical standpoint. An SRM regime can be enacted early under the "common heritage of mankind" approach following Antarctica, Outer Space and the MP; or, regime formation may be delayed until SRM becomes a matter of "national appropriation", following arms control treaties. The analytic framework for the proposed SRM regime supports the former approach.

Considering the "common heritage" treaties for environmental protection and the regulation of unexplored territory, variations in information in terms of scientific uncertainty affect the outcomes. For Antarctica and the MP, high scientific uncertainty led to flexible regimes with small memberships that were expanded and legalized over time. For instance, The 1991 Madrid Protocol of the Antarctic Treaty, with its liability provisions providing deeper commitments would not have been agreed to in 1959. The process of treaty formation for Outer Space was constructed around the use of competing analogies to previous institutional designs, including Antarctica[50]. However, Outer Space differs from Antarctica and the MP through its low scientific uncertainty and a fixed, one-off agreement with an extensive liability scheme was agreed. Given the high

[50] Peterson 1997.

uncertainty for SRM this inference positively supports a flexible SRM regime design. Antarctica and the MP also contain accountability through scientific research, as proposed for the SRM regime. Thus, Antarctica and the MP support the proposed SRM regime design for acting early under the "common heritage of mankind", with a flexible regime that expands and legalizes with time from an initially small membership requiring weak commitments.

Is the proposed SRM regime feasible?

We have argued that a new SRM regime with small membership and weak legalization would be most effective in upholding a number of widely-held governance principles on SRM. In this section we consider whether the proposed SRM regime is politically feasible. To be feasible, states must determine if the SRM regime is in their self-interest, and leave them better off compared to the choices of unilateral governance or utilizing existing institutions. For instance it is arguable that the Stockholm Convention, UNEP/FCCC, ENMOD, or others, could be modified to cover SRM, even though these institutions were not expressly designed for such purpose[51]. The UN Convention on Biological Diversity has already included language on geoengineering methods that affect biodiversity[52]. Given the interests and preferences of states (see Introduction), will states have sufficient incentive to participate and ratify with a new SRM regime? What are the obstacles to regime formation?

Why would states participate, ratify, and comply with the proposed SRM regime?
There are three reasons in support of this question: states will seek to have a voice and 'lock-in' their policy preferences; the regime would reduce the likelihood of unilateral SRM deployment; and collaborative scientific research would reduce uncertainty.

First, the most important answer is that states will want to have a voice in 'SRM diplomacy' and influence the actions of others. A new international order could be created for SRM, similar to the building of institutions after major wars[53], or offer states the opportunity to 'lock-in' their policy preferences as described in Principal-Agent theory[54]. Powerful states will be willing to accept short-term cost in creating institutions that 'lock-in' their power in the long-term, and less powerful states will desire to join these institutions to allow them greater platform to communicate their interests. For example, the US and Europe established membership and control mechanisms that maintained their power over the long-term for institutional arrangements such as the Bretton-Woods agreement, the IMF, and NATO.

Second, participation in a new regime by SRM-capable states would reduce the risk of unilateral action by requiring a temporary moratorium on SRM deployment. Ratification

---

[51] 1972 UN Conference on the Human Environment (the Stockholm Convention); 1992 Rio Declaration on Environment and Development; Environmental Modification Convention (ENMOD).
[52] UN Convention on Biological Diversity, 10^{th} Conference of the Parties.
[53] Ikenberry 2001.
[54] Hawkins et. al. 2006.

and compliance with the regime would increase the likelihood that any decision on the use of SRM would be collective, rather than individual. The regime would also provide a forum in the case of unilateral SRM interventions by a state or nonstate actor.

Third, participating states would stand to benefit from collaboration on scientific research, and accountability of SRM activities would be provided by evaluation of SRM proposals both ex ante and ex post. Scientific collaboration would build mutual trust and lessen the risk of harmful impacts from unilateral SRM activities.

What are the obstacles to regime formation?
i) Power and the heterogeneity of preferences: A greater extent of heterogeneous preferences could make it more likely that power constraints would lead to a sub-optimal regime[55]. However, a smaller membership generally implies less variation in preferences since membership is confined to states with similar interests. These interests may reflect a collective vulnerability to climate change, the technical capacity and financial means to perform an SRM intervention, and a desire to reduce SRM uncertainty and control the actions of others. With time, these interests may lead to greater convergence of SRM policy preferences, as with other environmental issue areas[56].

Of course, there will still be fundamental differences between, for instance, the US or the E.U., and emerging states such as Brazil, India, China, or South Africa who may approach SRM as an economically viable solution to climate change. These differences will present significant barriers to i) ratification, ii) compliance, and iii) future deepening of legal commitments.

ii) Legitimacy. We emphasize that the focus of this paper is on the effectiveness of an SRM regime, and that a full account of the SRM regime's legitimacy merits further exploration[57]. However we raise a few issues. SRM deployment would create global impact, and any regime with small membership would contain externalities to non-members. The legitimacy of the SRM regime is therefore brought into question. A scientific body would provide some measure of legitimacy through accountability and transparency, and contribute to meeting Buchanan and Keohane's Complex Standard for Global Governance Institutions[58]. Ultimately, though, it may not compensate the perceived 'legitimacy-deficit'. Modeling the SRM regime around similar frameworks starting with small membership such as Montreal or Antarctica, with the intention of future expansion, would help to provide legitimacy.

Under conditions of large scientific uncertainty it is not clear whether a highly centralized regime (Antarctica or Outer Space) or a regime complex (climate change) may emerge on SRM[59]. In the case of an SRM regime complex the proposed SRM regime, with small

[55] Moe 2005.
[56] Holzinger, Knill, and Sommerer 2008.
[57] The legitimacy of SRM experimentation is addressed in Morrow, Kopp, and Oppenheimer 2011, forthcoming.
[58] Buchanan and Keohane 2005.
[59] On regime complexes, see Alter and Meunier 2009; Keohane and Victor 2011.

membership, could be coupled to the UNGA or UNFCCC to provide greater legitimacy. Alternatively, coalitions on SRM may form through existing regional bodies, for instance linking institutions such as the EU, ASEAN, the African Coalition, or the Major Economies Forum on Energy and Climate.

Conclusion

The potential for future SRM deployment by an individual actor presents a threat to all states, and can be viewed as a problem of collective "non-action." While different in nature to the problem of climate change, SRM deployment and climate change are inherently connected. SRM is also unique in that states could jointly agree on deployment as a global public good if states are highly vulnerable to climate change, uncertainty in SRM can be reduced sufficiently, and the benefits of acting outweigh the costs. An international regime for SRM is needed to avoid diversion of resources from climate change, remove decision making powers from nonstate actors, encourage transparency, and reduce the likelihood of unilateral action.

Based on the nature and uncertainty of SRM and the interests and preferences of states, we propose an SRM regime that would install collaboration and accountability through a subsidiary scientific body, and require a temporary moratorium on SRM deployment. The Antarctic Treaty, Outer Space Treaty, and Montreal Protocol provide positive analogies for successful models of international cooperation that are preventative in nature. The regime would initially have limited membership and weak legalization, solely encompass the issue of SRM, and be flexible, allowing for future institutional reforms towards deeper commitments and broader membership.

References

Abbott, Kenneth W, Robert O. Keohane, Andrew Moravcsik, Anne-Marie Slaughter, and Duncan Snidal. 2001. The Concept of Legalization. In *Legalization and World Politics*, edited by Judith Goldstein, Miles Kahler, Robert O. Keohane, and Anne-Marie Slaughter. Camridge, MA: MIT Press.

Alter, Karen J., and Sophie Meunier. 2009. The Politics of International Regime Complexity. Symposium. *Perspectives on Politics* 7 (1): 13–24.

Aurora Flight Services. 2010. *Geoengineering Cost Analysis*. Prepared under contract to the University of Calgary.

Axelrod, Robert, and Robert O. Keohane. 1985. Achieving Cooperation Under Anarchy: Strategies and Institutions. *World Politics* 38 (1): 226–254.

Barrett, Scott. 2008. The Incredible Economics of Geoengineering. *Environmental and Resource Economics* 39 (1): 45–54.

Benedick, Richard E. 1998. *Ozone Diplomacy: New Directions In Safeguarding the Planet*. Cambridge, MA: Harvard University Press, 2nd ed.

Benedick, Richard E. 2010. Considerations on Governance for Geoengineering Research and Deployment. *Asilomar Confererence on Climate Intervention Technologies*.

Bodansky, Daniel. 1996. May we Engineer the Climate? *Climatic Change* 33 (3): 309–321.

Buchanan, Alan, and Robert O. Keohane. 2006. The Legitimacy of Global Governance Institutions. *Ethics and International Affairs* 20 (4): 405–437.

Crutzen, Paul J. 2006. Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma? *Climatic Change*, 77 (3-4): 211–219.

Dahl, Robert A. 1957. The Concept of Power. *Behavioral Science*, 2 (3): 201–215.

Downs, George W., David M. Rocke, and Peter N. Barsoom. 1996. Is the Good News about Compliance Good News about Cooperation? *International Organization* 50 (3): 379–406.

Grant, Ruth W., and Robert O. Keohane. 2005. Accountability and Abuses of Power in World Politics. *American Political Science Review* 99 (1): 29–43.

Grobe, Christian. 2010. The power of words: Argumentative persuasion in international negotiations. *European Journal of International Relations*. 16 (1): 5–29.

Hawkins, Darren, David A. Lake, Daniel Nielson, and Michael Tierney, eds. 2006. *Delegation and Agency in International Organizations*. New York, NY: Cambridge University Press.

Holzinger, Katharina, Christoph Knill, and Thomas Sommerer. 2008. Environmental Policy Convergence: The Impact of International Harmonization, Transnational Communication, and Regulatory Competition. *International Organization* 62 (4): 553–587.

International Panel on Climate Change (IPCC), Fourth Assessment Report. 2007. *Impacts, Adaptation, and Vulnerability*. Technical Summary.

Ikenberry, John. 2001. *After Victory: Institutions, Strategic Restraint, and Rebuilding of Order after Major Wars*. Princeton, NJ: Princeton University Press.

Keith, David W. 2000. Geoengineering the Climate: History and Prospect. *Annual Review of Energy and the Environment*. 25: 245–284.

Keohane, Robert O., and David G. Victor. 2011. The Regime Complex for Climate Change. *Perspectives in Politics* 9 (1): 7–23.

Koremenos, Barbara, Charles Lipson, and Duncan Snidal. 2001. The Rational Design of International Institutions. *International Organization* 55 (4): 761–799.

Krasner, Stephen D. 1991. Global Communications and National Power: Life on the Pareto Frontier. *World Politics* 43 (2): 336–366.

Mitchell, Ronald. 2006. Problem Structure, Institutional Design, and the Relative Effectiveness of International Environmental Agreements. *Global Environmental Politics* 6 (3): 72–89.

Moe, Terry M. 2005. Power and Political Institutions. *Perspectives on Politics* 3 (2): 215–33.

Morrow, David R., Robert E. Kopp, and Michael Oppenheimer. 2009. Toward Ethical Norms and Institutions for Climate Engineering Research. *Environmental Research Letters* 4: 045106.

Morrow, David R., Robert E. Kopp, and Michael Oppenheimer. Forthcoming. Political Legitimacy in Decisions about Experiments in Solar Radiation Management. In *Geo-Engineering the Climate: Law, Ethics and Policy Considerations*, edited by William C. G. Burns and Andrew Strauss. Cambridge, UK: Cambridge University Press.

Nordhaus, William D., and Joseph Boyer. 2000. *Warming the World: Economic Models of Global Warming*. Cambridge, MA: MIT Press.

Olson, Mancur. 1965. *The logic of collective action*. Cambridge, MA: Harvard University Press.

Peterson, M. J. 1980. Antarctica, the Last Great Land Rush on Earth. *International Organization* 34 (3): 377–403.

Peterson, M. J. 1988. *Managing the Frozen South: The Creation and Evolution of the Antarctic Treaty System*. Berkeley, CA: University of California Press.

Peterson, M. J. 1997. The Use of Analogies in Developing Outer Space Law. *International Organization* 51 (2): 245–74.

Rasch, Philip J., Simone Tilmes, Richard P. Turco, Alan Robock, Luke Oman, Chih-Chih (Jack) Chen, Georgiy L. Stenchikov, and Rolando R. Garcia. 2008. An overview of geoengineering of climate using stratospheric sulfate aerosols. *Philosophical Transactions of the Royal Society A* 366 (1882): 4007–4037.

Rayner, Steve, Catherine Redgwell, Julian Savulescu, Nick Pidgeon, and Tim Kruger.

2009. Memorandum submitted by Tim Kruger to the UK House of Commons. *Science and Technology Committee*. GEO 07a.

Ricke, Katharine L., M. Granger Morgan, and Myles R. Allen. 2010. Regional Climate Rresponse to Solar-Radiation Management. *Nature Geoscience* 3: 537–541.

Robock, Alan. 2008. 20 Reasons why Geoengineering may be a Bad Idea. *Bulletin of the Atomic Sciences* 64 (2): 14–18.

Sands, Phillipe. 2003. *Principles of International Environmental Law, Ch. 14,* 2nd. Ed. Cambridge, UK: Cambridge University Press.

Schneider, Stephen. 2008. Geoengineering: Could We or Should We Make It Work? *Philosophical Transactions of the Royal Society A*. 366 (1882): 3843-3862.

Shepherd, John, et al. 2009. Geoengineering the Climate: Science, Governance and Uncertainty. *The Royal Society*, London.

Snidal, Duncan. 1985. The Limits of Hegemonic Stability Theory. *International Organization* 39 (4): 579–614.

Thompson, Alan. 2010. Rational Design in Motion: Uncertainty and Flexibility in the Global Climate Regime. *European Journal of International Relations*, 16 (2): 269–296.

UK House of Commons. 2010. The Regulation of Geoengineering. *Fifth report of session 2009-2010*: HC221.

US Government Accountability Office. 2010. A Coordinated Strategy could Focus Federal Geoengineering Research and Inform Governance Efforts. GAO-10-903.

Victor, David G. 2008. On the Regulation of Geoengineering. *Oxford Review of Economic Policy* 24 (2): 322–336.

Victor, David G., M. Granger Morgan, Jay Apt, John Steinbruner, and Katharine Ricke, 2009: The Geoengineering Option: A Last Resort Against Global Warming? *Foreign Affairs* 88 (2): 64–76.

Virgoe, John. 2009. International Governance of a Possible Geoengineering Intervention to Combat Climate Change. *Climatic Change* 95 (1-2): 103-119.

Wendt, Alexander. 2001. Driving with the Rearview Mirror: On the Rational Science of Institutional Design. *International Organization* 55 (4): 1019–49.

Wigley, Tom M. L. 2006. A Combined Mitigation/Geoengineering Approach to Climate Stabilization. *Science* 314 (5798): 452–454.