PROCEEDINGS A

royalsocietypublishing.org/journal/rspa

Reveiw

Cite this article: Reynolds JL. 2019 Solar geoengineering to reduce climate change: a review of governance proposals. *Proc. R. Soc. A* **475**: 20190255.
http://dx.doi.org/10.1098/rspa.2019.0255

Received: 26 April 2019
Accepted: 29 July 2019

Subject Areas:
climatology, atmospheric science

Keywords:
climate change, geoengineering, climate engineering, solar radiation management, governance, policy

Author for correspondence:
Jesse L. Reynolds
e-mail: reynolds@law.ucla.edu

Solar geoengineering to reduce climate change: a review of governance proposals

Jesse L. Reynolds

Emmett Institute on Climate Change and the Environment,
University of California, Los Angeles School of Law, 385 Charles E.
Young Drive East, Los Angeles, CA 90095, USA

JLR, 0000-0002-0624-5741

Although solar geoengineering (alternatively 'solar radiation management' or 'solar radiation modification') appears to offer a potentially effective, inexpensive and technologically feasible additional response to climate change, it would pose serious physical risks and social challenges. Governance of its research, development and deployment is thus salient. This article reviews proposals for governing solar geoengineering. Its research may warrant dedicated governance to facilitate effectiveness and to reduce direct and socially mediated risks. Because states are not substantially engaging with solar geoengineering, non-state actors can play important governance roles. Although the concern that solar geoengineering would harmfully lessen abatement of greenhouse gas emissions is widespread, what can be done to reduce such displacement remains unclear. A moratorium on outdoor activities that would surpass certain scales is often endorsed, but an effective one would require resolving some critical, difficult details. In the long term, how to legitimately make decisions regarding whether, when and how solar geoengineering would be used is central, and suggestions how to do so diverge. Most proposals to govern commercial actors, who could provide goods and services for solar geoengineering, focus on intellectual property policy. Compensation for possible harm from outdoor activities could be through liability or a compensation fund. The review closes with suggested lines of future inquiry.

THE ROYAL SOCIETY
PUBLISHING

1. Introduction

In 2015, the world's countries resolved in the Paris Agreement to keep 'the increase in the global average temperature to well below 2°C above pre-industrial levels' and to pursue efforts to limit warming to 1.5°C. Despite this ambition, staying within the 2°C limit appears extremely unlikely; the 1.5°C one nearly impossible. The current round of pledges under the Paris Agreement—*if* all states fulfil them—could keep warming to within perhaps 2.7°C by the end of this century [1]. To have a 2/3 chance of meeting the 2°C and 1.5°C limits, greenhouse gas emissions would henceforth need to linearly reduce to zero emissions in approximately 45 and 25 years, respectively [2,3]. Yet global emissions keep increasing, on average 1.7% annually since the first international climate agreement, the 1992 UN Framework Convention on Climate Change (UNFCCC) [4]. In principle, this requisite rapid decarbonization could be delayed if later compensated through net negative emissions that would be achieved via carbon dioxide removal (CDR) technologies, but these technologies' technical feasibility, costs and environmental and social impacts at such large scales remain uncertain. Even then, climate change would exceed the targets during the 'overshoot', with concomitant impacts.

Given this situation, some scientists and others are increasingly considering a more radical response. 'Solar geoengineering' (sometimes called 'solar radiation management', 'solar radiation modification' or 'solar climate engineering') is a set of proposed technologies to intentionally alter the Earth's radiative balance through means other than changing atmospheric concentrations of greenhouse gases [5,6]. Most proposals would reflect or block a small portion of incoming solar radiation. Current evidence indicates that some suggested solar geoengineering techniques could reduce climate change and its associated risks effectively, globally, rapidly, reversibly and inexpensively. They also seem be technologically feasible. At the same time, they would pose multiple serious physical risks and social challenges. Nevertheless, solar geoengineering may be necessary to stay within internationally-agreed upon warming limits.

The governance of solar geoengineering has been a central question in scholarly, policy and popular discourses. A seminal report from the Royal Society concluded that 'The greatest challenges to the successful deployment of geoengineering may be the social, ethical, legal and political issues associated with regulation, rather than scientific and technical issues' [7]. Many academics and others have offered diverse possible governance mechanisms.

This article reviews proposals for how solar geoengineering should be governed. These span multiple axes: the actors to be governed and to do the governing; governing instruments' form; the breadth of activities, opportunities, risks and challenges addressed; and the envisioned depth of actors' commitments regarding the activities they would undertake, encourage, discourage and prohibit. The resulting conceptual landscape is multidimensional, and the article's sections consequently overlap somewhat in scope. The next section introduces solar geoengineering's methods; how they might relate to other responses to climate change; and their apparent effectiveness, physical risks and possible social challenges. Section 3 offers a foundation for governance discussions, including a brief history of the early discourse, central issues, relevant problems structures and extant governance mechanisms. Section 4 explores the governance of solar geoengineering research, and §5 thereafter focuses on governance by non-state actors. Section 6 considers responses to perhaps the most common concern: that emissions abatement would be lessened in the face of solar geoengineering. Possible moratoria on solar geoengineering activities are next reviewed in §7. Decision-making regarding deployment—which may be governance's central question—is tackled next. The last two substantive sections summarize proposals to manage private actors—especially commercial ones—in solar geoengineering research, development and implementation, and possible compensation and liability for harm. The article concludes with a handful of recommended avenues of future inquiry.

Because the article's scope must be constrained, there are numerous salient questions that are not addressed here. What values should guide governance [8,9], and how should proposals be assessed [10]? Given solar geoengineering's expected global impacts, with what standards of legitimacy—that is, the quality of being worthy of acceptance and support—should its governance comport [11,12]? How can the governance of solar geoengineering be conceptually theorized in ways that might be informative to conceptions of governance more generally [13,14]? What are the proper roles of expertise and knowledge [15,16]? What about perceptions [17], politics [18] and power [19]? I encourage interested readers to explore these questions elsewhere.

2. Solar geoengineering

Solar geoengineering would intentionally alter the Earth's radiative balance, and most proposed methods would do so by increasing its albedo. The leading one would mimic the cooling effect of large volcanic eruptions, whose residual atmospheric ash particles and sulphuric acid droplets scatter and reflect some incoming sunlight (figure 1). Humans could inject an aerosol or precursor thereof into the stratosphere, where it would remain aloft for months due to the lack of precipitation. A common suggested substance for injection is sulfur due to volcanic evidence, but others are under consideration. The recent Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5°C global warming concludes 'with *high agreement* that [this stratospheric aerosol injection (SAI)] could limit warming to below 1.5°C' [2]. Models indeed consistently indicate that its judicious use could reduce both the temperature and precipitation anomalies at regional and sub-regional scales [21,22]. Estimates of the direct financial costs of SAI's implementation are approximately USD 2 to 10 billion annually [23–25]. (For comparison, the costs of climate change damages and aggressive mitigation might each be a couple of trillion USD annually [26].)

Another proposed solar geoengineering method would aim to increase the albedo of relatively dark stratocumulus clouds [27,28]. Because clouds composed of a greater number of smaller water droplets are brighter, they could be brightened by introducing more cloud condensation nuclei into the lower atmosphere. If seawater were sprayed upwards as a fine mist, then after its evaporation, some salt particles would stay suspended. Although marine cloud brightening (MCB) may be able to compensate for approximately 1°C of global warming, there remains substantial uncertainty in this capacity, and its effects would necessarily be spatially heterogeneous. MCB's deployment costs are poorly characterized but might be around USD 10 billion annually [5]. Figure 2 shows ship tracks, which provide evidence of MCB, and a possible delivery vehicle.

The third proposed solar geoengineering method that seems technologically feasible and inexpensive would alter the Earth's radiative balance by increasing outgoing longwave radiation. In general, clouds both reflect some incoming shortwave radiation and trap some outgoing longwave radiation. High altitude cirrus clouds are believed to have a net warming effect. Dispersing them could thus reduce global warming and could be done by injecting ice nuclei, such as bismuth triiodide, into the areas where cirrus clouds are likely to form. Although cirrus cloud thinning (CCT) may be able to lower global mean temperature by 1.4°C [30], it could also have a net warming effect [31]. Notably, CCT is not strictly *solar* geoengineering but is sufficiently similar in key regards to be grouped therewith.

Solar geoengineering research to date is modest. It received about USD 8 million in each of 2017 and 2018 [32], in comparison to the approximately USD 3.5 billion spent annually on climate change research in the United States alone [33]. Almost all work to date uses models and, to a lesser extent, natural analogues. Depending on how one classifies them, there may have been two outdoor solar geoengineering experiments [34,35]. A few are at various stages of planning, and others are possible [36]. For example, a Harvard-based group intends to inject small quantities of various materials into the stratosphere to assess impacts on atmospheric chemistry [37].

The climate would respond differently to albedo-increasing solar geoengineering (that is, methods other than CCT) than to emissions abatement or CDR. For one thing, greenhouse gases absorb outgoing longwave radiation at all times and latitudes, whereas incoming sunlight is reflected in proportion to solar irradiance, which is greatest during the summer, at midday and at low latitudes. To some degree, this imperfection could be moderated through seasonal and latitudinal control [38]. Furthermore, albedo-increasing solar geoengineering would lessen

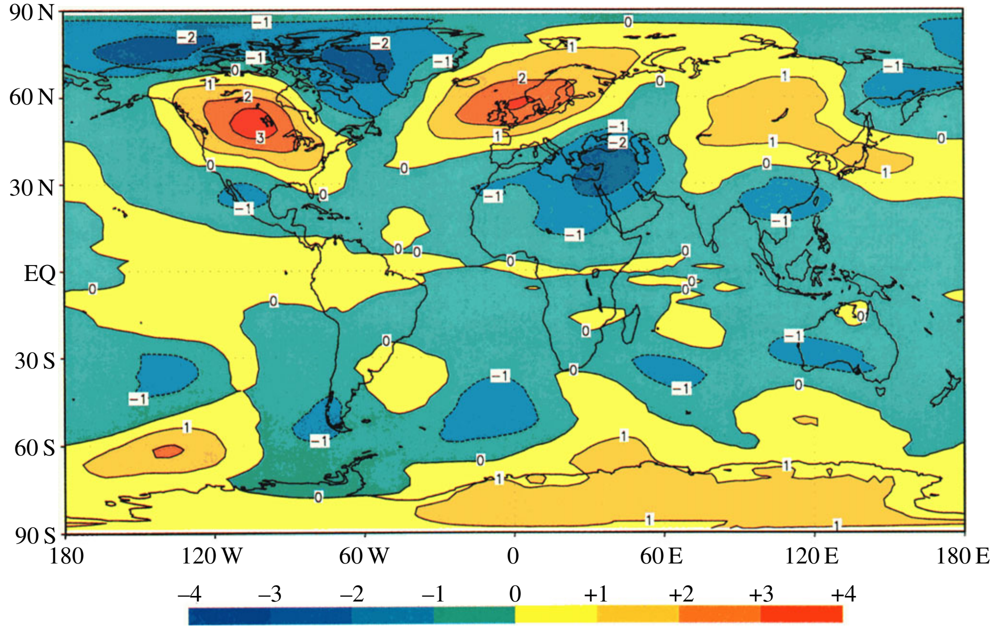

Figure 1. Stratospheric aerosol injection is inspired and, to a degree, demonstrated by volcanoes. The June 1991 eruption of Mount Pinatubo (The Philippines) cooled the planet by approximately 0.6°C during the next 15 months, albeit heterogeneously. The figure shows the temperature anomaly (°C) in the December, January and February following the eruption [20]. (Online version in colour.)

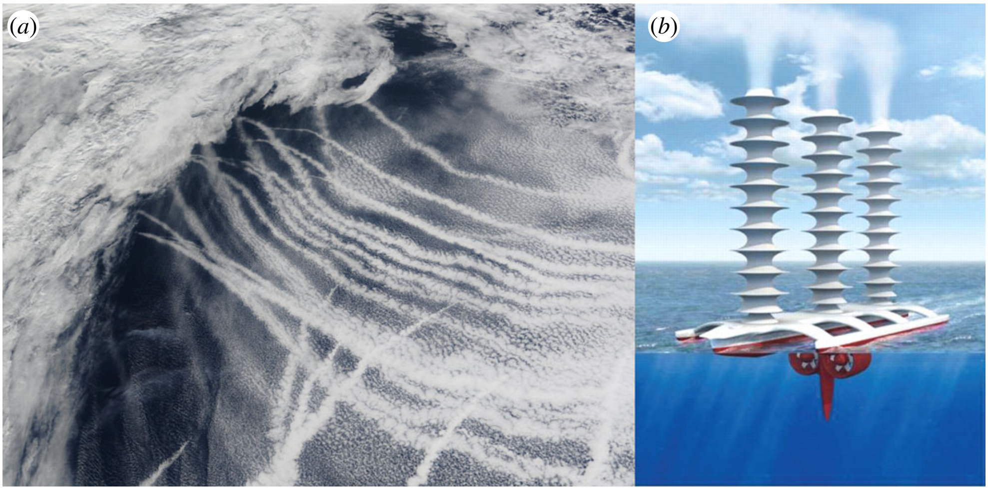

Figure 2. Marine cloud brightening. Left: Particulates from ships act as cloud condensation nuclei, offering evidence of MCB's potential effectiveness. Public domain image courtesy of NASA/Goddard Space Flight Center Scientific Visualization Studio. Right: Unmanned Flettner rotor ships could spray the seawater. Image by John McNeill [29]. (Online version in colour.)

the hydrological cycle's intensity. For these reasons and others, solar geoengineering should complement—not substitute for—emissions abatement, CDR and adaptation.

Another way in which the climate would respond differently to solar geoengineering is that the effects would manifest relatively rapidly—on a timescale of months—and would be reversible on a similar timescale. In contrast, the avoided climate change from emissions abatement and CDR is delayed by decades due to the time required to meaningfully affect greenhouse

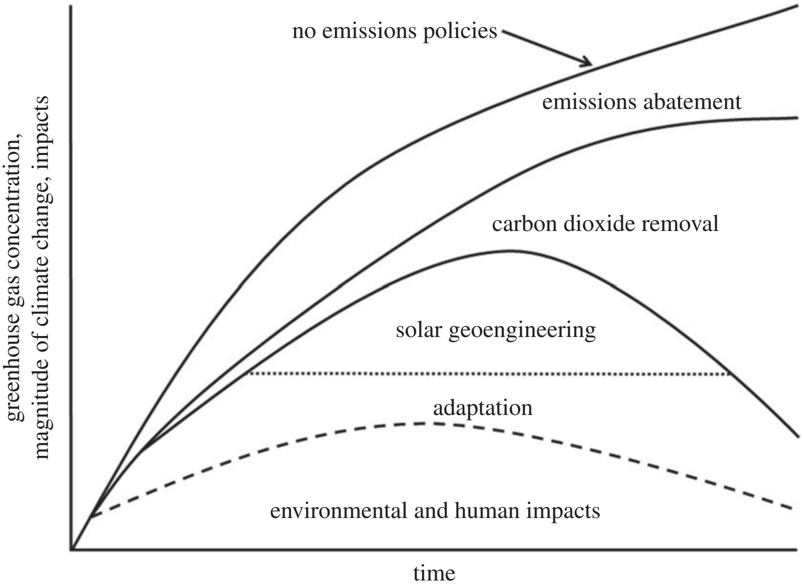

Figure 3. Ideal complementary roles of responses to climate change. The vertical *Y* axis represents three different but roughly proportional variables. Emissions abatement is slow and cannot reduce greenhouse gas concentrations over time. CDR is also slow but can reduce them over time. Solar geoengineering would not affect greenhouse gas concentrations but could rapidly reduce climate change, such as by 'shaving the peak' of dangerous climate change. Adaptation does not affect climate change but can reduce impacts. Author's rendition based on John Shepherd's 'napkin diagram' [41].

gas concentrations. This indicates that solar geoengineering could be used to manage short-term climate change risks from extant emissions in ways that emissions abatement and CDR cannot [39] and could be a valuable complement to other responses [40,41]. For example, solar geoengineering could be used as a temporary means to slow climate change [22] and/or to limit warming as atmospheric greenhouse gas concentrations 'overshoot' the levels associated with warming targets [42]. Figure 3 displays how the four primary responses to climate change—emissions abatement, CDR, solar geoengineering and adaptation—could complementarily reduce impacts on humans and the environment.

Solar geoengineering would pose physical risks. As described above, it would imperfectly compensate climate change, causing residual regional temperature and especially precipitation anomalies. SAI could slow the recovery of stratospheric ozone [43], although some materials might not or could even help restore ozone [44]. Injecting sulfur would contribute to acid rain, but this would likely be insignificant [45]. Long-term oscillations of natural climate-relevant systems, for example, El Niño, might be affected [46]. Other, unexpected environmental impacts cannot be ruled out. Because solar geoengineering would not directly lower the elevated atmospheric CO_2 concentration, it would not prevent ocean acidification [47].

Solar geoengineering would be accompanied by multiple diverse social challenges. The IPCC Special Report on 1.5°C global warming concludes that:

> Uncertainties surrounding solar radiation modification (SRM) measures constrain their potential deployment. These uncertainties include . . . a weak capacity to govern, legitimize and scale such measures . . . . Even in the uncertain case that the most adverse side-effects of SRM can be avoided, public resistance, ethical concerns and potential impacts on sustainable development could render SRM economically, socially and institutionally undesirable [2].

First, the most common concern is that solar geoengineering's research, development and possible use could cause emissions abatement to be less than it otherwise would be. Second, given solar geoengineering's generally global effects and the nature of the international order, decision-making regarding whether, when and how to deploy it is a central issue. States and other actors might disagree and dispute the legitimacy of decision-making processes. Afterwards, they could blame—sincerely or not—the deploying actors for harmful weather events and could demand compensation. Furthermore, because of the apparent low direct costs and technical feasibility, solar geoengineering might be implemented by one or a handful of states or even non-state actors, contrary to the international community's wishes, too soon, or at too great an intensity (i.e. the magnitude of its radiative forcing). These political phenomena could exacerbate international tensions, such as between industrialized and developing countries, or fuel new ones. Another major social challenge is that, because of the speed and reversibility of solar geoengineering's climatic effects, its sudden and sustained termination after being used at a great intensity would cause quick and dangerous warming. The research and development of solar geoengineering might also bias future decision-making, a possibility that is sometimes characterized as a 'slippery slope' or 'lock-in'. Finally, solar geoengineering poses serious ethical issues, a situation that is amplified by its global effects and the world's divergent normative frameworks [9].

3. Governance thus far

Solar geoengineering's multiple serious physical risks and social challenges necessitate some form of governance. This has been central to the discourse almost since its beginning. The first scientific publication on solar geoengineering foregrounds concerns of decision-making, blame, attribution and compensation [48]. In a 1983 US National Academies report on anthropogenic CO_2 emissions, Thomas Schelling identifies the possibility of unilateral deployment [49]. A decade later, another US National Academies report devotes a chapter to solar geoengineering and CDR, collectively called 'geoengineering', but does not consider governance beyond recommending research and caution [50]. Later that year, David Keith and Hadi Dowlatabadi raised the questions of decision-making authority; distribution of benefits, costs and impacts; liability; and international security [51]. A symposium at the 1994 American Association for the Advancement of Science meeting was the first public event dedicated to geoengineering, and the papers in the resulting collection address the emissions abatement displacement concern [52], international law [53], ethics [54] and problem structure [55]. Nevertheless, solar geoengineering remained largely taboo within climate change circles until Paul Crutzen argued that emissions abatement efforts 'have been grossly unsuccessful' and look 'like a pious wish', and that SAI should be seriously considered [56]. The Royal Society soon formed a working group and released an influential report in 2009 [7]. Research and other solar geoengineering activities somewhat accelerated thereafter, including a full report from the US National Academies in 2015 [5], major Climate Engineering Conferences in Berlin in 2014 and 2017 and the birth of a handful of non-governmental organizations dedicated to fostering dialogue and governance. The US National Academies have recently established a committee to suggest a research agenda and options for governance of solar geoengineering.

Governance—here meant broadly as the goal-oriented, sustained and explicit use of authority to influence behaviour—of solar geoengineering is difficult for a number of reasons. First, large-scale outdoor activities would have transboundary effects, and implementation (as it is generally understood) would have global ones. Because of this and because states will seek to retain decision-making authority over intentionally changing the climate, they will be the central actors. However, the international order lacks centralized rule making, enforcement and adjudication. Instead, states have the sovereignty to act that is shaped and limited by international law, which they create and enforce themselves. Importantly, states have no rights or obligations from treaties that they do not choose to ratify. Otherwise, they would need to consent to any additional multilateral agreement to specifically constrain their latitude to use solar geoengineering.

Second, solar geoengineering orthogonally intersects traditional politics. For more than half a century, contemporary environmentalism has been dominated by the belief that less intervention in the natural world is a central means to achieve sustainability and other normatively desirable social outcomes. Furthermore, solar geoengineering threatens to divide the environmental political coalition that has been effective at advancing climate governance. In this, those actors who focus on reducing risks are likely to be open to researching and developing it, whereas those whose objectives include or prioritize reducing humans' impact on nature or the redistribution of wealth and power can be expected to resist it [57]. Consequently, politicians—who are necessary for both state and international governance—lack incentives to engage with the issue. Indeed, there has been little state involvement with solar geoengineering governance, and this seems unlikely to substantially change in the near future.

Third, solar geoengineering's problem structure is difficult, although not as much as that of emissions abatement [58]. Even though emissions abatement (as well as CDR) produces net benefits globally, each possible contributor bears all the costs but receives only a small portion of the benefits. It is thus in each actor's individual interest to not contribute and 'free ride', which is an important reason that abatement has been far from sufficient. In contrast, because of solar geoengineering's low deployment costs, it could produce net benefits for a single actor—for example, a state—that undertakes it. An actor of this sort might proceed, even though others may not agree on whether, when and how to use solar geoengineering. Although states and other actors may be tempted to implement it too soon or at too great an intensity, collectively it may be in their interests to cooperate in restraining themselves and preventing this 'free driving' [59] as well as possible political backlash. In short, whereas abatement's central challenge is getting all actors to do more, that of solar geoengineering deployment is 'upside down': keeping those with the capacity to refrain from doing too much, too soon [55,60].

Fourth and finally, suggesting governance for the use of solar geoengineering is to some degree speculative. Arguably, this is *not* primarily because of uncertainties regarding the climatic effects of greenhouse gases and solar geoengineering, although these are relevant. Instead, the most salient uncertainties seem political. We do not know, several decades hence, how (un)cooperative international relations will be, whether states will desire the same global climatic conditions—such as the preindustrial one or that with 1.5 to 2°C warming—or divergent ones, or how strongly states will prioritize having their preferred climates relative to other objectives. At the same time, current solar geoengineering decision-making concerns not deployment but instead—for example—establishing and detailing norms, facilitating responsible and effective research, minimizing any harmful displacement of emissions abatement and preventing undue lock-in. The values, interests and capacities surrounding these issues are less uncertain and the associated governance consequently less speculative.

Despite occasional claims to the contrary [61,62], solar geoengineering is not being researched and developed in a governance vacuum. (In fact, additional governance that is dedicated to solar geoengineering is not strictly necessary, at least in a legal sense [63].) Although there are no binding legal instruments that are specific to solar geoengineering and in effect, there is an existing framework of applicable national and international rules, institutions and norms—that is, general standards used to assess decisions and actions. Because these have been extensively reviewed elsewhere [64], only a brief summary of extant legal governance follows.

As solar geoengineering activities move outdoors and increase in scale, they will pose environmental risks, initially of modest potential impact and spatial and temporal scales. The industrialized countries and many developing ones have robust domestic environmental and liability laws. For example, in the United States, the site of most current solar geoengineering research, the National Environmental Policy Act would require the federal government to assess and consider the environmental impacts of projects or programmes that it undertakes, funds or approves and that may have major effects; the Clean Air Act could regulate substances injected into the atmosphere as air pollutants; the Endangered Species Act could prohibit proposed activities that would jeopardize endangered or threatened species' existence or have adverse impacts on their critical habitats; and the Weather Modification Reporting Act would mandate reporting of solar geoengineering activities to the federal government. Furthermore, the common law of torts could hold those who undertake solar geoengineering liable for harm to others.

As noted, international law will be salient in the governance of large-scale outdoor experiments and deployment. Although treaties may come first to mind, existing customary international law—that which is binding after widespread and consistent state practice that appears to arise from a sense of obligation—already governs large-scale outdoor solar geoengineering activities. In this, states' sovereignty regarding their territory and persons is limited by, among other things, their obligation to reduce risks of significant transboundary harm. They are not expected to eliminate all transboundary risks but instead to control them with a due diligence standard. This is generally understood to call for—among other things—requiring authorization for the activity, assessing environmental impacts, notifying and cooperating in good faith with potentially affected states, informing the public, and developing contingency plans for an emergency [65]. If a state acts contrary to this or other international law to which the state is obligated, it should cease the activity, assure that it will not recur, and make full reparations for any injuries [66].

Treaties are the other source of binding international law, and some of them are or could be applicable to solar geoengineering. The climate regime seems a good starting point, but its foundational UNFCCC may be inapplicable. Its objective is the stabilization of atmospheric greenhouse gas concentrations, which would not be directly affected by solar geoengineering. The related Paris Agreement is more flexible, as its goal is limiting global warming and states have latitude in how they contribute to this. For example, its parties could incorporate solar geoengineering activities into their nationally determined contributions to achieving the Agreement's warming target and in their required adaptation plans, and it could be part of the regular global stocktaking process. The Vienna Convention and its Montreal Protocol regulate states' emissions of specific ozone depleting substances. Although SAI could slow the recovery of stratospheric ozone, the Montreal Protocol's parties would need to take action to regulate the material as a controlled ozone depleting substance. There is likewise a set of treaties under the Convention on Long-range Transboundary Air Pollution that limits industrialized countries' emissions of acid rain precursors, including sulfates. Large-scale testing or implementation of SAI with sulfates could be contrary to parties' obligations under this regime. The UN Convention on the Law of the Sea governs a wide range of activities in or that affect the oceans, among which are obligations for states to protect the marine environment and their rights in conducting marine scientific research. Notably, its definition of pollution that states are to prevent, reduce and control implicitly encompasses global warming, greenhouse gases, and—if it were likely to result in deleterious effects—solar geoengineering. This presents a tension, in that solar geoengineering could in this context be both a means to prevent, reduce and control pollution as well as a source of it. The London Protocol regulates marine dumping, and its 51 parties have approved an amendment that would regulate 'marine geoengineering', defined so that it could cover solar geoengineering. In general, this can restrict listed marine geoengineering activities to legitimate scientific research, but the amendment is not in force due to insufficient ratifications. The Environmental Modification Convention prohibits the military or hostile use of techniques that, by implication, can include solar geoengineering. Finally, the parties to the widely-ratified Convention on Biological Diversity (CBD) have issued a few non-binding decisions regarding geoengineering. One of these, agreed upon in 2010, calls for states to consider not allowing 'climate-related geo-engineering activities that may affect biodiversity' in the absence of an adequate scientific basis, impact assessment and a global mechanism for governance (Decision X/33). A more recent one calls for more transdisciplinary geoengineering research in order to better understand potential impacts (Decision XIII/14).

International law is more than binding rules. Principles such as cooperation, equity, polluter pays, common but differentiated responsibilities, precaution and the environment as a common concern of humankind guide its interpretation, implementation and further development. International institutions offer sites for information sharing, coordinating, deliberating and developing and crystallizing norms. For example, in March 2019, the UN Environment Assembly considered but did not approve a proposed decision to assess solar geoengineering's methods, evidence, current governance and possible future governance [67]. The World Meteorological Organization, the IPCC, the UN General Assembly and the UN Security Council could also play future roles.

4. Governance of research

Governance of solar geoengineering research may be warranted for multiple reasons. One objective could simply be that substantial research actually occurs [68–72]. Although this observation may seem mundane, numerous institutional reviews and authoritative statements consistently recommend greater funding of solar geoengineering research (or geoengineering research more generally): by the US National Academies in 1992 and 2015 [5,50], the Royal Society [7], the American Geophysical Union [73,74], the American Meteorological Society [75], Australia's Office of the Chief Scientist [76], the German Research Foundation [77], the Netherlands' scientific assessment institute [78], the German Federal Ministry of Education and Research [79], the parties to the Convention on Biological Diversity (Decision XIII/14) and the US Global Change Research Program [80]. Nevertheless, worldwide funding of solar geoengineering remains modest, a minority of which is from government sources [32]. Some scholars assert that *public* financial support of research is essential in order to, among other things, build accountability and legitimacy [70,81,82].

A significant increase in the scale of solar geoengineering research would likely entail dedicated programmes at the national, subnational, or European Union levels, which might call for particular programmatic characteristics. According to the authors of the Royal Society report, a programme should consider both potential and risk as well as the technical means of geoengineering [7]. The 2015 US National Academies report emphasizes the lines of solar geoengineering research that could also improve understanding of climatic systems in general and also recommends that research be coordinated across agencies [5]. A common recommendation is for international cooperation (especially with developing countries), coordination and cost-sharing [69,83–85]. A task force of the Bipartisan Policy Center concludes that a coordinated programme should pursue risk minimization, diverse and independent oversight informed by public engagement, transparency, international cooperation and communication, adaptive management and diverse lines of research including efforts that identify solar geoengineering's potentials and opportunities as well as its limitations and risks [86]. It also suggests, in the case of the United States, where among government agencies a research programme should be administrated and overseen as well as specific avenues of research. David Winickoff and Mark Brown add that the US would benefit from a national government advisory commission on solar geoengineering research, one that is 'independent, transparent, deliberative, publicly engaged and broadly framed' [87]. (US states could provide an alternate site for an advisory commission [88].) In Keith's view, separating CDR from solar geoengineering, emphasizing risks, including engineering, and diversifying lines of research would increase the value of a research programme [89].

Some observers assert that solar geoengineering research programmes of increasing scale would have particular governance needs [82,90–95]. A frequent—but not universal—refrain is that the governance of research should be kept separate from that of implementation [96], although the functional distinction between the two domains of activities blurs and maybe disappears as outdoor research increases in scales [97]. Some further suggestions for the governance of research are common. First, a research programme should arguably be mission-oriented and coordinated as such [41,98]. Second, because opportunities and risks will vary by the scale and magnitude of climatic intervention, multiple tiers of governance may be warranted [5,82,91,99]. In this, solar geoengineering experiments and projects below a certain scale may not warrant additional dedicated governance [100]. Third, many if not most direct environmental health and safety risks—at least those arising from small-scale experiments—can be managed by extant domestic and substate law and regulation as well as international law, although modest amendments may be necessary [101–103]. (However, some scholars are worried about regulatory gaps [104,105].) Fourth, governance of research should encourage or require transparency [106]; public engagement [11,107,108]; ex ante project and programmatic impact assessments [93,99,109], independent review and—where appropriate—approval of outdoor experiments; ongoing monitoring and reporting [87,110]; independent ex post assessment of results (perhaps by the IPCC [83]); and adaptive [111] or anticipatory [112] governance processes. Finally, the international regulation of other technologies offers some useful models [113,114]. Specifically, the regulation of marine geoengineering in general and ocean fertilization CDR specifically under the aegis of the London Convention and London Protocol differentiates and offers criteria for 'legitimate scientific research' [94,105,115]. Authors diverge regarding aspects such as the extent to which the governance of research can manage socially mediated challenges, the scope of activities that should be governed as 'solar geoengineering research', and which institutions or other actors should govern [116].

5. Non-state governance

Governance is broader than legally binding, state-generated rules and includes rules that are not legally binding and those that are developed, implemented, monitored and/or enforced by non-state actors. This non-state governance could play important roles in managing solar geoengineering, especially indoor and smaller-scale outdoor research [70,95,117,118]. The 2015 US National Academies report concludes:

> 'Governance' is not a synonym for 'regulation.' Depending on the types and scale of the research undertaken, appropriate governance of albedo modification research could take a wide variety of forms ranging from the direct application of existing scientific research norms, to the development of new norms, to mechanisms that are highly structured and extensive [5].

Non-state governance can be relatively more responsive to changing knowledge, values and conditions; effectively influence transboundary actors and phenomena; develop when states are not acting; and lay the foundation for future governance by state actors [119]. Even when weakly developed, informal, general, uncodified and implicit, non-state rules can sometimes be effective, including for solar geoengineering [5,69,82,120–124]. An advocate of non-binding norms' importance in solar geoengineering governance is David Victor, who says that they:

> will be needed soon . . . . [E]fforts to craft new norms 'bottom up' will be more effective. Such an approach, which would change the underlying interests of key countries and thus make them more willing to adopt binding norms in the future, will require active, open research programmes and assessments of geoengineering [60].

Here, he speaks of norms for *using* solar geoengineering, although others argue that norms and other non-state governance are applicable to early research efforts [125]. Norms could arise from key actors' socialization [60], scientific and professional societies, national academies of science [82], a new national or international commission dedicated to the task [81,95,126,127], or even 'downward' from states or substate jurisdictions [5,86,88,128]. In time, those norms that are more advisory, general and self-implemented can form the basis for subsequent ones that are obligatory, precise and delegated and that are developed and enforced by states [92].

Yet in the case of solar geoengineering, informed writers largely highlight non-state governance's limitations. For one thing, the governing actors might not be well-qualified to assess activities' possible long-term risks and social challenges [122,129]. They may also be vulnerable to undue influence by the targets of governance [130]. Furthermore, its provisions may remain too vague to be genuinely effective [102,131]. Legitimacy—which is critical in governing a controversial practice such as solar geoengineering—is essential, but non-state governance arrangements and especially self-regulation (when governing actors and their targets substantially overlap) may not be perceived as sufficiently legitimate [126]. Accountability, which is often an important source of legitimacy, may be lacking [132].

Scholars and other non-state observers have put forth various explicit non-binding rules for solar geoengineering, some of which have been called 'principles', sometimes also addressing

CDR as well, and sometimes focusing on the research context. Their substances largely overlap and generally concur [86,90,91,133,134]. In 1996, Dale Jamieson offered three general principles: 'the importance of democratic decision-making, the prohibition against irreversible environmental changes and the significance of learning to live with nature' [54]. The Royal Society report is a bit more specific, asserting that 'Research activity should be as open, coherent and as internationally coordinated as possible and trans-boundary experiments should be subject to some form of international governance, preferably based on existing international structures' [7]. Soon after that report's publication, David Morrow and colleagues drew from medical ethics to offer principles in which 'the scientific community [should] secure the global public's consent, . . . strive for a favourable risk–benefit ratio and a fair distribution of risks and anticipated benefits, all while protecting the basic rights of affected individuals . . . [and] minimiz[ing] the extent and intensity of each experiment' [135].

The most influential set of principles was developed by a group of British academics, including two members of the Royal Society's geoengineering working group. Grounded in norms such as transparency, justice and the need for legitimacy, these five 'Oxford Principles' are:

1. Geoengineering to be regulated as a public good;
2. Public participation in geoengineering decision-making;
3. Disclosure of geoengineering research and open publication of results;
4. Independent assessment of impacts; and
5. Governance before deployment [136].

Their authors envision that these could 'lay[] down the basic parameters for decision-making', be operationalized as 'part of a flexible architecture . . . shap[ing] a culture of responsibility among researchers', inform bottom-up self-regulation and contribute subsequently to more strongly legalized governance mechanisms. The text that accompanies the principles touches on three specific issues that remain unsettled. First, according to the Oxford group, regulating as a public good implies 'a presumption against exclusive control of geoengineering technology by private individuals or corporations [because] the distribution of intellectual property rights can result in, or exacerbate existing injustices'. Second, those who have been harmed by geoengineering may need to be compensated. These first two unsettled issues are discussed in dedicated sections below. Third, part of public participation in decision-making is to 'ideally obtain the prior informed consent of, those affected by the research activities'. However, the Oxford authors note that it is unclear how a population's consent could be obtained without granting each individual a veto, echoing Morrow and colleagues' observations [135]. The UK House of Commons Science and Technology Committee and the government later endorsed the Oxford Principles, with some qualifications and additions [137,138].

One recent set of principles is a critique of the Oxford Principles' instrumentality, procedural emphasis and ambiguity [139]. Philosophers Stephen Gardiner and Augustin Fragnière base their 'Tollgate Principles' on a more diverse and stringent set of foundational norms, among which are ecological ones. The limitation of the Tollgate Principles is one that is common among attempts to operationalize demanding deontological ethical norms, which can be internally contradictory, vary substantially among populations and be susceptible to recursive questioning. As an example, these authors write that 'Geoengineering policy should respect well-founded ecological norms, including norms of environmental ethics and governance,' and cite 'respect for nature' as among these. But on whose ethics and version of respect for nature should the policy rely? In another of their principles, Gardiner and Fragnière assert that 'Geoengineering decision-making . . . should be done by bodies acting on behalf of (e.g. representing) the global, intergenerational and ecological public'. However, decision-making bodies of this sort do not exist and will most likely not for the foreseeable future.

Legal scholars affiliated with the UN have put forth a single non-binding rule. The advisory International Law Commission codifies and, in some cases, progressively develops unwritten principles, custom, or emerging international law. Since 2013, it has been working towards Guidelines on the Protection of the Atmosphere that seek to capture relevant existing international law. The Commission has provisionally adopted a draft set of guidelines and transmitted them to countries for comment. One of these guidelines is that 'Activities aimed at intentional large-scale modification of the atmosphere should be conducted with prudence and caution, subject to any applicable rules of international law' [140]. The accompanying commentary notes that this includes but is not limited to solar geoengineering.

Principles that could guide the development, use and governance of solar geoengineering can also be found in international law, as noted in the previous section. One of these that has received particular attention is precaution. Although its articulation varies among international agreements, that in the UNFCCC seems most salient:

> The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost. (Article 3.3)

What this means for solar geoengineering—which would be a measure to prevent or minimize climate change and the resulting adverse effects but could also pose serious risks of its own—is unclear. Numerous scholars of law and other fields have commented on the possible implications. One group believes that precaution can offer some, albeit limited, guidance for managing risks [134,141–150]. Others assert that it is a poor fit for governing solar geoengineering due to the high-stakes risk–risk trade-off or to a conclusion that here it yields only muddled insights. [110,151–154]. A third cohort conclude that—if anything—precaution lends support to pursuing solar geoengineering in some manner, such as through research or possible future use in response to severe climate change impacts [151,155,156]. Finally, a few observers argue that a genuinely precautious response would prohibit solar geoengineering [131,157,158].

A code of conduct—that is, a set of explicit non-binding rules of greater precision and sense of obligation than general norms or principles—could also contribute to governing solar geoengineering and its research. The Royal Society report suggests a code or a set of best practices [7], as do some subsequent publications [11,86,115,159]. For example, Granger Morgan and colleagues emphasize that any code must ensure transparency of research's results, delineate criteria for outdoor solar geoengineering experiments that would be unlikely to have adverse impacts, and ensure that researchers do not undertake outdoor work beyond these criteria until national and international governance frameworks are in place [82]. Further, a 2018 report from a dozen academics recommends that funders should make their support for research contingent on compliance with an applicable code of conduct [95]. Legal scholar Anna-Maria Hubert offers a 'Code of Conduct for Responsible Geoengineering Research' [160]. Originally co-drafted with David Reichwein, it is based largely on existing international law and presented as a set of articles with commentary. The code aims to minimize harms, promote responsible research and enhance legitimacy, especially for outdoor experiments. It is directed towards a full spectrum of actors: state, intergovernmental and non-state ones. The code adopts a strongly precautionary default, in that 'no geoengineering activities should take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of environmental and other effects'.

6. Abatement displacement

The concern that the consideration, research and development of solar geoengineering would harmfully undermine emissions abatement has been widespread. Given emissions abatement's justified position as the leading response to climate change, as well as the initial resistance to adaptation and CDR, it is unsurprising that this concern of emissions abatement displacement—sometimes elsewhere inaccurately called 'moral hazard'—has served as the basis for a taboo on discussing solar geoengineering seriously. Wallace Broecker observed this as early as 1985 [161], and the concern manifested when the authors of a 1992 US National Academies climate change report were hesitant to include a chapter on geoengineering [50,52]. Since then, many solar geoengineering research advocates appropriately emphasize that abatement should remain primary and that solar geoengineering should, at most, be a complement to abatement [5,7,40].

After Crutzen's paper and the Royal Society's report largely broke the taboo, scholars began to address the abatement displacement concern. For example, Benjamin Hale unpacks the concept and concludes that arguments against geoengineering grounded in the abatement displacement concern 'are both ambiguous and vague' [162]. However, he—like many others—does not offer governance recommendations to reduce any abatement displacement, as developing actual suggestions is difficult. After all, how could authoritative actors realistically influence the relevant numerous actions and underlying preferences of others—and themselves—now and in the future? The only sure way to do so would be take solar geoengineering off the table and prevent any further discussion. Indeed, Gerd Winter suggests that the law prohibits geoengineering due to expected emissions abatement displacement [131]. Regardless, we can never know with any certainty whether and to what degree solar geoengineering has influenced actual abatement because reality lacks counterfactuals. Moreover, the additional climate change arising from modestly greater emissions could be outweighed by reduced climate change from solar geoengineering. This highlights the diversity of climate change policy's often implicit objectives: reducing or even ending greenhouse gas emissions; effectively avoiding harmful climate impacts; facilitating sustainable development; 'pursuing a broader concept of well-being'; 'sharing of limited resources within and across countries as well as across generations'; protecting the environment; furthering equity, fairness and procedural, distributive and compensatory justice [163]; and building an entirely new economic system [164].

Focusing on opportunities for scientists, Morrow offers three recommendations to reduce abatement displacement [147]. According to him, they should explore a wide array of alternative responses to climate change to provide a broad information base for policy-makers. Researchers should also communicate their results carefully, including by emphasizing the differences among solar geoengineering methods and avoiding language that others could misinterpret or miscommunicate. Finally, Morrow calls for scientists to robustly engage with the public and decision-makers.

Taking a cue from the insurance industry, Albert Lin emphasizes international policies [165]. He first suggests that, if the consensus of the international community is to allow geoengineering, it should carefully delineate the boundaries of acceptable activities. Second, research should emphasize geoengineering's possible risks, uncertainties and limitations. Also, these and other results should be communicated to decision-makers and the public through dedicated outreach efforts. Third, Lin says that decisions should be made in neutral, democratically accountable institutions that have no stake in geoengineering and that include designated, influential advocates for emissions abatement. Fourth, he proposes to make geoengineering activities contingent on abatement.

Like Lin, Edward Parson also proposes linking emissions abatement and solar geoengineering policies, specifically suggesting, at least rhetorically, that states agree to implement solar geoengineering only if they have met abatement targets [166]. He recognizes that this would be a sort of non-credible intertemporal threat by the present to the future: if future decision-makers failed to meet these targets and their jurisdictions faced serious harmful impacts from climate change, then they may renege on the commitment to withhold solar geoengineering. In addition, such a policy linkage could give states incentives to set unambitious abatement targets so that they would retain the solar geoengineering option. Parson thus puts forth a more elaborate linkage proposal, in which only those states that meet emissions abatement targets would be allowed to participate in international decision-making regarding solar geoengineering. States' motivations to 'have a seat at the table' would depend upon how widely their preferences concerning the solar geoengineering's parameters—such as timing, location, intensity and form—diverge.

While conceding that policy-makers might have restricted capacity to effectively reduce displacement, I offer a few modest suggestions [103]. First, further research of all policy responses to climate change—among which is solar geoengineering—should be expeditiously pursued so that decision-makers and others can better understand the responses' expected benefits and costs. In addition, the results should be transparent, independently assessed, effectively communicated and made compatible with other relevant sets of information. Second, decision-making should strive to integrate informed public preferences in order to prevent undue disconnection between policy-makers and the public. Importantly, developing countries should be proactively engaged, including through international research cooperation, as they will gain or lose the most from solar geoengineering. Third, policies should allow future generations of decision-makers some flexibility because their preferences may differ from ours. Fourth—and somewhat in tension with the previous recommendation—current decision-makers could try to make it easier for future ones to abate emissions and more difficult to unduly rely on solar geoengineering. This could perhaps be accomplished by limiting through regulation the growth and influence of actors who have concentrated interests in solar geoengineering and by using it to compensate for only a portion of anthropogenic climate change.

7. Moratoria

Scholars, advocates and others frequently suggest that outdoor solar geoengineering activities that surpass certain scales not take place until certain conditions have been met [82,83,93,104,120–122,125,141,160,167–172]. Daniel Bodansky states that moratoria 'have the attraction of simplicity. They create bright-line rules, and thus avoid the need for complex, ongoing decision-making, which may be beyond the institutional capacity of the international community, particularly in cases of significant uncertainty' [70].

These writers offer diverse reasons [173]. A demarcating policy could help prevent risky activities until we have better understanding of and less uncertainty concerning the potential benefits and risks and until more detailed, obligatory governance is in place [93,95,172]. Furthermore, by delaying debate on the generally more contentious issue of solar geoengineering implementation, reaching agreement on governing outdoor research may be more achievable [93]. Moratoria could also address some of solar geoengineering's second-order social challenges including lock-in, slippery slope, abatement displacement, premature or 'rogue' unilateral implementation and international distrust of states' motives [83,93,95,104,120,125,147,172]. They could allow time for broader and deeper public engagement as well as credible assurances that early small-scale activities would not necessarily lead to larger-scale ones [93,95,115,172]. Likewise, scientists would have greater assurance and clarity that some activities are permitted and implicitly endorsed [95,172]. Finally, opponents of solar geoengineering could use a moratorium as a means to slow activities, with the hope that it ossifies into permanence or that a full explicit prohibition could be later realized [174].

In some cases, support for moratoria is often implicit. The widespread call for 'governance before deployment'—as in the Oxford Principles [136–138]—indicates that the implementation of solar geoengineering should not occur until effective oversight is in place [5,95,160,169]. Others take a firmer line and argue for governance before outdoor experiments, which again would implicitly be a moratorium [139,159,175,176]. A similarly semantic issue surrounds whether the 2010 decision by the Conference of Parties to the CBD, noted above, is a moratorium. Some scholars call it such [104,122,154,171,177–180], but others dispute this characterization [95,115,141,143,166,181,182].

A potential moratorium would require the resolution of some critical details. First, what is the scope of activities that would be temporarily prohibited? The distinctions between solar geoengineering and other avenues of climatological research—especially that involving aerosols and clouds—are not sharp. Furthermore, a rule would need to delineate the boundaries beyond which activities may not take place. Some writers call for a moratorium on large-scale outdoor experiments [121,122,167] or deployment [93,104,120,125,141,170,171], but these shift the question to what constitutes 'large scale' or 'deployment'. Others point to criteria of expected impact [122,141,167] or of quantifiable spatial scale, temporal scale and intensity [82]. Along these lines, Parson and Keith tentatively suggest 'a level where global climate response is barely detectable—for example, global-annual-average $\Delta \mathrm{RF} > \sim 10^{-2}\,\mathrm{Wm}^{-2}$' (where RF is radiative forcing) [172]. More conservative commentators call for a moratorium on all outdoor research [83,93].

Second, the criteria for lifting the moratoria would also need to be made explicit. One approach would be to limit it to a specific length of time [83,141], while another would depend on particular characteristics of effective governance including legitimate decision-making processes, scientific justification and sufficient understanding and consideration of potential benefits and risks [82,121,122,171].

Third, one should specify which actors would implement, manage and possibly lift the moratorium, which only a few observers do [95,115]. This issue, in which matters of compliance, legitimacy and participation intersect in complex ways, warrants particular attention. A group of scientists—the most important target of governance—would likely comply with their own moratorium or that of a representative organization. A bottom-up declaration by researchers or authoritative quasi- and non-state institutions is thus one option [82,167,172]. However, another group of researchers might not perceive the moratorium as legitimate enough to justify compliance. This might be due to a sense that they were not adequately represented in the decision-making, particularly if these two groups significantly differ in geography, culture, or specialization. Furthermore, substantial time might pass between a moratorium's implementation and its review for lifting. Because of this, another potential source of a moratorium is states, which have long institutional lives, legitimacy and relatively robust governance apparatuses (for the most part). Various scholars point to all or most states [125,172] and individual states, with the hope that more follow [104,120].

A moratorium would have other drawbacks, limitations and difficulties. One problem would be a type of adverse selection, in which the more responsible scientists, organizations and states implement and comply with moratoria while the less responsible ones remain outside [7,70,104]. Because commitments from all relevant actors would be needed, a truly effective moratorium appears difficult to develop, implement and enforce [91,93]. Furthermore, a moratorium on research could stifle activities that could reduce uncertainty regarding a potential means to effectively counter climate change [7,70,86,115,143]. A moratorium could evolve—perhaps unintentionally—into a de facto prohibition, which would be more likely if it was poorly crafted. Scientists might also furtively describe their solar geoengineering activities as research into aerosols, clouds and other atmospheric and climatic phenomena, which would reduce transparency and inhibit international cooperation [115]. Regardless, the results of less research, transparency and cooperation could be poorly informed subsequent decision-making and greater climate change impacts. It is for these reasons and others that some scholars are critical of moratoria [115,147,183,184].

8. Operational decision-making

In the long term, the central question of governing solar geoengineering will be whether, when, and how it would be used—perhaps globally—to reduce climate change and its risks. This is made challenging by solar geoengineering's combination of low apparent direct financial costs of implementation, which may enable net benefits for a single deploying country (that is, 'free driving') and transboundary if not global impacts. Because of this, informed observers are essentially unanimous in their belief that any operational decision-making should be the domain solely of state actors. In such decision-making, legitimacy—again, the quality of being worthy of acceptance and support—would be central. Beyond this, however, opinions as to how these decisions should be made diverge, and I divide them here among five top-level categories.

First, some scholars argue that any operational decision-making should lie with a deliberative intergovernmental institution that counts all or most of the world's states as members, that is grounded in international law, and (often) whose decisions are considered legally binding. The most common reason for this position is that, because solar geoengineering would presumably affect all countries, widespread if not universal consent is needed for its deployment to be legitimate. Many of these writers offer the UNFCCC as the ideal home for operational decision-making due to the regime's centrality in international climate change governance, linkages with emissions abatement and adaptation and institutional knowledge [83,141,143,185,186]. For example, Lin calls for a protocol to the UNFCCC in which the parties would agree to, and regularly revisit, 'a default presumption against the implementation of any geoengineering project' [187]. Although the UNFCCC's objective is limited to 'stabilization of greenhouse gas concentrations in the atmosphere', this could reasonably be interpreted to cover solar geoengineering, either because the objective also references 'protecting the climate system' in general [185] or because solar geoengineering is expected to indirectly reduce atmospheric CO_2 concentrations [188]. In contrast, because of this limited objective and because 'negotiations under the UNFCCC are already characterized by a very high level of complexity and being politicized', Ralph Bodle and colleagues argue that the CBD would be the best institutional site for the governance of solar geoengineering and its implementation [110]. In this, the CBD parties should adopt a precautionary 'general prohibition of geoengineering activities [including field experiments] that entail significant transboundary risks, combined with the possibility of exemptions'. Yet governing solar geoengineering seems outside the CBD's objective as well. Some scholars suggest that an entirely new multilateral agreement to govern geoengineering is warranted [189,190]. Adam Abelkop and Jonathan Carlson describe a multilateral agreement that is open to all countries, in which decision-making is majoritarian and members' votes are weighted by their greenhouse gas emissions [142]. However, such an arrangement could reinforce a perception that those most responsible for climate change sought to continue emitting greenhouse gases and that powerful states were using solar geoengineering to maintain their positions of greater power. Independent of the institutional home, relying on an international agreements with (near-)universal participation for operational decision-making regarding solar geoengineering would face further limitations, especially if the regime were to default to prohibiting deployment in the absence of explicit proactive consensus. Because international law is based on sovereign states' consent, those that wished to retain the option to use solar geoengineering—the very ones that are most important to have among the participants in governance—would remain outside of any restrictive regulatory regime. Even if an international agreement like this came into effect, enforcing its provisions would be difficult.

The second category of governance proposals also points to intergovernmental institutions with widespread participation, but here their proponents suggest that these bodies establish only general contours for deployment decisions [185,191]. For example, Chiara Armeni and Catherine Redgwell note that UN Environment (formerly UNEP), the World Meteorological Organization, the Commission of Sustainable Development and the United Nations Educational, Scientific and Cultural Organization could be loci of the growth of norms, rules and new institutions [192]. Likewise, Bodansky and others exclude from their proposed multilateral governance mechanisms operational decision-making concerning whether, when and how to deploy [70]. Instead, they suggest that a multilateral agreement or intergovernmental institution address transparency and information sharing; prior impact assessment; notification, public engagement and consultation prior to planned large-scale outdoor activities; public disclosure and independent assessment of results; coordination of activities; a forum for discussions, including setting standards and considering compensation for harm; and obligations of good faith efforts toward resolving disputes.

Third, some argue that a small number of states should take the lead in governing the use of solar geoengineering [123]. For example, Ian Lloyd and Michael Oppenheimer describe a weakly legalized regime with up to thirty participating states, among which should be some that do not have deployment capacity but are vulnerable to climate change impacts [125]. Its initial purpose would be to prevent premature implementation, encourage research collaboration and authorize deployment pursuant to 'a difficult voting process'. In a monograph, I consider two tiers of decision-making modelled somewhat on the UN, in which an executive committee makes operational decisions and a large general assembly could agree on non-binding guiding resolutions [193]. The aims of former diplomat Richard Benedick are more modest, in that his council of approximately 25 states would work to develop guidelines and processes for ‘ongoing consultation and collaboration’ [194]. The UN Security Council could serve as a backstop forum for solar geoengineering decision-making [130,195], which could fall under its scope of maintaining international peace and security. Even then, one of its five permanent members could block decisions through its veto. Regardless, decisions concerning whether, when and how to deploy that are made by a relatively small number of states would be open to accusations of insufficient legitimacy, even if these decisions were endorsed or made by the UN Security Council.

The fourth general approach to governing solar geoengineering implementation is to keep the conversation entirely out of international institutions, at least for now. Specifically, introducing the topic could raise divisive questions whose possible resolution would yield little benefit. Doing so could also unnecessarily widen further divisions and lead towards a poorly informed, ultimately counterproductive prohibition, as most countries might see little to gain from solar geoengineering in the near future [53,60,120]. Acting within the UNFCCC could be particularly disruptive to the sensitive politics therein [141,196]. One response would be to focus on the bottom-up development of general norms and codes of conduct, as discussed above. Other paths forward are possible. Parson proposes a World Commission on Climate Engineering that could be authorized and funded by—but operationally independent from—an international institution [95,197]. Such a body could consider policy interactions among solar geoengineering, emissions abatement, CDR and adaptation; the social and political implications of solar geoengineering research; and the functional needs of institutions to later consider deployment. Importantly, he emphasizes that the Commission need not answer all salient questions; merely identifying and clarifying them may productively contribute to future governance. Another suggested response is that, because solar geoengineering may likely be first used in reaction to local and regional impacts of climate change, governance should initially focus on smaller scales and be facilitated by regional forums for cooperation [95,198,199].

Fifth, a handful of scholars and others believe that solar geoengineering should not be used. Their reasons for this opposition vary. Mike Hulme asserts that solar geoengineering cannot be democratically and effectively governed [200]; Paul Nightingale and Rose Cairns point primarily to security concerns [201]; and Winter claims that solar geoengineering is contrary to international environmental law [202]. However, none of these authors describes a process through which a prohibition could feasibly and effectively be developed, implemented and enforced.

Many of the proposals described above consider what singular international agreement or institution could or should legitimately govern the use of solar geoengineering. Indeed, some of these proposals are grounded in a concern that numerous rules and bodies would overlap—perhaps contradictorily so—and leave governance gaps [104,143,189,203]. Although this fragmentation might be ineffective, a unitary governance regime may be infeasible. Indeed, a polycentric set of ‘hard’ and ‘soft’, top-down and bottom-up mechanisms could be a source of flexibility, experimentation and dynamism to govern a heterogeneous set of emerging technologies [118,124,127,204,205]. At the same time, greater coordination among extant regimes and institutions may be needed, or at least beneficial [196].

A set of issues that informed observers have largely overlooked is the governance needs after solar geoengineering has begun. Sébastien Philippe discusses the challenges of collecting, integrating, sharing and validating relevant information regarding deployment in order to facilitate cooperation, trust and effective risk management [206]. He points to the Comprehensive Nuclear-Test Ban Treaty as a potential model. Although many writers have noted that solar geoengineering would need to be maintained in order to prevent a ‘termination shock’, only a handful have described how this could be prevented [205]. Andy Parker and Peter Irvine conclude that geographically distributed, well protected and redundant implementation hardware among multiple relatively powerful countries coupled with sharing of the requisite knowledge should be able to prevent sudden and sustained cessation [207].

9. Private actors and intellectual property

Although states are usually central in discussions of developing and implementing solar geoengineering, they are not the sole actors. Governance through non-state actors was discussed above. Private philanthropists also presently fund research, especially in the US [32]. And at least in principle, non-state actors could decide to implement solar geoengineering. Victor describes how a wealthy 'self-appointed protector of the planet' might do so out of a desire to prevent and reduce dangerous climate change [60]. Although he and others have invoked this narrative to highlight the difficulty of governing solar geoengineering, those who have further considered this scenario usually conclude that it seems unlikely. States will presumably consider operational decision-making regarding whether and how to intentionally alter the climate to be their prerogative, not that of non-state actors. They will use regulation, political pressure and the threat or use of force to ensure this [70]. A state that tolerated non-state solar geoengineering deployment by its domestic actors would come under international pressure or even threats to stop it. Moreover, sustained solar geoengineering would have substantial technological requirements and costs that, while low in terms of climate change economics and some states' budgets, exceed non-state actors' capacities [123,208]. Although some writers assert that solar geoengineering deployment could be profitable [209], a prospective commercial operation could not monetize it because of its non-excludable nature. Highly decentralized non-state solar geoengineering through, for example, numerous small high-altitude balloons that deliver an aerosol or its precursor appears technologically and financially feasible [193]. Nevertheless, even in this case, states could still control large-scale outdoor solar geoengineering activities within their territories.

A more salient issue is the roles of private actors—especially commercial ones—in the research, development and delivery of solar geoengineering. Some scholars and others express concern that this sort of involvement could create conflicts of interest, increase environmental risks, reduce transparency, undermine public trust, cause injustice, contribute to lock-in and engender vested interests that could unduly influence critical decision-making [81,82,90,93–95,122,131,136,142,151,157,169,210–217]. For example, the first of the Oxford Principles—'Geoengineering to be regulated as a public good'—is elaborated:

> While the involvement of the private sector in the delivery of a geoengineering technique should not be prohibited, and may indeed be encouraged to ensure that deployment of a suitable technique can be effected in a timely and efficient manner, regulation of such techniques should be undertaken in the public interest by the appropriate bodies at the state and/or international levels [136].

Jane Long and Dane Scott suggest reducing unwanted influence by non-state actors through transparency, robust public institutions mission-driven research programmes, deep public deliberation and independent advisory bodies [81]. In contrast, other observers emphasize commercial actor's abilities to accelerate innovation and attract capital [208,218–220]. Because states will almost certainly retain operational decision-making, firms would likely be contracted through procurement to provide goods and services for large-scale activities. If solar geoengineering scales up to a multi-billion US dollar endeavour, then commercial actors would have opportunities to profit from their inventions.

A leading way in which states govern commercial interests in an innovative domain is through intellectual property law, especially that of patents. Although assertions that there should be no private solar geoengineering patents are common, only a few experts have offered specifics of possible governance of patents that are related to solar geoengineering [95]. Indeed, there presently is an opportunity to develop such dedicated governance of intellectual property because there are very few relevant patents, because scientists exhibit a culture that is opposed to patenting, and because commercial actors are not significantly involved in research and development. The reasons to develop dedicated patent policies for solar geoengineering include avoiding the risks, lock-in and undue influence cited above as well the patent thickets, anti-commons effects and broad, early patents that can often arise with emerging technologies. However, to be effective, a policy would need to govern transnational actors and activities, not unduly stifle innovation, and not push innovators to rely on trade secrets instead of patents. This is made more difficult by state actors' reticence to address solar geoengineering through policy. Furthermore, the distinctions between patentable inventions that are and are not related to solar geoengineering will be often unclear, especially early on. Here, I summarize four sets of proposals for intellectual property policies that would be specific to solar geoengineering.

First, patents for inventions related to solar geoengineering could be prohibited or restricted. [82,85,131,211,217]. States have adopted similar policies in areas such as nuclear weapons. Like a moratorium or ban on solar geoengineering itself, this has the apparent advantage of clarity. Perhaps the greatest shortcoming of these proposals is that they would require all relevant states either to adopt appropriate legislation or administrative regulation or to agree upon, ratify and implement a multilateral agreement. Excluding patents would also inhibit innovation, require distinguishing which inventions are sufficiently related to solar geoengineering and incentivize researchers to use trade secrets and to misrepresent their work's possible applications.

Second, Anthony Chavez suggests a patent pool, in which holders of related patents agree to allow access to each other's patents, to jointly manage them, to grant joint licences and to share the revenue in some agreed-upon way [215]. Patent pools are usually voluntary but can be compulsory through state intervention. They can facilitate further innovation and utilization of the constituent technologies, especially when the patents are complementary, as in extant cases of patent pools for agricultural biotechnologies and medicines. However, solar geoengineering is not presently a set of complementary inventions. To the contrary, which techniques—if any—will ultimately prove effective and acceptable remains uncertain. A patent pool would run the risk of locking-in certain technologies in an emerging field like this. Nevertheless, patent pools might later be beneficial for one or more specific solar geoengineering techniques.

Third, some solar geoengineering researchers have practised defensive patenting and defensive publishing [221–223]. Each of these tactics are undertaken *not* in order to generate revenue but instead to prevent others from obtaining a patent. In the former approach, an innovator files for a patent, whereas in the latter, he or she publishes enough details to try to establish prior art, hindering others' potential future patent requests. These practices can advance transparency and avoid some problems of widespread patenting by commercial actors. Yet defensive patenting in solar geoengineering opens scientists up to accusations of conflicts of interest. Furthermore, whether a given defensive publication has established sufficient prior art to prevent future patents would remain unclear until tested by such a patent claim.

Fourth, Jorge Contreras, Joshua Sarnoff and I propose a multi-part intellectual property policy for solar geoengineering [224], the centrepiece of which is a patent pledge. Briefly stated, in this, a researcher would pledge to not assert his or her patents related to solar geoengineering against others who make the same pledge in their legitimate solar geoengineering research, development and implementation activities. The patent pledge's advantages are that it does not rely on state action and that it would have global effect. If successful, the pledge initiates a positive feedback cycle, in which researchers would, by pledging, gain access to a greater quantity of valuable relevant patents. Eventually, state and intergovernmental actors could become involved in managing the intellectual property policy, perhaps gradually legalizing it and linking it with other governance instruments.

10. Compensation and liability

Another persistent question in discussions of governance of solar geoengineering has been whether and how those who believe that they have been harmed by outdoor activities could be compensated. Indeed, the authors of the first academic article on solar geoengineering said, '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 favoured climate' [48]. Compensation could—but not necessarily—be through liability on the part of those who undertake solar geoengineering. Alternatively, some actors might be worried prior to a planned activity that they will be harmed. They could ask for prior assurances of compensation, possibly as a precondition for not opposing the activity.

Yet compensating potential victims of solar geoengineering would be difficult for many reasons [8,225]. First, observers diverge on why victims should be compensated, which has implications for policy-making. Approaches that are based on ex post corrective justice, for example, would differ substantially from those based on altering actors' ex ante incentives to encourage socially optimal outcomes. Second, for which harms should victims be compensated? Many of solar geoengineering's risks are indirect and socially mediated; whether and how harm from them could and should be compensated is unclear. Third, attributing a given harm to a particular solar geoengineering activity would be necessary yet challenging [226]. Attribution of extreme weather events to anthropogenic climate change remains at an early stage; that of solar geoengineering seems even more complex. Fourth, with which climatic baseline should solar geoengineering's effects be compared: a preindustrial one, one immediately prior to the activity, or the likely conditions in the absence of solar geoengineering [227]? This is complicated by the long lengths of time that might be involved. Fifth, who deserves compensation and blame [228]? A state or other actor that prefers an anthropogenically warmed climate could claim harm from solar geoengineering's cooling effects. On the other side, a developing country that has low historical greenhouse gas emissions and is vulnerable to climate change might have deployed solar geoengineering and harmed high-emitting industrialized countries in the process of safeguarding its essential interests. Compensation from the (poor) former to the (wealthy) latter seems wrong. Sixth, the amount of damages could be great enough that the deploying actor would be unable to pay, even if the solar geoengineering created large welfare gains worldwide. This implies that other beneficiaries might need to contribute to any compensation. Finally, states—who would likely be the central actors—must consent to paying compensation, yet they are generally very reluctant to do so, much less to concede to international legal liability.

As implied, one possible basis for compensation is international law. Existing customary international law provides—at least in principle—that a state that has harmed another through an act contrary to international law should provide compensation. One legal rule that large-scale solar geoengineering could violate is states' obligations of conduct to reduce significant transboundary risks [229,230]. However, this and other existing international law of liability are unable to equitably and effectively compensate in the case of solar geoengineering [231]. Gareth Davies asserts that these legal inabilities might actually be for the better, because 'Too much insight into the specific links between consumption, emission and land use in a particular area, on the one hand, and particular unpleasant weather events, on the other, could be politically destabilizing,' leading to numerous international liability claims for diverse human activities [151].

Other approaches involve establishing a dedicated international compensation mechanism for transboundary harm from solar geoengineering. The first such proposal was from Bidisha Banerjee, who suggests that researchers post environmental assurance bonds [157]. She notes her proposal's limitations, especially the need to estimate an activity's largest potential future harm. Drawing from ethical principles, Pak-Hang Wong and colleagues describe a general state-financed fund that would compensate victims of all climate-related harms, whether from anthropogenic climate change or solar geoengineering [232]. Joshua Horton and colleagues (as well as others) make similar recommendations, drawing from the legal regimes for nuclear accidents, space activities and especially maritime oil spills [186,233,234]. Using an economic analysis of law, I also suggest an international compensation fund whose contributions would be based on some combination of states' expected benefits from solar geoengineering, their net historical greenhouse gas emissions and their ability to pay [235]. The deploying state(s) would be obligated to reimburse the compensation fund up to some limited amount if it (or they) acted contrary to international law and/or prevailing research standards.

More recently, Horton and Keith offer a somewhat different mechanism, in which deploying states offer insurance-like contracts to other states that claim to expect harm [236]. Pay-outs would occur if specified parametric climatic indices—most importantly, temperature and rainfall—differ significantly from specified historical ranges. If deployers' beliefs about solar geoengineering's effectiveness turn out to be correct, then climate risks will be reduced and pay-outs will not be triggered. In contrast, if concerned states' expectations of harm are borne out, then they would be compensated. Some difficulties to this proposal remain. For example, if deploying countries needed to make many large pay-outs, then they might not have the financial assets to underwrite the scheme.

11. Conclusion

The dozen years during which the governance of solar geoengineering has been seriously discussed have produced a substantial corpus of knowledge, analyses and proposals from scholars, public agencies, think tanks and advocates. The more than 200 citations in this review attest to this. The publications have mapped the core concepts, opportunities, challenges and governance gaps and have explored many of them—including the governance of research, operational decision-making regarding deployment, compensation and intellectual property—fairly well. Nevertheless, even these issues have remaining questions and prospects for intellectual progress. I highlight here a handful of lines of inquiry that seem to warrant further emphasis.

First, state action in this space will likely remain largely absent in domestic and international policy-making arenas. For example, one interpretation of the recent failure of a modest proposed UN Environment Assembly decision regarding geoengineering's assessment and governance is that most states are unwilling to spend much political capital on moving the issue forward. Given this, the understanding of non-state actors' capacities and limitations to govern early-stage solar geoengineering activities should be refined. Which non-state actors could most effectively, legitimately and feasibly exert authority? Could this governance include a moratorium on large-scale outdoor solar geoengineering activities? How could regulatory capture be prevented, and accountability and transparency ensured? What secondary roles could state and intergovernmental actors assume in non-state governance, perhaps in order to facilitate its gradual legalization?

Second, research will likely proceed while solar geoengineering remains controversial. Some process of engaging with the public, non-governmental organizations, public agencies, commercial actors and others is necessary to identify and establish the contours of support, acceptability and concerns. At the moment, the burden for this falls by default on the scientists who conduct early research. However, this not only seems inappropriate and inefficient, it could also cause each project or experiment to become a proxy debate on solar geoengineering as a whole. Which actors could and should lead public engagement processes, and how? What should the objectives be? In what ways should this undertaking be limited?

Third, if solar geoengineering research and development are scaled up, and certainly if it is implemented, commercial actors will play essential, growing roles in providing requisite goods and services. This will raise prospects—both legitimate and perceived—of undue influence in decision-making, conflicts of interest, inadequate transparency, lock-in and profiting from a controversial practice. Intellectual property policy is one means to govern commercial actors. What other governance mechanisms could effectively leverage their capacities while avoiding the risks and pitfalls? The scholarship of regulating public procurement could offer some guidance.

Fourth, although the IPCC and its reports are remarkably influential in climate change policy-making, they have not thoroughly assessed solar geoengineering's capacities and limitations to reduce climate change and manage its risks. For example, the recent special report on 1.5°C warming explicitly excludes solar geoengineering from its central 1.5°C pathways, and its conclusion 'with *high agreement* that [SAI] could limit warming to below 1.5°C'—a target that otherwise appears out of reach without substantial warming 'overshoot' followed by CDR at very large scales—is buried in a box in chapter 4 [2]. Serious consideration of solar geoengineering would likely require integrating it into the IPCC's leading scenarios, yet given its low direct financial deployment costs, doing so in benefit–cost optimization or cost minimization analyses would run the risk of unduly portraying the advantages of excessive reliance on it. How the IPCC and other authoritative bodies could responsibly assess the opportunities, limitations and risks of solar geoengineering would itself arguably be a form of governance, one that remains underexplored.

Finally, little writing has considered the governance needs and potential responses that would arise subsequent to any solar geoengineering deployment. If undertaken, solar geoengineering would be a complex, challenging and in many ways novel human endeavour. Although such explorations might seem premature, they could identify possible problematic outcomes and undesirable situations that could be avoided with appropriate foresight and pre-emptive action.

Data accessibility. This article has no additional data.

Competing interests. I declare I have no competing interests.

Funding. This work was supported by the Open Philanthropy Project.

Acknowledgements. The author thanks two anonymous reviewers for their helpful comments and reviews editor Michel Destrade for the invitation. He is also grateful to his funder for enabling the work.

References

1. Rogelj J *et al.* 2016 Paris agreement climate proposals need a boost to keep warming well below 2°C. *Nature* **534**, 631–639. (doi:10.1038/nature18307)
2. Intergovernmental Panel on Climate Change. 2018 *Global warming of 1.5*°C. Intergovernmental Panel on Climate Change. See https://www.ipcc.ch/sr15/ (accessed 19 April 2019).
3. United Nations Environment. 2018 *The emissions gap report 2018*. Nairobi, Kenya: United Nations Environment Programme. See https://www.unenvironment.org/resources/emissions-gap-report-2018 (accessed 19 April 2019).
4. Olivier JGJ, Peters JAHW. 2018 *Trends in global CO_2 and total greenhouse gas emissions: 2018 report*. The Hague, The Netherlands: PBL Netherlands Environmental Assessment Agency. See https://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2018-trends-in-global-co2-and-total-greenhouse-gas-emissons-2018-report_3125.pdf (accessed 19 April 2019).
5. National Research Councils Committee on Geoengineering Climate. 2015 *Climate intervention: reflecting sunlight to cool Earth*. Washington, DC: National Academies Press.
6. Irvine PJ, Kravitz B, Lawrence MG, Muri H. 2016 An overview of the Earth system science of solar geoengineering. *WIREs Clim. Change* **7**, 815–833. (doi:10.1002/wcc.423)
7. Shepherd J *et al.* 2009 *Geoengineering the climate: science, governance and uncertainty*. London, UK: The Royal Society. See https://royalsociety.org/topics-policy/publications/2009/geoengineering-climate/ (accessed 19 April 2019).
8. Svoboda T. 2017 *The ethics of climate engineering: solar radiation management and non-ideal justice*. London, UK and New York, NY: Routledge.
9. Heyward C. 2019 Normative issues of geoengineering technologies. In *Managing global warming: an interface of technology and human issues* (ed. TM Letcher), pp. 639–657. Cambridge, MA: Academic Press.
10. McKinnon C. 2019 Sleepwalking into lock-in? Avoiding wrongs to future people in the governance of solar radiation management research. *Environ. Polit.* **28**, 441–459. (doi:10.1080/09644016.2018.1450344)
11. Frumhoff PC, Stephens JC. 2018 Towards legitimacy of the solar geoengineering research enterprise. *Phil. Trans. R. Soc. A* **376**, 20160459. (doi:10.1098/rsta.2016.0459)
12. Gardiner SM, Fragnière A. 2018 Geoengineering, political legitimacy and justice. *Ethics Policy Environ.* **21**, 265–269. (doi:10.1080/21550085.2018.1562524)
13. Zelli F, Möller I, Asselt H. 2017 Institutional complexity and private authority in global climate governance: the cases of climate engineering, REDD+ and short-lived climate pollutants. *Environ. Polit.* **26**, 669–693. (doi:10.1080/09644016.2017.1319020)
14. Jinnah S. 2018 Why govern climate engineering? A preliminary framework for demand-based governance. *Int. Stud. Rev.* **20**, 272–282. (doi:10.1093/isr/viy022)
15. Heyward C, Rayner S. 2015 Uneasy expertise: geoengineering, social science, and democracy in the Anthropocene. In *Policy legitimacy, science and political authority: knowledge and action in liberal democracies* (eds M Heazle, J Kane), pp. 101–121. London, UK: Earthscan.

16. Schäfer S, Low S. 2018 The discursive politics of expertise: what matters for geoengineering research and governance? In *Work in progress: economy and environment in the hands of experts* (eds F Trentmann, AB Sum, M Rivera), pp. 291–312. Munich, Germany: Oekom Verlag.
17. Burns ET, Flegal JA, Keith DW, Mahajan A, Tingley D, Wagner G. 2016 What do people think when they think about solar geoengineering? A review of empirical social science literature, and prospects for future research. *Earth's Future* **4**, 536–542. (doi:10.1002/2016EF000461)
18. Horton JB, Reynolds JL. 2016 The international politics of climate engineering: a review and prospectus for international relations. *Int. Stud. Rev.* **18**, 438–461. (doi:10.1093/isr/viv013)
19. Biermann F, Möller I. 2019 Rich man's solution? Climate engineering discourses and the marginalization of the global south. *Int. Environ. Agreements Polit. Law Econ.* **19**, 151–167. (doi:10.1007/s10784-019-09431-0)
20. Robock A. 2000 Volcanic eruptions and climate. *Rev. Geophys.* **38**, 191–219. (doi:10.1029/1998rg000054)
21. Kravitz B *et al.* 2014 A multi-model assessment of regional climate disparities caused by solar geoengineering. *Environ. Res. Lett.* **9**, 074013. (doi:10.1088/1748-9326/9/7/074013)
22. Irvine P, Emanuel K, He J, Horowitz LW, Vecchi G, Keith D. 2019 Halving warming with idealized solar geoengineering moderates key climate hazards. *Nat. Clim. Change* **9**, 295–299. (doi:10.1038/s41558-019-0398-8)
23. McClellan J, Keith DW, Apt J. 2012 Cost analysis of stratospheric albedo modification delivery systems. *Environ. Res. Lett.* **7**, 034019. (doi:10.1088/1748-9326/7/3/034019)
24. Moriyama R, Sugiyama M, Kurosawa A, Masuda K, Tsuzuki K, Ishimoto Y. 2016 The cost of stratospheric climate engineering revisited. *Mitig. Adapt. Strateg. Glob. Change* **22**, 1207–1228. (doi:10.1007/s11027-016-9723-y)
25. Smith W, Wagner G. 2018 Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. *Environ. Res. Lett.* **13**, 124001. (doi:10.1088/1748-9326/aae98d)
26. Nordhaus WD. 2013 *The climate casino: risk, uncertainty, and economics for a warming world*. New Haven, CT: Yale University Press.
27. Cooper G, Foster J, Galbraith L, Jain S, Neukermans A, Ormond B. 2014 Preliminary results for salt aerosol production intended for marine cloud brightening, using effervescent spray atomization. *Phil. Trans. R. Soc. A* **372**, 20140055. (doi:10.1098/rsta.2014.0055)
28. Latham J, Gadian A, Fournier J, Parkes B, Wadhams P, Chen J. 2014 Marine cloud brightening: regional applications. *Phil. Trans. R. Soc. A* **372**, 20140053. (doi:10.1098/rsta.2014.0053)
29. Latham J *et al.* 2012 Marine cloud brightening. *Phil. Trans. R. Soc. A* **370**, 4217–4262. (doi:10.1098/rsta.2012.0086)
30. Storelvmo T, Boos WR, Herger N. 2014 Cirrus cloud seeding: a climate engineering mechanism with reduced side effects? *Phil. Trans. R. Soc. A* **372**, article 20140116. (doi:10.1098/rsta.2014.0116)
31. Lohmann U, Gasparini B. 2017 A cirrus cloud climate dial? *Science* **357**, 248–249. (doi:10.1126/science.aan3325)
32. Necheles E, Burns L, Keith D. 2018 Funding for solar geoengineering from 2008 to 2018. See https://geoengineering.environment.harvard.edu/blog/funding-solar-geoengineering (accessed 19 April 2019).
33. Grieneisen ML, Zhang M. 2011 The current status of climate change research. *Nat. Clim. Change* **1**, 72–73. (doi:10.1038/nclimate1093)
34. Izrael Y *et al.* 2009 Field studies of a geo-engineering method of maintaining a modern climate with aerosol particles. *Russ. Meteorol. Hydrol.* **34**, 635–638. (doi:10.3103/s106837390910001x)
35. Russell LM *et al.* 2013 Eastern Pacific emitted aerosol cloud experiment. *Bull. Am. Meteorol. Soc.* **94**, 709–729. (doi:10.1175/BAMS-D-12-00015.1)
36. Keith DW, Duren R, MacMartin DG. 2014 Field experiments on solar geoengineering: report of a workshop exploring a representative research portfolio. *Phil. Trans. R. Soc. A* **372**, article 20140175. (doi:10.1098/rsta.2014.0175)
37. Dykema JA, Keith DW, Anderson JG, Weisenstein D. 2014 Stratospheric controlled perturbation experiment: a small-scale experiment to improve understanding of the risks of solar geoengineering. *Phil. Trans. R. Soc. A* **372**, article 20140059. (doi:10.1098/rsta.2014.0059)
38. MacMartin DG, Kravitz B. 2019 The engineering of climate engineering. *Annu. Rev. Control Robot. Auton. Syst.* **2**, 445–467. (doi:10.1146/annurev-control-053018-023725)

39. Heyward C. 2013 Situating and abandoning geoengineering: a typology of five responses to dangerous climate change. *PS Polit. Sci. Polit.* **46**, 23–27. (doi:10.1017/S1049096512001436)
40. Wigley TML. 2006 A combined mitigation/geoengineering approach to climate stabilization. *Science* **314**, 452–454. (doi:10.1126/science.1131728)
41. Long JCS, Shepherd JG. 2014 The strategic value of geoengineering research. In *Global environmental change* (ed. B Freedman), pp. 757–770. Dordrecht, The Netherlands: Springer.
42. MacMartin DG, Ricke KL, Keith DW. 2018 Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target. *Phil. Trans. R. Soc. A* **376**, article 20160454. (doi:10.1098/rsta.2016.0454)
43. Eastham SD, Weisenstein DK, Keith DW, Barrett SRH. 2018 Quantifying the impact of sulfate geoengineering on mortality from air quality and UV-B exposure. *Atmos. Environ.* **187**, 424–434. (doi:10.1016/j.atmosenv.2018.05.047)
44. Keith DW, Weisenstein DK, Dykema JA, Keutsch FN. 2016 Stratospheric solar geoengineering without ozone loss. *Proc. Natl Acad. Sci. USA* **113**, 14 910–14 914. (doi:10.1073/pnas.1615572113)
45. Kravitz B, Robock A, Oman L, Stenchikov G, Marquardt AB. 2009 Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols. *J. Geophys. Res.* **114**, D14109. (doi:10.1029/2009jd011918)
46. Gabriel CJ, Robock A. 2015 Stratospheric geoengineering impacts on El Niño/Southern Oscillation. *Atmos. Chem. Phys.* **15**, 11 949–11 966. (doi:10.5194/acp-15-11949-2015)
47. Williamson P, Turley C. 2012 Ocean acidification in a geoengineering context. *Phil. Trans. R. Soc. A* **370**, 4317–4342. (doi:10.1098/rsta.2012.0167)
48. Kellogg WW, Schneider SH. 1974 Climate stabilization: for better or for worse? *Science* **186**, 1163–1172. (doi:10.1126/science.186.4170.1163)
49. Schelling TC. 1983 Climatic change: implications for welfare and policy. In *Changing climate: report of the carbon dioxide assessment committee* (eds WA Nierenberg, PG Brewer, L Machta, WD Nordhaus, RR Revelle, TC Schelling, J Smagorinsky, PE Waggoner, GM Woodwell), pp. 449–497. Washington, DC: National Academy Press.
50. Institute of Medicine, National Academy of Sciences, National Academy of Engineering. 1992 *Policy implications of greenhouse warming: mitigation, adaptation, and the science base*. Washington, DC: National Academy Press.
51. Keith DW, Dowlatabadi H. 1992 A serious look at geoengineering. *EOS* **73**, 289, 292–293. (doi:10.1029/91EO00231)
52. Schneider SH. 1996 Geoengineering: could—or should—we do it? *Clim. Change* **33**, 291–302. (doi:10.1007/bf00142577)
53. Bodansky D. 1996 May we engineer the climate? *Clim. Change* **33**, 309–321. (doi:10.1007/bf00142579)
54. Jamieson D. 1996 Ethics and intentional climate change. *Clim. Change* **33**, 323–336. (doi:10.1007/bf00142580)
55. Schelling TC. 1996 The economic diplomacy of geoengineering. *Clim. Change* **33**, 303–307. (doi:10.1007/bf00142578)
56. Crutzen PJ. 2006 Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Clim. Change* **77**, 211–220. (doi:10.1007/s10584-006-9101-y)
57. Reynolds JL. 2017 Solar climate engineering, law, and regulation. In *The Oxford handbook of law, regulation, and technology*) (eds R Brownsword, E Scotford, K Yeung), pp. 799–822. Oxford: Oxford University Press.
58. Barrett S. 2007 *Why cooperate? The incentive to supply global public goods*. Oxford, UK: Oxford University Press.
59. Weitzman ML. 2015 A voting architecture for the governance of free-driver externalities, with application to geoengineering. *Scand. J. Econ.* **117**, 1049–1068. (doi:10.1111/sjoe.12120)
60. Victor DG. 2008 On the regulation of geoengineering. *Oxford Rev. Econ. Policy* **24**, 322–336. (doi:10.1093/oxrep/grn018)
61. Chalecki EL, Ferrari LL. 2018 A new security framework for geoengineering. *Strat. Stud. Quart.* **12**, 82–106. See https://www.airuniversity.af.edu/Portals/10/SSQ/documents/Volume-12_Issue-2/Chalecki_Ferrari.pdf (accessed 19 April 2019).
62. Gupta A, Möller I. 2018 De facto governance: how authoritative assessments construct climate engineering as an object of governance. *Environ. Polit.* **28**, 480–501. (doi:10.1080/09644016.2018.1452373)

63. Bodansky D. 2019 Solar geoengineering and international law. In *Governance of the deployment of solar geoengineering* (eds RN Stavins, RC Stowe), pp. 119–123. Cambridge, MA: Harvard Project on Climate Agreements. See https://www.belfercenter.org/publication/governance-deployment-solar-geoengineering (accessed 19 April 2019).
64. Gerrard MB, Hester T. (eds) 2018 *Climate engineering and the law: regulation and liability for solar radiation management and carbon dioxide removal*. Cambridge, UK: Cambridge University Press.
65. International Law Commission. 2001 Draft articles on prevention of transboundary harm from hazardous activities, with commentaries. In *Report of the International Law Commission on the work of its fifty-third session*. UN Doc A/56/10, pp. 148–170. New York, NY: United Nations. See http://legal.un.org/ilc/texts/instruments/english/commentaries/9_7_2001.pdf (accessed 19 April 2019).
66. International Law Commission. 2001 Draft articles on responsibility of states for internationally wrongful acts, with commentaries. In *Report of the International Law Commission on the work of its fifty-third session*. UN Doc A/56/10, pp. 31–143. New York, NY: United Nations. See http://legal.un.org/ilc/texts/instruments/english/commentaries/9_6_2001.pdf (accessed 19 April 2019).
67. Chemnick J. 2019 U.S. Blocks U.N. Resolution on geoengineering. E&E News. See https://www.scientificamerican.com/article/u-s-blocks-u-n-resolution-on-geoengineering/ (accessed 19 April 2019).
68. Michaelson J. 1998 Geoengineering: a climate change Manhattan project. *Stanford Environ. Law J.* **17**, 73–140. See https://heinonline.org/HOL/LandingPage?handle=hein.journals/staev17&div=9&id=&page= (accessed 19 April 2019).
69. Keith DW, Parson E, Morgan MG. 2010 Research on global sun block needed now. *Nature* **463**, 426–427. (doi:10.1038/463426a)
70. Bodansky D. 2013 The who, what, and wherefore of geoengineering governance. *Clim. Change* **121**, 539–551. (doi:10.1007/s10584-013-0759-7)
71. Long JCS, Loy F, Morgan MG. 2015 Start research on climate engineering. *Nature* **518**, 29–31. (doi:10.1038/518029a)
72. Robock A. 2016 Albedo enhancement by stratospheric sulfur injections: more research needed. *Earth's Future* **4**, 644–648. (doi:10.1002/2016EF000407)
73. American Geophysical Union Council. 2009 AGU position statement: geoengineering the climate system: statement adopted by Council 13 December 2009 Adopted from the statement written by the American Meteorological Society and adopted by the AMS Council on 20 July 2009. *Eos Trans. AGU* **91**, 146–147. (doi:10.1029/2010EO160013)
74. American Geophysical Union Council. 2018 Climate intervention requires enhanced research, consideration of societal and environmental impacts, and policy development. See https://sciencepolicy.agu.org/files/2018/01/Climate-Intervention-Position-Statement-Final-2018-1.pdf (accessed 19 April 2019).
75. American Meteorological Society Council. 2009 AMS policy statement on geoengineering the climate system. See https://www.ametsoc.org/index.cfm/ams/about-ams/ams-statements/statements-of-the-ams-in-force/geoengineering-the-climate-system/ (accessed 19 April 2019).
76. Reekie T, Howard W. 2012 Geoengineering. Australia's Chief Scientist (Occasional Paper Series 1). See http://www.chiefscientist.gov.au/2012/04/ops1 (accessed 19 April 2019).
77. Deutsche Forschungsgemeinschaft. 2012 Climate engineering: Forschungsfragen einer gesellschaftlichen herausforderung. See https://www.dfg.de/download/pdf/dfg_im_profil/reden_stellungnahmen/2012/stellungnahme_climate_engineering_120403.pdf (accessed 19 April 2019).
78. Riphagen M, Brom F (eds) 2013 *Klimaatengineering: hype, hoop of wanhoop?* Den Haag: Rathenau Instituut. See https://www.rathenau.nl/sites/default/files/2018-05/Het_Bericht_Klimaatengineering_-_Rathenau_Instituut.pdf (accessed 19 April 2019).
79. Schütte G. 2014 Speech by State Secretary Dr Georg Schütte, Federal Ministry of Education and Research, at the international conference on 'Climate Engineering – Critical Global Discussions' of the Institute for Advanced Sustainability Studies Berlin, 18 August 2014. See https://www.bmbf.de/pub/reden/Rede_StSchuette_IASS__Konferenz_18_08__engl.pdf (accessed 19 April 2019).
80. US Global Change Research Program. 2017 *National global change research plan 2012–2021: a triennial update*. Washington, DC: US Global Change Research Program. See https://www.

globalchange.gov/browse/reports/national-global-change-research-plan-2012--2021-triennial-update (accessed 19 April 2019).
81. Long JCS, Scott D. 2013 Vested interests and geoengineering research. *Issues Sci. Technol.* **29**, 45–52. See https://issues.org/long-4/ (accessed 19 April 2019).
82. Morgan MG, Nordhaus RR, Gottlieb P. 2013 Needed: research guidelines for solar radiation management. *Issues Sci. Technol.* **29**, 37–44. See https://issues.org/morgan-3/ (accessed 19 April 2019).
83. Zürn M, Schäfer S. 2013 The paradox of climate engineering. *Glob. Policy* **4**, 266–277. (doi:10.1111/gpol.12004)
84. Winickoff DE, Flegal JA, Asrat A. 2015 Engaging the global south on climate engineering research. *Nat. Clim. Change* **5**, 627–634. (doi:10.1038/nclimate2632)
85. Ghosh A. 2018 Environmental institutions, international research programmes, and lessons for geoengineering research. In *Geoengineering our climate? Ethics, politics, and governance* (eds J Blackstock, S Low), pp. 199–213. London, UK: Earthscan.
86. Bipartisan Policy Center's Task Force on Climate Remediation Research. 2011 *Geoengineering: A national strategic plan for research on the potential effectiveness, feasibility, and consequences of climate remediation technologies*. Bipartisan Policy Center. See https://bipartisanpolicy.org/library/task-force-climate-remediation-research/ (accessed 19 April 2019).
87. Winickoff DE, Brown MB. 2013 Time for a government advisory committee on geoengineering research. *Issues Sci. Technol.* **29**, 79–85. See https://issues.org/time-for-a-government-advisory-committee-on-geoengineering-research/ (accessed 19 April 2019).
88. Jinnah S, Nicholson S, Flegal J. 2019 Toward legitimate governance of solar geoengineering research: a role for sub-state actors. *Ethics Policy Environ.* **21**, 362–381. (doi:10.1080/21550085.2018.1562526)
89. Keith DW. 2017 Toward a responsible solar geoengineering research program. *Issues Sci. Technol.* **33**. See https://issues.org/toward-a-responsible-solar-geoengineering-research-program/ (accessed 19 April 2019).
90. Asilomar Scientific Organizing Committee. 2010 *The Asilomar Conference recommendations on principles for research into climate engineering techniques*. Washington, DC: Climate Institute. See http://jreynolds.org/wp-content/uploads/2018/05/MacCracken-2010-The-Asilomar-Conference-Recomm.pdf (accessed 19 April 2019).
91. Solar Radiation Management Governance Initiative. 2011 Solar radiation management: the governance of research. See http://www.srmgi.org/files/2016/02/SRMGI.pdf (accessed 19 April 2019).
92. Dilling L, Hauser R. 2013 Governing geoengineering research: why, when and how? *Clim. Change* **121**, 553–565. (doi:10.1007/s10584-013-0835-z)
93. Lin A. 2016 The missing pieces of geoengineering research governance. *Minn. Law Rev.* **100**, 2509–2576. See http://www.minnesotalawreview.org/wp-content/uploads/2016/08/Lin_Online.pdf (accessed 19 April 2019).
94. Burger M, Gundlach J. 2018 Research governance. In *Climate engineering and the law: regulation and liability for solar radiation management and carbon dioxide removal* (eds MB Gerrard, TD Hester), pp. 269–323. Cambridge, UK: Cambridge University Press.
95. Chhetri N *et al.* 2018 *Governing solar radiation management*. Washington, DC: Forum for Climate Engineering Assessment, American University.
96. Reynolds J. 2011 The regulation of climate engineering. *Law Innov. Technol.* **3**, 113–136. (doi:10.5235/175799611796399821)
97. Robock A, Bunzl M, Kravitz B, Stenchikov GL. 2010 A test for geoengineering? *Science* **327**, 530–531. (doi:10.1126/science.1186237)
98. MacMartin DG, Kravitz B. 2019 Mission-driven research for stratospheric aerosol geoengineering. *Proc. Natl Acad. Sci.USA* **116**, 1089–1094. (doi:10.1073/pnas.1811022116)
99. Du H. 2017 *An international legal framework for geoengineering: managing the risks of an emerging technology*. London, UK and New York, NY: Routledge.
100. Morgan MG, Ricke K. 2010 *Cooling the Earth through solar radiation management: the need for research and an approach to its governance*. Geneva, Switzerland: International Risk Governance Council. See https://irgc.org/wp-content/uploads/2012/04/SRM_Opinion_Piece_web.pdf (accessed 19 April 2019).
101. Hester T. 2011 Remaking the world to save it: applying U.S. environmental laws to climate engineering projects. *Ecol. Law Q.* **38**, 851–901. (doi:10.15779/Z38027P)

102. Scott KN. 2015 Engineering the 'mis-Anthropocene': international law, ethics and geoengineering. *Ocean Yearbook* **29**, 61–84. (doi:10.1163/22116001-02901005)
103. Reynolds JL. 2019 *The governance of solar geoengineering: managing climate change in the Anthropocene*. Cambridge, UK: Cambridge University Press.
104. Chavez AE. 2014 A Napoleonic approach to climate change: the geoengineering branch. *Wash. Lee J. Energy Clim. Environ.* **5**, 93–163. See https://scholarlycommons.law.wlu.edu/jece/vol5/iss1/5/ (accessed 19 April 2019).
105. McDonald J, McGee J, Brent K, Burns W. 2019 Governing geoengineering research for the Great Barrier Reef. *Clim. Policy* **19**, 801–811. (doi:10.1080/14693062.2019.1592742)
106. Craik N, Moore N. 2014 Disclosure-based governance for climate engineering research. Centre for International Governance Innovation (CIGI Papers 50). See https://www.cigionline.org/sites/default/files/no.50.pdf (accessed 10 April 2019).
107. Carr W, Yung L, Preston C. 2014 Swimming upstream: engaging the American public early on climate engineering. *Bull. At. Sci.* **70**, 38–48. (doi:10.1177/0096340214531180)
108. Gullberg AT, Hovi J. 2016 Regulating solar radiation management. *Eur. J. Risk Regul.* **7**, 75–86. (doi:10.1017/S1867299X00005419)
109. Craik N. 2015 International EIA law and geoengineering: do emerging technologies require special rules? *Clim. Law* **5**, 111–141. (doi:10.1163/18786561-00504002)
110. Bodle R, Oberthür S, Donat L, Homann G, Sina S, Tedsen E. 2014 Options and proposals for the international governance of geoengineering. Umweltbundesamt (Climate Change 14/2014). See https://www.umweltbundesamt.de/publikationen/options-proposals-for-the-international-governance (accessed 19 April 2019).
111. Payne CR, Shwom R, Heaton S. 2015 Public participation and norm formation for risky technology: adaptive governance of solar-radiation management. *Clim. Law* **5**, 210–251. (doi:10.1163/18786561-00504005)
112. Foley RW, Guston DH, Sarewitz D. 2018 Towards the anticipatory governance of geoengineering. In *Geoengineering our climate? Ethics, politics and governance* (eds J Blackstock, S Low), pp. 223–243. London, UK: Earthscan.
113. Stilgoe J, Watson M, Kuo K. 2013 Public engagement with biotechnologies offers lessons for the governance of geoengineering research and beyond. *PLoS Biol.* **11**, e1001707. (doi:10.1371/journal.pbio.1001707)
114. Reynolds J. 2014 The international regulation of climate engineering: lessons from nuclear power. *J. Environ. Law* **26**, 269–289. (doi:10.1093/jel/equ006)
115. Parker A. 2014 Governing solar geoengineering research as it leaves the laboratory. *Phil. Trans. R. Soc. A* **372**, 20140173. (doi:10.1098/rsta.2014.0173)
116. Andersen SO. 2017 We can and must govern climate engineering. *Nature* **551**, 415. (doi:10.1038/d41586-017-07296-4)
117. Armeni C. 2015 Global experimentalist governance, international law and climate change technologies. *Int. Comp. Law Q.* **64**, 875–904. (doi:10.1017/S0020589315000408)
118. Reynolds JL. 2018 Governing experimental responses: negative emissions technologies and solar climate engineering. In *Governing climate change: polycentricity in action?* (eds A Jordan, D Huitema, H Van Asselt, J Forster), pp. 285–302. Cambridge, UK: Cambridge University Press.
119. Coglianese C, Mendelson E. 2010 Meta-regulation and self-regulation. In *The Oxford handbook of regulation* (eds R Baldwin, M Cave, M Lodge), pp. 146–168. Oxford, UK: Oxford University Press.
120. Davis WD. 2009 What does 'green' mean? Anthropogenic climate change, geoengineering, and international environmental law. *Ga. Law Rev.* **43**, 901–951. See https://heinonline.org/HOL/LandingPage?handle=hein.journals/geolr43&div=24&id=&page= (accessed 19 April 2019).
121. Blackstock JJ, Long JCS. 2010 The politics of geoengineering. *Science* **327**, 527. (doi:10.1126/science.1183877)
122. Olson RL. 2011 *Geoengineering for decision makers*. Washington, DC: Woodrow Wilson International Center for Scholars. See https://www.wilsoncenter.org/publication/geoengineering-for-decision-makers (accessed 19 April 2019).
123. Parson EA, Ernst LN. 2013 International governance of climate engineering. *Theor. Inq. Law* **14**, 307–338. (doi:10.1515/til-2013-015)
124. Nye JS. 2019 Notes on insights from other regimes: Cyber. In *Governance of the deployment of solar geoengineering* (eds RN Stavins, RC Stowe), pp. 55–59. Cambridge, MA:

Harvard Project on Climate Agreements. See https://www.belfercenter.org/publication/governance-deployment-solar-geoengineering (accessed 19 April 2019).

125. Lloyd ID, Oppenheimer M. 2014 On the design of an international governance framework for geoengineering. *Glob. Environ. Polit.* **14**, 45–63. (doi:10.1162/GLEP_a_00228)
126. Conca K. 2018 Prospects for a multi-stakeholder dialogue on climate engineering. *Environ. Polit.* **28**, 417–440. (doi:10.1080/09644016.2018.1522065)
127. Nicholson S, Jinnah S, Gillespie A. 2018 Solar radiation management: a proposal for immediate polycentric governance. *Clim. Policy* **18**, 322–334. (doi:10.1080/14693062.2017.1400944)
128. Lempert RJ, Prosnitz D. 2011 *Governing geoengineering research: a political and technical vulnerability analysis of potential near-term options*. Santa Monica, CA: RAND Corporation. See https://www.rand.org/pubs/technical_reports/TR846.html (accessed 19 April 2019).
129. Schäfer S, Low S. 2014 Asilomar moments: formative framings in recombinant DNA and solar climate engineering research. *Phil. Trans. R. Soc. A* **372**, 20140064. (doi:10.1098/rsta.2014.0064)
130. Lin A. 2012 Geoengineering's thermostat dilemma. In *The law of the future and the future of law: volume II* (eds S Muller, S Zouridis, M Frishman, L Kistemaker), pp. 173–183. The Hague, The Netherlands: Torkel Opsahl. See http://www.toaep.org/lotfs-pdf/1-muller-zouridis-frishman-kistemaker (accessed 19 April 2019).
131. Winter G. 2013 Climate engineering and international law: final exit or the end of humanity? In *Climate change: international law and global governance: volume I: legal responses and global responsibility* (eds OC Ruppel, C Roschmann, K Ruppel-Schlichting), pp. 979–1012. Baden-Baden, Germany: Nomos Verlagsgesellschaft.
132. Stilgoe J. 2016 Geoengineering as collective experimentation. *Sci. Eng. Ethics* **22**, 851–869. (doi:10.1007/s11948-015-9646-0)
133. Kössler GP. 2012 *Geo-engineering: Gibt es wirklich einen plan(eten) B?* Berlin, Germany: Heinrich Böll Foundation. See https://www.boell.de/de/content/geo-engineering-gibt-es-wirklich-einen-planeten-b (accessed 19 April 2019).
134. Chavez AE. 2016 Using legal principles to guide geoengineering deployment. *NYU. Environ. Law J.* **24**, 59–110. See https://www.nyuelj.org/wp-content/uploads/2016/09/24.1-Chavez_Final.pdf (accessed 19 April 2019).
135. Morrow DR, Kopp RE, Oppenheimer M. 2009 Toward ethical norms and institutions for climate engineering research. *Environ. Res. Lett.* **4**, article 045106. (doi:10.1088/1748-9326/4/4/045106)
136. Rayner S, Heyward C, Kruger T, Pidgeon N, Redgwell C, Savulescu J. 2013 The Oxford principles. *Clim. Change* **121**, 499–512. (doi:10.1007/s10584-012-0675-2)
137. Great Britain Department of Energy and Climate Change. 2010 *Government response to the House of Commons Science and Technology Committee 5th report of session 2009–10: The regulation of geoengineering*. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/47928/569-gov-response-commons-science-tech-5th.pdf (accessed 19 April 2019).
138. UK House of Commons, Science and Technology Committee. 2010 The regulation of geoengineering. See https://publications.parliament.uk/pa/cm200910/cmselect/cmsctech/221/22102.htm (accessed 19 April 2019).
139. Gardiner SM, Fragnière A. 2018 The Tollgate Principles for the governance of geoengineering: moving beyond the Oxford Principles to an ethically more robust approach. *Ethics Policy Environ.* **21**, 143–174. (doi:10.1080/21550085.2018.1509472)
140. International Law Commission. 2018 Text of the draft guidelines on the protection of the atmosphere, together with preamble, adopted by the Commission on first reading. In *Report of the International Law Commission, seventieth session*. UN Doc A/73/10, pp. 158–200. New York, NY: United Nations. See http://legal.un.org/docs/?symbol=A/CN.4/L.909 (accessed 19 April 2019).
141. Rickels W *et al.*. 2011 *Large-scale intentional interventions into the climate system? Assessing the climate engineering debate*. Kiel, Germany: Kiel Earth Institute. See https://www.kiel-earth-institute.de/scoping-report-climate-engineering.html (accessed 19 April 2019).
142. Abelkop ADK, Carlson JC. 2013 Reining in Phaëthon's chariot: principles for the governance of geoengineering. *Transnatl Law Contemp. Probl.* **21**, 763–807. See https://heinonline.

org/HOL/LandingPage?handle=hein.journals/tlcp10&div=1&src=home (accessed 19 April 2019).

143. Scott KN. 2013 International law in the Anthropocene: responding to the geoengineering challenge. *Mich. J. Int. Law* **34**, 309–358. See https://repository.law.umich.edu/mjil/vol34/iss2/2/ (accessed 19 April 2019).
144. Tedsen E, Homann G. 2013 Implementing the precautionary principle for climate engineering. *Carbon Clim. Law Rev.* **7**, 90–100. (doi:10.21552/CCLR/2013/2/250)
145. Doelle M. 2014 Geo-engineering and dispute settlement under UNCLOS and the UNFCCC: stormy seas ahead? In *Climate change impacts on ocean and coastal law: U.S. and international perspectives* (ed. RS Abate), pp. 345–365. Oxford, UK: Oxford University Press.
146. Garg V. 2014 Engineering a solution to climate change: suggestions for an international treaty regime governing geoengineering. *Univ. Ill. J. Law Technol. Policy*, 197. See http://illinoisjltp.com/journal/wp-content/uploads/2014/05/Garg.pdf (accessed 19 April 2019).
147. Morrow DR. 2014 Ethical aspects of the mitigation obstruction argument against climate engineering research. *Phil. Trans. R. Soc. A* **372**, 20140062. (doi:10.1098/rsta.2014.0062)
148. Reichwein D, Hubert A-M, Irvine PJ, Benduhn F, Lawrence MG. 2015 State responsibility for environmental harm from climate engineering. *Clim. Law* **5**, 142–181. (doi:10.1163/18786561-00504003)
149. Fleurke F. 2016 Future prospects for climate engineering within the EU legal order. *Eur. J. Risk Regul.* **7**, 60–74. (doi:10.1017/S1867299X00005407)
150. Ryngaert C. 2016 Climate change mitigation techniques and international law: assessing the externalities of reforestation and geoengineering. *Ratio Juris* **30**, 273–289. (doi:10.1111/raju.12154)
151. Davies GT. 2008 Law and policy issues of unilateral geoengineering: moving to a managed world. In *Select proceedings of the European Society of International Law* (eds H Ruiz Fabri, R Wolfrum, J Gogolin), pp. 627–640. Oxford, UK: Hart.
152. Elliott K. 2010 Geoengineering and the precautionary principle. *Int. J. Appl. Philos.* **24**, 237–253. (doi:10.5840/ijap201024221)
153. Humphreys D. 2011 Smoke and mirrors: some reflections on the science and politics of geoengineering. *J. Environ. Dev.* **20**, 99–120. (doi:10.1177/1070496511405302)
154. Adelman S. 2017 Geoengineering: rights, risks and ethics. *J. Hum. Rights Environ.* **8**, 119–138. (doi:10.4337/jhre.2017.01.06)
155. Lin AC. 2013 International legal regimes and principles relevant to geoengineering. In *Climate change geoengineering: philosophical perspectives, legal issues, and governance frameworks* (eds WCG Burns, AL Strauss), pp. 182–189. Cambridge, UK: Cambridge University Press.
156. Reynolds JL, Fleurke F. 2013 Climate engineering research: a precautionary response to climate change? *Carbon Clim. Law Rev.* **7**, 101–107. (doi:10.21552/CCLR/2013/2/251)
157. Banerjee B. 2011 The limitations of geoengineering governance in a world of uncertainty. *Stanford J. Law Sci. Policy* **4**, 15–36. See https://law.stanford.edu/publications/the-limitations-of-geoengineering-governance-in-a-world-of-uncertainty/ (accessed 19 April 2019).
158. Hartzell-Nichols L. 2012 Precaution and solar radiation management. *Ethics Policy Environ.* **15**, 158–171. (doi:10.1080/21550085.2012.685561)
159. Schafer S, Irvine PJ, Hubert A-M, Reichwein D, Low S, Stelzer H, Maas A, Lawrence MG. 2013 Field tests of solar climate engineering. *Nat. Clim. Change* **3**, 766. (doi:10.1038/nclimate1987)
160. Hubert A-M. 2017 Code of conduct for responsible geoengineering research. See https://www.ucalgary.ca/grgproject/files/grgproject/revised-code-of-conduct-for-geoengineering-research-2017-hubert.pdf (accessed 19 April 2019).
161. Broecker WS. 1985 *How to build a habitable planet*. Palisades, NY: Eldigio.
162. Hale B. 2012 The world that would have been: moral hazard arguments against geoengineering. In *Engineering the climate: the ethics of solar radiation management* (ed. CJ Preston), pp. 113–132. Lanham, MD: Lexington.
163. Edenhofer O *et al.* (eds) 2014 *Climate change 2014: mitigation of climate change: contribution of Working Group III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. New York, NY: Cambridge University Press.
164. Klein N. 2014 *This changes everything: capitalism vs. the climate*. New York, NY: Simon & Schuster.

165. Lin A. 2013 Does geoengineering present a moral hazard? *Ecol. Law Q.* **40**, 673–712. (doi:10.15779/Z38JP1J)
166. Parson EA. 2014 Climate engineering in global climate governance: implications for participation and linkage. *Transnatl Environ. Law* **3**, 89–110. (doi:10.1017/S2047102513000496)
167. Cicerone R. 2006 Geoengineering: encouraging research and overseeing implementation. *Clim. Change* **77**, 221–226. (doi:10.1007/s10584-006-9102-x)
168. UK House of Commons, Science and Technology Committee, King D, Van Aalst M. 2010 Examination of witnesses (questions 34–50). See https://publications.parliament.uk/pa/cm200910/cmselect/cmsctech/221/10011305.htm (accessed 19 April 2019).
169. Markus T, Ginzky H. 2011 Regulating climate engineering: paradigmatic aspects of the regulation of ocean fertilization. *Carbon Clim. Law Rev.* **5**, 477–490. (doi:10.21552/CCLR/2011/4/197)
170. Redgwell C. 2011 Geoengineering the climate: technological solutions to mitigation-failure or continuing carbon addiction? *Carbon Clim. Law Rev.* **5**, 178–189. (doi:10.21552/CCLR/2011/2/177)
171. Umweltbundesamt. 2011 *Geoengineering: effective climate protection or megalomania?* Dessau-Roßlau, Germany: Umweltbundesamt. See https://www.umweltbundesamt.de/en/publikationen/geoengineering-effective-climate-protection (accessed 19 April 2019).
172. Parson EA, Keith DW. 2013 End the deadlock on governance of geoengineering research. *Science* **339**, 1278–1279. (doi:10.1126/science.1232527)
173. Parson EA, Herzog MM. 2016 Moratoria for global governance and contested technology: The case of climate engineering. University of California, Los Angeles, School of Law (UCLA Public Law & Legal Theory Series). See https://escholarship.org/uc/item/2c28w2tn (accessed 19 April 2019).
174. Kraemer AR. 2010 Schöner leben im labor? Geo-engineering und das recht, die welt zu verändern. *Internationale Politik* **65**, 70–75. See https://zeitschrift-ip.dgap.org/de/ip-die-zeitschrift/archiv/jahrgang-2010/januar-februar/sch%C3%B6ner-leben-im-labor (accessed 19 April 2019).
175. Editorial. 2012 A charter for geoengineering. *Nature* **485**, 415. (doi:10.1038/485415a)
176. Robock A. 2012 Is geoengineering research ethical? *Sicherheit und Frieden (S+ F)/Security and Peace* **3**, 226–229. (doi:10.5771/0175-274x-2012-4-226)
177. Preston CJ. 2013 Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and carbon dioxide removal. *WIREs Clim. Change* **4**, 23–37. (doi:10.1002/wcc.198)
178. Anshelm J, Hansson A. 2014 Battling Promethean dreams and Trojan horses: revealing the critical discourses of geoengineering. *Energy Res. Soc. Sci.* **2**, 135–144. (doi:10.1016/j.erss.2014.04.001)
179. Brent KA. 2017 The role of the no-harm rule in governing solar radiation management geoengineering. PhD Thesis, University of Tasmania. See https://eprints.utas.edu.au/23783/ (accessed 19 April 2019).
180. Sikka T. 2018 Activism and neoliberalism: two sides of geoengineering discourse. *Capitalism Nat. Social.* online ahead of print. (doi:10.1080/10455752.2018.1554690)
181. Reynolds JL, Parker A, Irvine P. 2016 Five solar geoengineering tropes that have outstayed their welcome. *Earth's Future* **4**, 562–568. (doi:10.1002/2016EF000416)
182. Talberg A, Christoff P, Thomas S, Karoly D. 2017 Geoengineering governance-by-default: an Earth system governance perspective. *Int. Environ. Agreements Polit. Law Econ.* **18**, 229–263. (doi:10.1007/s10784-017-9374-9)
183. Schuppert F, Stelzer H. 2016 How much risk ought we to take? Exploring the possibilities of risk-sensitive consequentialism in the context of climate engineering. *Environ. Values* **25**, 69–90. (doi:10.3197/096327115X14497392134928)
184. Callies DE. 2019 The slippery slope argument against geoengineering research. *J. Appl. Philos.* **36**, 675–687. (doi:10.1111/japp.12345)
185. Burns W, Nicholson S. 2016 Governing climate engineering. In *New Earth politics: essays from the Anthropocene* (eds S Nicholson, S Jinnah), pp. 344–366. Cambridge, MA: MIT Press.
186. Marshall JB. 2018 Geoengineering: a promising weapon or an unregulated disaster in the fight against climate change? *Fla. St. Univ. J. Land Use Environ. Law* **33**, 6. See https://ir.law.fsu.edu/jluel/vol33/iss1/6/ (accessed 19 April 2019).
187. Lin A. 2009 Geoengineering governance. *Issues Legal Scholarsh.* **8**, article 2. (doi:10.2202/1539-8323.1112)

188. Keith DW, Wagner G, Zabel CL. 2017 Solar geoengineering reduces atmospheric carbon burden. *Nat. Clim. Change* **7**, 617–619. (doi:10.1038/nclimate3376)
189. Zedalis RJ. 2010 Climate change and the National Academy of sciences' idea of geoengineering: one American academic's perspective on first considering the text of existing international agreements. *Eur. Energy Environ. Law Rev.* **19**, 18–32. See https://www.kluwerlawonline.com/abstract.php?area=Journals&id=EELR2010002 (accessed 19 April 2019).
190. Strong A. 2011 Toward an international geoengineering agreement: the promises (and pitfalls) of negotiating a convention on global climate interventions. In *Papers on international environmental negotiation, volume 18: the next generation of environmental agreements* (eds LE Susskind, W Moomaw, NJ Waters), pp. 23–24. See https://pon.harvard.edu/wp-content/uploads/images/posts/Toward_an_International_Geoengineering_Agreement_vol18_2011.pdf (accessed 19 April 2019).
191. Barrett S. 2010 Geoengineering's governance: Written statement prepared for the U.S. House of Representatives Committee on Science and Technology hearing on 'Geoengineering III: Domestic and international research governance'. See https://www.govinfo.gov/content/pkg/CHRG-111hhrg53007/html/CHRG-111hhrg53007.htm (accessed 19 April 2019).
192. Armeni C, Redgwell C. 2015 International legal and regulatory issues of climate geoengineering governance: Rethinking the approach. (Climate Geoengineering Governance Working Paper 21). See http://www.geoengineering-governance-research.org/perch/resources/workingpaper21armeniredgwelltheinternationalcontextrevise-.pdf (accessed 19 April 2019).
193. Reynolds JL, Wagner G. 2019 Highly decentralized solar geoengineering. *Environ. Polit.*, online ahead of print. (doi:10.1080/09644016.2019.1648169)
194. Benedick RE. 2011 Considerations on governance for climate remediation technologies: lessons from the 'ozone hole'. *Stanford J. Law Sci. Policy* **4**, 6–9. See https://law.stanford.edu/publications/considerations-on-governance-for-climate-remediation-technologies-lessons-from-the-ozone-hole/ (accessed 19 April 2019).
195. Bunn M. 2019 Governance of solar geoengineering: learning from nuclear regimes. In *Governance of the deployment of solar geoengineering* (eds RN Stavins, RC Stowe), pp. 51–54. Cambridge, MA: Harvard Project on Climate Agreements. See https://www.belfercenter.org/publication/governance-deployment-solar-geoengineering (accessed 19 April 2019).
196. Kuokkanen T, Yamineva Y. 2013 Regulating geoengineering in international environmental law. *Carbon Clim. Law Rev.* **7**, 161–167. (doi:10.21552/CCLR/2013/3/261)
197. Parson EA. 2017 Starting the dialogue on climate engineering governance: A world commission. Centre for International Governance Innovation (Fixing Climate Governance Series 9). See https://www.cigionline.org/publications/starting-dialogue-climate-engineering-governance-world-commission (accessed 19 April 2019).
198. Hester TD. 2013 A matter of scale: regional climate engineering and the shortfalls of multinational governance. *Carbon Clim. Law Rev.* **7**, 168–176. (doi:10.21552/CCLR/2013/3/258)
199. Long JCS. 2013 A prognosis, and perhaps a plan, for geoengineering governance. *Carbon Clim. Law Rev.* **7**, 177–186. (doi:10.21552/CCLR/2013/3/262)
200. Hulme M. 2014 *Can science fix climate change? A case against climate engineering*. Cambridge, UK: Polity.
201. Cairns R, Nightingale P. 2014 The security implications of geoengineering: Blame, imposed agreement and the security of critical infrastructure. (Climate Geoengineering Governance Working Paper 18). See http://www.geoengineering-governance-research.org/perch/resources/workingpaper18nightingalecairnssecurityimplications.pdf (accessed 19 April 2019).
202. Winter G. 2011 Climate engineering and international law: last resort or the end of humanity? *Rev. Eur. Community Int. Environ. Law* **20**, 277–289. (doi:10.1111/j.1467-9388.2012.00730.x)
203. Honegger M, Sugathapala K, Michaelowa A. 2013 Tackling climate change: where can the generic framework be located? *Carbon Clim. Law Rev.* **7**, 125–135. (doi:10.21552/CCLR/2013/2/254)
204. Armeni C, Redgwell C. 2015 Geoengineering under national law: a case study of the United Kingdom. (Climate Geoengineering Governance Working Paper 23). See http://www.geoengineering-governance-research.org/perch/resources/workingpaper23armeniredgwelltheukcombine.pdf (accessed 19 April 2019).

205. Rabitz F. 2019 Governing the termination problem in solar radiation management. *Environ. Polit.* **28**, 502–522. (doi:10.1080/09644016.2018.1519879)
206. Philippe S. 2019 Monitoring and verifying the deployment of solar geoengineering. In *Governance of the deployment of solar geoengineering* (eds RN Stavins, RC Stowe), pp. 71–74. Cambridge, MA: Harvard Project on Climate Agreements. See https://www.belfercenter.org/publication/governance-deployment-solar-geoengineering (accessed 19 April 2019).
207. Parker A, Irvine PJ. 2018 The risk of termination shock from solar geoengineering. *Earth's Future* **6**, 456–467. (doi:10.1002/2017EF000735)
208. Reynolds JL, Contreras JL, Sarnoff JD. 2017 Solar climate engineering and intellectual property: toward a research commons. *Minn. J. Law Sci. Technol.* **18**, 1–110. See https://scholarship.law.umn.edu/mjlst/vol18/iss1/1/ (accessed 19 April 2019).
209. Gunderson R, Petersen B, Stuart D. 2018 A critical examination of geoengineering: economic and technological rationality in social context. *Sustainability* **10**, 269. (doi:10.3390/su10010269)
210. Robock A. 2008 20 reasons why geoengineering may be a bad idea. *Bull. At. Sci.* **64**, 14–18. (doi:10.2968/064002006)
211. Parthasarathy S, Avery C, Hedberg N, Mannisto J, Maguire M. 2010 A public good? Geoengineering and intellectual property. University of Michigan Science, Technology, and Public Policy Program (STPP Working Paper 10-1). See http://jreynolds.org/wp-content/uploads/2018/08/Parthasarathy-2010-A-Public-Good_-Geoengineeri.pdf (accessed 19 April 2019).
212. Hourdequin M. 2012 Geoengineering, solidarity, and moral risk. In *Engineering the climate: the ethics of solar radiation management* (ed. CJ Preston), pp. 15–32. Lanham, MD: Lexington.
213. Szerszynski B, Kearnes M, Macnaghten P, Owen R, Stilgoe J. 2013 Why solar radiation management geoengineering and democracy won't mix. *Environ. Plann. A Econ. Space* **45**, 2809–2816. (doi:10.1068/a45649)
214. Cairns RC. 2014 Climate geoengineering: issues of path-dependence and socio-technical lock-in. *WIREs Clim. Change* **5**, 649–661. (doi:10.1002/wcc.296)
215. Chavez AE. 2015 Exclusive rights to saving the planet: the patenting of geoengineering inventions. *Northwest. J. Technol. Intellect. Prop.* **13**, article 1. See https://scholarlycommons.law.northwestern.edu/njtip/vol13/iss1/1/ (accessed 19 April 2019).
216. Nicholson S. 2016 Reimagining climate engineering: the politics of tinkering with the sky. In *Reimagining climate change* (eds P Wapner, S Nicholson), pp. 110–130. London, UK and New York, NY: Routledge.
217. Rimmer M. 2018 Intellectual ventures: patent law, climate change, and geoengineering. In *Intellectual property and clean energy: the Paris agreement and climate justice* (ed. M Rimmer), pp. 235–271. Singapore: Springer.
218. Bracmort K, Lattanzio RK. 2013 *Geoengineering: governance and technology policy*. Washington, DC: Congressional Research Service. See https://fas.org/sgp/crs/misc/R41371.pdf (accessed 19 April 2019).
219. Davies G. 2013 Privatisation and de-globalisation of the climate. *Carbon Clim. Law Rev.* **7**, 187–193. (doi:10.21552/CCLR/2013/3/263)
220. Lockley A. 2016 Licence to chill: building a legitimate authorisation process for commercial SRM operations. *Environ. Law Rev.* **18**, 25–40. (doi:10.1177/1461452916630082)
221. Science Media Center. 2012 Expert reaction to decision not to launch the 1 km balloon as part of the SPICE geoengineering research project (press release). See http://www.sciencemediacentre.org/expert-reaction-to-decision-not-to-launch-the-1km-balloon-as-part-of-the-spice-geoengineering-research-project-2/ (accessed 19 April 2019).
222. Keith D, Dykema J. 2018 Why we chose not to patent solar geoengineering technologies. See https://keith.seas.harvard.edu/blog/why-we-chose-not-patent-solar-geoengineering-technologies (accessed 19 April 2019).
223. Marine cloud brightening for the great barrier reef. See https://www.savingthegreatbarrierreef.org/cloud-brightening (accessed 19 April 2019).
224. Reynolds JL, Contreras JL, Sarnoff JD. 2018 Intellectual property policies for solar geoengineering. *WIREs Clim. Change* **9**, e512. (doi:10.1002/wcc.512)
225. Hester T. 2018 Liability and compensation. In *Climate engineering and the law: regulation and liability for solar radiation management and carbon dioxide removal* (eds MB Gerrard, T Hester), pp. 224–268. Cambridge, UK: Cambridge University Press.

226. Svoboda T, Irvine PJ. 2014 Ethical and technical challenges in compensating for harm due to solar radiation management geoengineering. *Ethics Policy Environ.* **17**, 157–174. (doi:10.1080/21550085.2014.927962)
227. Bunzl M. 2011 Geoengineering harms and compensation. *Stanford J. Law Sci. Policy* **4**, 69–75. See https://law.stanford.edu/publications/geoengineering-harms-and-compensation/ (accessed 19 April 2019).
228. Heyward C. 2014 Benefiting from climate geoengineering and corresponding remedial duties: the case of unforeseeable harms. *J. Appl. Philos.* **31**, 405–419. (doi:10.1111/japp.12075)
229. Brent K. 2018 Solar radiation management geoengineering and strict liability for ultrahazardous activities. In *Global environmental change and innovation in international law* (eds CSG Jefferies, N Craik, SL Seck, T Stephens), pp. 161–179. Cambridge, UK: Cambridge University Press.
230. Pfrommer T. 2018 A model of solar radiation management liability. University of Heidelberg (Department of Economics Discussion Paper 644). (doi:10.11588/heidok.00023978)
231. Saxler B, Siegfried J, Proelss A. 2015 International liability for transboundary damage arising from stratospheric aerosol injections. *Law Innov. Technol.* **7**, 112–147. (doi:10.1080/17579961.2015.1052645)
232. Wong P-H, Douglas T, Savulescu J. 2014 Compensation for geoengineering harms and no-fault climate change compensation. (Climate Geoengineering Governance Working Paper 8). See http://geoengineering-governance-research.org/perch/resources/workingpaper8wongdouglassavulescucompensationfinal-.pdf (accessed 19 April 2019).
233. Horton JB, Parker A, Keith D. 2015 Liability for solar geoengineering: historical precedents, contemporary innovations, and governance possibilities. *NYU Environ. Law J.* **22**, 225–273. See https://www.nyuelj.org/wp-content/uploads/2015/02/Horton_READY_FOR_WEBSITE.pdf (accessed 19 April 2019).
234. Packard L. 2018 Designing an international liability regime to compensate victims of solar radiation management. *Environ. Claims J.* **30**, 71–86. (doi:10.1080/10406026.2017.1403832)
235. Reynolds JL. 2015 An economic analysis of liability and compensation for harm from large-scale solar climate engineering field research. *Clim. Law* **5**, 182–209. (doi:10.1163/18786561-00504004)
236. Horton JB, Keith DW. 2019 Multilateral parametric climate risk insurance: a tool to facilitate agreement about deployment of solar geoengineering? *Clim. Policy* **19**, 820–826. (doi:10.1080/14693062.2019.1607716)