C2G
Carnegie Climate Governance Initiative

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EVIDENCE BRIEF

Stratospheric Aerosol Injection and its Governance

25 March 2021

Summary

This briefing summarises the latest evidence around Stratospheric Aerosol Injection (SAI), a form of Solar Radiation Modification (SRM). It describes the proposed technique, explores its technical readiness, current research, applicable governance frameworks, and other socio-political considerations and provides an overview of key existing governance instruments of relevance to its governance.

The Carnegie Climate Governance Initiative (C2G) has no position on whether SAI should be researched, tested or deployed. It seeks to raise awareness about climate-altering techniques, such as SAI, with policymakers, and to catalyse debate about their future governance. C2G has prepared several other briefs exploring various existing and proposed carbon dioxide removal (CDR) and SRM techniques and associated issues. These are available on our website.

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Introduction

Five years after the Paris Agreement on climate change was signed, recognition is growing that without a rapid acceleration in action, limiting global average temperature rise to 1.5 – 2 degrees Celsius (°C) above pre-industrial temperatures will not be achieved through emissions reductions or existing carbon removal practices alone (IPCC, 2018). Scientists have begun exploring the additional use of large-scale interventions to limit climate impacts, including proposed and existing Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM) techniques. SRM is an approach to altering the climate and refers to the intentional modification of the Earth's shortwave radiative budget with the aim of reducing warming. Artificial injection of stratospheric aerosols, marine cloud brightening (MCB), cirrus cloud thinning, and land surface albedo modification are examples of proposed SRM methods (IPCC, 2018). SRM does not fall within the definitions of mitigation and adaptation (p558, IPCC, 2012) but is, rather, considered a third type of climate intervention in its own right. SRM is also referred to as solar radiation management, solar geoengineering, atmospheric climate intervention (ACI), albedo enhancement or simply, geoengineering.

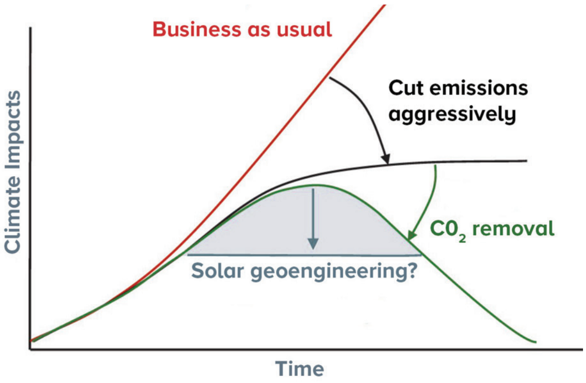
This briefing focuses on one SRM technique, Stratospheric Aerosol Injection (SAI).

The underlying objective of SAI is to increase the reflectivity, known as ‘albedo’, of the Earth. An increase in the amount of sunlight, known as solar radiation, returning to space would alter the Earth’s radiation balance, diffusing light and working like a shade to counter some of the effects of greenhouse warming. There is modelling evidence that SAI could deliver enough radiative forcing to offset at least half of the radiative forcing caused by a doubling of carbon dioxide (CO_2) concentrations. In addition, evidence shows that SAI may be able to produce uniform radiative forcing (Kravitz et al., 2017) and reduce key climate hazards substantially (Irvine and Keith, 2020).

Given the response to securing the goals of the Paris Agreement which has, to date, been slow, the idea of a ‘temperature overshoot and peak-shaving’ scenario is emerging as a possible SAI strategy (Asayama and Hulme, 2019). Such a scenario relies upon the temporary deployment of SAI, combined with CDR, to compensate for delayed mitigation, cooling the global climate to ensure target temperatures are not exceeded, whilst CDR capacity is sufficiently ramped up, creating a potential strategic interdependency between CDR and SAI. This approach, demonstrated in the so-called ‘Napkin diagram’ (Figure 1.), has been viewed both optimistically (Geden & Löschel, 2017) and as a cause for concern because it may avoid the harms of exceeding temperature targets, or create a risk of escalating ‘climate debt’ by slowing emissions reductions and CDR development and deployment (McLaren, 2016, Asayama and Hulme, 2019).

SAI alone could not be a substitute for emissions reductions to net zero, and then net negative, as it does not address the underlying cause of global warming - increased greenhouse gas (GHG) concentrations (Robock, 2018). Because climate variables would react differently to SAI radiative forcing than to GHG radiative forcing, it would not be possible to eliminate all GHG derived climate changes, even if SAI were used to reduce radiative forcing to zero (Kravitz et al., 2013), meaning if SAI were deployed, it would still be important to bring net emissions to zero if a stable climate is desired (Keith and Irvine, 2019).

Figure 1. 'The Napkin diagram'.



For the purposes of illustration, it may be helpful to note that a doubling of CO_2 concentrations from pre-industrial levels is expected to create 3°C of global warming (IPCC 2018) and, if SAI were ever deployed with the intention of countering this amount of warming, it would need to reflect roughly 2% of sunlight back out into space (Shepherd, 2009).

Interest in the potential for SAI to cool the global climate, for example to temporarily reduce the amount and duration of an overshoot of the Paris temperature goals, should reduction and removal of CO_2 emissions not happen fast enough, is growing (Asayama, 2019). However, SAI remains a complex technical, socio-political and governance challenge. For example, the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (2018) notes: *"Although some SRM measures may be theoretically effective in reducing an overshoot, they face large uncertainties and knowledge gaps as well as substantial risks, institutional and social constraints to deployment related to governance, ethics, and impacts on sustainable development. They also do not mitigate ocean acidification."*

This evidence brief is not a comprehensive, detailed assessment of SAI. Rather, it provides an overview of the evidence on the technological readiness, research landscape, governance, security and socio-political issues associated with SAI. In section one the technique is described, and section two offers an overview of the tools and instruments of governance that may apply.

SECTION I: Technique overview

Introduction

This section introduces SAI, briefly describing its technical readiness, current research, governance issues, and other socio-political considerations. For information, C2G uses the IPCC's definition of governance - '*A comprehensive and inclusive concept of the full range of means for deciding, managing, implementing and monitoring policies and measures. Whereas government is defined strictly in terms of the nation-state, the more inclusive concept of governance recognises the contributions of various levels of government (global, international, regional, sub-national and local) and the contributing roles of the private sector, of nongovernmental actors, and of civil society to addressing the many types of issues facing the global community*' (IPCC, 2018).

The Principle

The fundamental principle underlying SAI is to increase the amount of reflective aerosol particles in the lower stratosphere, thereby enhancing albedo (i.e., increasing the amount of sunlight that is deflected back out into space), hence achieving cooling.

An aerosol is a suspension of airborne solid or liquid particles, with a typical size between a few nanometres and 10 micrometres that reside in the atmosphere for at least several hours, they may be of either natural or anthropogenic origin (IPCC, 2018). Aerosols may influence climate through interactions that scatter and/or absorb radiation, diffusing light and through interactions with cloud microphysics and other cloud properties, or upon deposition on snow or ice covered surfaces thereby altering their albedo and contributing to climate feedback (IPCC, 2018).

Table 1 - A key points summary of SAI

Proposed Technique		Technique's Readiness	Governance Challenges
	Reflective aerosols would be deployed in the stratosphere. Modelling suggests planetary cooling within a year is possible. Cost per year of per unit of radiative forcing ($W m^{-2}$) are estimated to be between \$17.5 and \$100 billion (Smith and Wagner, 2018, Robock, 2020)[1].	Theoretical understandings of the technique are informed by studies of volcanic eruptions climate effects. Mechanisms for delivery not yet developed. However, assessments suggest SAI would be feasible, effective and less expensive than other SRM techniques with similar potential.	Which governance instruments may apply is moot. Relevant instruments are likely to include state and customary law, the Convention on Biological Diversity (CBD), the UN Framework Convention on Climate Change (UNFCCC) and amended instruments such as air pollution instruments, the Vienna Convention and others. Evidence suggests deployment, or plans to deploy might strain international relations, institutions and cooperation. It may be that potential security issues could arise. Potential for moral hazard or mitigation deterrence. Constraints in climate science mean it may be challenging to attribute some effects of SAI, particularly at the regional scale, directly to a deployment – this may be resolved with research.

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[1] A doubling of CO_2 from pre-industrial levels would create a radiative forcing of 3.7 $W m^{-2}$ (Salter 2008). -1$W m^{-2}$ would be the equivalent of reducing the warming effect of a doubling of CO_2 concentrations by 27%.

SAI would deploy aerosols in the stratosphere at between 7 and 25 kilometres (km) above sea level (Labitzke and Van Loon, 2012). The stratosphere is a relatively stable zone in the atmosphere at between 10 and 50km altitude where there is less vertical than horizontal mixing, meaning an aerosol particle could remain in the stratosphere, reflecting solar radiation for a period measured in years (Keith, 2013). If the injection were to take place in the lower, more easily accessed troposphere particles would quickly be caught in turbulent air and fall back to ground level in a matter of days. It is expected that SAI could be capable of delivering planetary scale cooling within a year (Keith, 2013).

Evidence of the effects of stratospheric aerosols on the climate is available in the natural environment. For example, in 1991, Mount Pinatubo, a volcano in the Philippines, erupted, discharging in the order of 20 million tonnes of sulphur dioxide, (SO_2), into the stratosphere. The resultant sulphate particles from Pinatubo increased global albedo, reflecting enough solar energy back into space to cool the global climate by an average of 0.5˚C (Dutton and Christy, 1992) after which the aerosols rained out and temperatures moved back to those commensurate with existing GHG concentrations. Other anthropogenic aerosols, such as by-products of fossil fuel combustion are also known to effect radiative forcing. They do not, however, remain in situ for long timeframes, nor do they attain the same altitudes as stratospheric volcanic aerosols. As such, they are not helpful as an analogy of SAI.

SAI would not address the cause of warming – the concentrations of GHGs, and it could also raise questions of moral hazard, i.e., it carries risks that it may undermine individual, collective or political incentives for delivering mitigation (Lin, 2012).

The technique and its readiness

Three key factors drive interest in SAI; the rapidity with which it may take effect (Keith, 2013), the high potential cooling efficiency and low direct cost of deployment. It is suggested that 1 kg of sulphur situated in the stratosphere could offset the warming effect of several hundred thousand kilograms of carbon dioxide (Keith, 2013). It has also been suggested that if a specially adapted fleet of 20 Gulfstream aircraft were deployed, they may be able to deliver enough radiative forcing to produce detectable climate cooling (Keith, 2013), although, because the particles will fall out of the stratosphere over time (estimates suggest between one and three years (Keith, 2013)), they would need to be continually replaced to maintain the level of cooling.

It is not yet clear in detail how the climate might respond to the large-scale forcing SAI is expected to be able to deliver. It is critical to note that modelled climate responses will vary according to the nature of any SAI interventions used in modelling studies. Some key variables include the latitudes at which injections take place, the season within which it is undertaken, the altitude of the injections and the choice of material. Importantly, then, it is not possible to talk about detailed climate responses to SAI in generic terms at this stage. Rather, likely responses can only be described in the context of the nature of any theorised use of the technique. This is an important factor to bear in mind when considering the balance of risks and benefits of any future use. No single reported potential outcome or impact should be considered as a likely generic outcome of any future use of SAI. For example, if one set of modelling scenarios and injection strategies indicates that there may be precipitation effects in a region, this does not mean the same precipitation effects will arise in all experimental scenarios or injection strategies.

Climate models suggest that SAI could be very efficient in reducing global warming (Irvine and Keith, 2020). Further, it is suggested that SAI could reduce globally aggregated risks of climate change (Irvine et al., 2019). In addition, SAI would likely be effective at offsetting climate change driven sea-level rise because the cooling it would deliver would reduce sea-ice and permafrost losses that would otherwise occur (NAS, 2015). However, SAI may increase some climate risks for some regions (Irvine et al., 2019). Such risks could conceivably include accelerated changes in dynamic transport of moisture and air, affecting weather systems and important local climate phenomena, such as precipitation (Kravitz et al., 2014, Mercado et al., 2009). For example, Gertler et al., (2020) suggest that some SAI scenarios may over correct climate induced changes in the tracks of extra-tropical cyclones in the Southern Hemisphere. However, there is strong evidence that if SAI were spatially uniform and adjusted to offset approximately half of the radiative forcing from GHGs, the changes in key climate variables would be reduced in the majority of locations and increased in only a very few (Keith and Irvine, 2016).

SAI aerosol delivery mechanisms are unresolved, although aircraft delivery is expected to be the most practicable and economic method (McClellan et al., 2012). A fleet of suitable aircraft would need to fly at approximately 20,000 meters and preferably higher, be capable of lofting a few million tonnes per annum and would have been fitted out with spraying equipment to deliver particles (Keith, 2013). Recently, some publications have theorised aircraft engineering solutions to the altitude and lofting challenges (Bingaman et al., 2020). Nozzles to eject aerosols of the desired size of some of the proposed particles are feasible but have not yet been developed or tested.

Large scale climate cooling effects would require complex aircraft solutions allowing them to fly at sufficient height and with a large payload, but these may be found by adapting existing aircraft technology. It is uncertain what the costs of the required airplane research and design might be. However, Smith and Wagner (2018) suggest that developing a new, purpose-built high-altitude tanker with substantial payload capabilities would neither be technologically difficult nor prohibitively expensive - cost estimates range from $1 to $3.4 billion (Bingaman et al., 2020, Smith and Wagner, 2018).

The theoretical relative ease of implementation, combined with the potential radiative efficiency of aerosols, suggests the direct costs of SAI might be low, relative to cutting emissions (Brahic, 2009). Keith (2013) estimates the annual direct cost of sufficient SAI to counteract the effects of a doubling of carbon dioxide concentrations could be over 100 times cheaper than producing the same temperature change by reducing carbon dioxide emissions alone. A Royal Society review suggested SAI would be in the order of 1,000 times less expensive than other approaches to altering the climate and, even if their direct costs rose by 100-fold, there would still be a large financial advantage over mitigation (Shepherd, 2009). However, MacKerron (2014) has drawn attention to the importance of indirect economic costs such as schemes to compensate ‘losers’, or costs stemming from social or international security frictions that might arise. In addition, as would be the case with climate change mitigation, the hidden costs of policy and governance development, could be even higher than the direct costs (Florin et al., 2020).

Whilst the costs of SAI may be low in comparison to comparable CDR and emissions reductions (Keith, 2013), because deployment scenarios assume SAI would be used in combination with CDR and emissions reductions, in order to compensate for delayed mitigation and to ensure target temperatures are not exceeded (see figure 1), SAI costs would be an additional cost, on top of the costs of the chosen levels of CDR and emissions reductions. This interdependency between SAI, CDR and emissions reductions in itself creates governance challenges, including questions such as how much CDR should be used and how quickly it should ramp up, how quickly emissions should be reduced, and for how long SAI should be deployed for to achieve what targets (Keith, 2013, IPCC, 2014).

Governance may also play an important role in maintaining or amending trajectories of SAI, CDR and emissions reductions over time (IPCC, 2015) in a scenario where SAI has been deployed. For example, if SAI were deployed and found to be effective, safe and less expensive than CDR, this might give rise to considerations regarding whether planned levels of more expensive CDR and emissions reductions should be sustained or reduced in favour of additional, cheaper SAI over a longer timeframe (Lockley, 2019).

The choice of materials to use in the formation of the aerosols is unresolved. Particle size is important because the aerosol needs to be as 'reflective' as possible and it should remain in situ and stable for as long as possible (Rasch et al., 2008). The larger particles are (larger than two tenths of a micron), the less effective at scattering light they become for a given mass deployed (Keith, 2013). Larger particles also fall out of the stratosphere more quickly than small particles.

The introduction of sulphates, one of several candidate particles, would not create a unique change to atmospheric chemistry because sulphates are continuously introduced into the atmosphere naturally. For example, meteoric dust, volcanic ejections (such as the Mount Pinatubo eruption which injected 20 megatonnes into the stratosphere) and emissions from natural marine, terrestrial, chemical and industrial sources all contain sulphates (Keith, 2013). Sulphate interaction within the atmosphere is already occurring and has been researched and, in part, understood (English et al., 2013).

The behaviour and interactions in the atmosphere of other possible SAI aerosols such as titania alumina, diamond and calcites are understood in less detail. How alumina impacts on the stratosphere is partially understood following NASA studies motivated by interests in how rocket plumes, which included quantities of alumina, might affect ozone (Ross and Sheaffer, 2014). In addition, there is a broader base of knowledge about alumina from its use as an industrial material (Weisenstein et al., 2015). Given calcite is the most seriously investigated alternative particle to sulphates, there has been some modelling of its use in SAI. There is a less well-established evidence base for diamond particles, a material suggested by Keith et al., (2016) for SAI purposes, although there is some evidence that diamond nanoparticles are non-toxic to biological systems (Schrand et al., 2007).

Modelling studies of a sulphur injection of 5 megatonnes suggest a 4.5% depletion in ozone might occur (Heckerdorn et al., 2009). Ozone protects all life on Earth from harmful ultra-violet rays and the potential for SAI which uses sulphate to lead to ozone loss has been considered a potentially important risk of deploying SAI (Morton, 2015, Robock, 2018). Changes in aerosols in the stratosphere could influence its chemistry and reduce ozone abundance (Tilmes and Mills, 2014). This effect was measured after the 1991 Mount Pinatubo eruption (Thomason et al., 2008, Dhomse, 2014), an example of how existing knowledge can inform SAI understandings.

While the ozone layer is still recovering from the effects of anthropogenic-depleting chlorofluorocarbons (CFCs), studies suggest any new stresses on the total ozone column, particularly at high and mid-latitudes, before 2050, would lead to a significant increase in ultra-violet light at the Earth's surface (Heckendorn et al., 2009).

Some potential SAI particles may, however, enhance ozone. Aluminium oxide (alumina) is a solid aerosol which would not, of itself, increase the volume of the aqueous sulfuric acid, the surface area of which drives the reactions in sulphates that lead to ozone loss (Keith, 2013). In addition, the injection of calcite may counter ozone loss by neutralising acids resulting from anthropogenic emissions, acids that contribute to the chemical cycles that destroy stratospheric ozone (Keith, 2016). However, there is uncertainty about the potential likelihood and scale of these effects, and they may introduce new risks, possibly including acting as a catalyst causing reactions that may affect ozone (Keith et al., 2016).

Sulphur dioxide (SO_2), one candidate particle, may cause harm as it drops out of the stratosphere into the troposphere forming acid rain or air pollution (Keith, 2013). Although recent modelling research suggests that, even in a very extreme SAI deployment scenario, the amount of sulphate falling out of the stratosphere to ground would approximately balance with the expected reduction in anthropogenically emitted SO_2 from other sources arising from recent interventions to reduce SO_2 (Visioni et al., 2020).

A deployment of SAI may mean that the geographical distribution of material falling to the surface, and the people and ecosystems affected by it, may change from the lower to higher latitudes (i.e., away from industrialised areas and to less populated areas) (Visioni et al., 2020). Such a change may reduce concentrations and the effects of rain out in areas of dense human population, although it may also increase the potential for aluminium mobilisation in soils, with possible consequences for local ecosystems and water reservoirs, in pristine areas (Visioni et al., 2020).

If SAI had ever been deployed, and if that deployment had cooled the planet and was then terminated over a short time period, a significant and rapid temperature 'bounce back' may result, whilst the climate re-stabilised (Kosgui, 2011). This rapid temperature increase, known as a 'termination shock', could increase temperatures rapidly to those that would have been experienced had the SAI not been undertaken, and could be damaging (Robock, 2018). Such a termination shock has the potential for large-scale environmental, economic and social effects (Matthews and Caldeira, 2007). However, Parker and Irvine (2018) have argued that there are no obvious scenarios under which rapid termination might be allowed to occur, suggesting that an understanding of the implications of cessation within a sound governance framework may be sufficient to ensure precautions are taken to ensure resilience in the global governance system.

The circulation of air in the stratosphere would influence the mixing and distribution of any SAI activity so, by selecting where to inject the aerosols, a uniform layer of aerosol could be created, or thicker layers could be created in high latitudes or different hemispheres.

Choices over the spatial patterning of injections remain subject to research and the outcomes are currently uncertain. It has been suggested that a SAI deployment that included a spatially patterned injection that increased forcing in the polar region might be most effective for limited SRM cooling scenarios (Macmartin et al., 2017). Modelling also suggests such profiles have the potential to increase the polar amplification (Collins, 2013). However, secondary effects may arise, including increasing heat travel from regions to the south into the Arctic which could counteract some effects of the SAI deployment (Tilmes et al., 2014). In addition, modelling suggests Arctic deployment of SAI could cause the inter-tropical conversion zone to move southward, negatively effecting climates in that region, including the monsoon (Nalam et al., 2017), unless it was balanced by comparable SAI deployment in the Southern Hemisphere (Nalam et al., 2018).

The use of SAI may have regional effects on plant productivity, although the nature and scale of any impact is currently uncertain given the productivity of plants depends on a range of factors, including temperature, precipitation, light types, levels and the availability of nutrients, some of which may be altered by SAI to varying degrees, depending on the deployment scenario being modelled and the specific ecosystems and location. For an example of one response of plants to an SAI scenario see Duan et al. (2020).

Were SAI to be used, it would be important to be able to detect and attribute any changes that may result (Szerszynski et al., 2013). It would both show whether an injection had any positive or negative effects and validate, or not, the decisions taken. The attribution of cause and effect would also be important for the purposes of understanding not only any successes, but also, any liabilities (Szerszynski et al., 2013). Any small-scale effects would probably be impossible to detect (Robock et al., 2010) and any unusual or harmful anomalies that occurred following a large-scale deployment of SAI would be very difficult to attribute. Such anomalies may become subject to contestation (Hulme, 2014) and would be difficult to resolve, because of the problem of understanding both what effects of a SAI deployment may have been, but also understanding what form the climate would have taken, with what results, had the SAI not been used.

Current research activity

To date, all SAI research has been theoretical - either exploring climate effects, based on climate models (Berdahl et al., 2014, Irvine et al., 2009), potential engineering solutions and, in particular seeking a better understanding of governance issues (Horton et al., 2018, Macnaghten and Owen, 2011, Stavins and Stowe, 2019, Florin et al., 2020) and the social appraisal of the technique (Bellamy et al., 2012, Stilgoe, 2015). Work on these areas is continuing through ad hoc research projects with, in 2018, funded research projects underway in eight countries (although only two of those countries were outside the USA and Europe) (Necheles et al., 2018).

Whilst modelling will remain a key element of the future research effort, it is interesting to note that the first SAI related physical sciences experiment ever to be conducted outside of the laboratory is now in development. Announced on 24 March 2017 (Temple, 2017), the Stratospheric Controlled Perturbation Experiment (SCoPEx) plans to advance 'understandings about how stratospheric aerosols may be relevant to solar engineering' (SCoPEx, 2019). The project aims to deploy an instrument package, under a controlled balloon, to the stratosphere where it will release between 100g and 2kg of calcium carbonate, and potentially sulphate, to create a perturbed air mass of 1km x 100m. The instrument will subsequently measure changes in the perturbed air, including changes in chemistry, aerosol density and how light is scattered (SCoPEx, 2019). The project is led by the Keutsch Group at Harvard University. It draws from a fund raised from philanthropic giving and internal Harvard research funds provided to professors Keith and Keutsch.

The project seeks to 'learn more about the efficiency and risks of solar geoengineering' (ScoPEx, 2019). The findings may improve the capacity for models to better predict how larger scale deployment could affect stratospheric ozone (SCoPEx, 2019). As part of the project's own governance, an independent Advisory Committee of experts has been established, in part to recognise and identify the social and political implications of conducting the proposed research, but also to provide advice to the SCoPEx Principal Investigator and the host institution (SCA, 2020).

Socio-political considerations

Whilst there have only been a limited number of studies, public responses to SAI have expressed concerns and reservations, although it has recently been suggested that people in the global south may be more positive about SAI (Sugiyama et al., 2020). There is, however, some evidence that well governed theoretical research into SAI would be acceptable (Pidgeon et al., 2012). Studies have identified, for example, that publics are likely to be most concerned about the uncertainty of the effects of deployment and the chances of harmful outcomes arising and what those may mean. Studies have also indicated that the public perceives SAI as a very powerful technology with far reaching capacity for effects with which scientists are taking on the role of 'playing god' (Macnaghten and Szerszynski, 2013, Pidgeon et al., 2012, Merk et al., 2015, Braun et al., 2018, Cummings et al., 2017).

There is recognition by some SAI researchers that they are in danger of either lacking or being perceived to be lacking humility, as they work toward developing the means to control the climate, an ambition that Keith (2013) has recognised may appear as hubris. It has also been suggested that researcher awareness of the social acceptability of other controversial research fields, such as nanotechnology and synthetic biology may have informed their thinking and encouraged a cautious approach to developing the technique (Sarewitz, 2010).

To date, few non specialists have participated in debates about the future of SAI. For example, indigenous peoples have figured widely in climate-altering literature as a key affected constituency, e.g., in the Arctic. However, some have noted that they have not yet been visible in debates about the future of SAI (Buck, 2018). More generally, there have been few attempts to explore justice concerns that vulnerable populations might harbour and how those concerns could inform ethics and policy discussions (Carr and Preston, 2017).

SAI has been identified not necessarily to be a straight-forward humanitarian project but, as suggested by Buck (2012) it could be pursued in the service of a wide range of interests. The involvement of philanthropists in funding research and debates about public funding have in themselves raised important questions about how research and development could or should be driven (Nisbet, 2019), and debates about which interests might be aligned with or antagonistic towards SAI are on-going. Some are concerned that SAI related mitigation deterrence may lead climate sceptics to pivot rapidly from a position of climate denial to strong advocacy of SAI (Morton,

2015) and that some groups already thought to be spending large sums on avoiding or postponing mitigation may choose to promote SAI as a way to achieve or protect their business models (McLaren, 2016).

Among publics there is a loosely formed group, called ‘Chemtrailers’ who believe that aircraft contrails are trails of unknown chemicals sprayed into the atmosphere as a large-scale programme of weather and climate modifications, or population control (Cairns, 2014). This group associates these beliefs closely with SAI. While this is a fringe phenomenon in 2017, the Cooperative Congressional Election Study suggested 10% of the United States (US) population were certain that *‘the chemtrail conspiracy was completely true’* and, a further 20 – 30% thought the theory was *‘somewhat true’* (Tingley and Wagner, 2017). This example illustrates that there are wider issues around trust, politics and communication and shows how technologies conceived in the abstract can enter into complex societal processes which may be challenging to incorporate into a rounded governance solution.

Governance

The need for governance of SAI arises from its capacity to intentionally effect the Earth’s climate Systems including the oceans, weather, agriculture, regional hydrologic cycles, stratospheric ozone, high-altitude troposphere clouds and biological productivity (Shepherd, 2009) as well as social systems, structures and deeply held values about questions of justice, faith and rights. The scale and scope of the potential benefits and risks of SAI has chimed with similar planetary scale management issues that have been raised by debate about the governance of the Anthropocene (Baskin, 2014), a proposed new epoch that gives rise to important governance and technocratic challenges about risk management, equality, stewardship, control and responsibility at the planetary scale, in similar ways to SAI. Some key questions (Baskin, 2015, Lynas, 2011) include, for example:

- who governs the planet, how and with what authority;
- should humanity have a new regime of active planetary management;
- how might uncertainty and risk be incorporated into planetary governance; and,
- what is the role of scientists in the governance and risk management processes?

The Anthropocene is, then, taken by some (Rockstrom et al., 2009) to mandate a new role for scientific experts in a technocratic future. That is that they should advise policy makers when humanity or the Earth System is in danger and help inform policy-making to protect against catastrophe (Lynas, 2011). Science could, in this model, be viewed as the authority that both defines and monitors the ‘safe operating space for humanity’ (Rockstrom, 2011), policing infringements on humanity’s behalf. A model in marked contrast to more nuanced understandings of the relationship between science, society and governance, which recognise that narrow, expert, science-based approaches are only part of a plural process (Stirling and Mayer, 2001, Jasanoff, 1994, Renn, 1998).

Importantly, SAI research and the surrounding debate may be the first test case for such governance challenges and recognition of the Anthropocene may unintentionally normalise SAI (and other climate-altering approaches) by creating an imagined future that may justify new investment in its research (Baskin, 2019).

It is unlikely that a SAI engineered climate could ever be constructed such that the resulting climate was perceived as optimal by all states, immediately creating a complex governance challenge. However, were it possible to reach global consensus about a 'new' temperature, through some as yet unidentified process or mechanisms, Ricke et al., (2013) suggest it may, then, be straightforward for states to agree how much SAI should be deployed and how to monitor it.

Given SAI deployment may or may not be perceived to have had differential affects, both positive and negative, it has been suggested that a deployment could potentially give rise to security governance issues. These might even, it has been suggested, include the threat or use of military force to stop a deploying state (Chalecki, 2018). Some have even suggested SAI might be used as some form of weapon (Kolpak, 2020). However, how and to what purpose SAI could realistically be weaponised is unclear (Rayner, 2017). C2G (2019) provides a more detailed exploration of the geopolitical and security issues associated with SAI and other SRM approaches.

The current lack of governance to stop a determined deployer has given rise to concerns about unilateral deployment (Robock, 2020). It has been suggested that small states with limited geopolitical power and/or economic strength might be deterred from deploying by the threat of sanctions or even military intervention, whereas powerful states, or a coalition of states working together, may not be so easily deterred (Robock, 2020).

Others suggest that unilateral deployment is unlikely (Parson and Ernst, 2013), contending that it would require physical and technical capability that are greater than would be possible for many but the largest, most powerful countries. Further, Horton (2011) suggests that the normal interdependencies in geopolitics, mutual reliance and the need for cooperation in a globalised world would dissipate a single country's will to act alone and deploy. However, others consider that large, powerful countries and coalitions of smaller states, including those most effected by climate change, for example, by sea level rise, may have the capacity and motivation to act (Ricke, et al., 2010; Chalecki and Ferrari, 2018).

Parker et al., (2018) suggests it would be possible for a large, powerful single state to deploy alone, which, given the minimal governance available at present, and because of such a state's wider political and economic power, may be unstoppable, at least initially. Such an action may be contested and create novel geopolitical problems. If such a state did deploy SRM and significant harm and loss were to arise or been seen to have arisen because of that deployment, a situation of geopolitical crisis could arise because of the perceptions of causality, whether or not correct. How the global community would resolve this, unless a form of functioning SAI governance had evolved in advance, is unknown. Barrett (2019) has suggested that, were a single state to consider deploying SRM, any treaty prohibiting it would have little effect, because those states likely to consider unilateral deployment would also be unlikely to be signatories to such a treaty.

In the case of a 'coalition of the willing' of smaller states, although not unilateral in the true sense, they would form what Parker et al., (2018) describe as a 'minilateral', which would be more robust to any pressures that could potentially be brought to bear on individual states alone. Such a coalition might be viewed as no more legitimate than a small single state SRM deployment, creating similar international tensions as those that arise in the large single state SRM deployment scenario. Were a minilateral group to form, it has been suggested (Lloyd & Oppenheimer, 2014) that such a group could be attractive to others and grow to become a more legitimate and powerful actor.

The potential for a termination shock, or the issues of moral hazard (or mitigation deterrence) raise important governance issues around decision making, monitoring, reporting and verification (Kosgui, 2011). In addition are questions about how to govern SAI research.

How SAI might be integrated alongside other climate policies is uncertain. It would decouple the links between CO_2 emissions and global-mean temperature, and temperature and climate change risks (Vaughan and Lenton, 2012). This creates some concerns that even discussing SAI could weaken the resolve to cut emissions, creating important governance issues, not least because the Paris Agreement's goals and the IPCC scenarios which frame much future planning, rely on the coupling (Vaughen and Lenton, 2012).

SAI is accompanied by questions about risks, benefits, justice and uncertainties; it is politically and economically complex and it may also deliver some environmental effects, both positive and, possibly, negative with differential effects on communities. In this context it is suggested (Stilgoe, 2015, Macnaghten and Owen, 2011, Buck, 2019) that citizens' perspectives on how SAI develops should be drawn into the processes of governance deliberation at the earliest stage, in a mode of co-production. This challenge gives rise to important questions about how to best engage the public and non-state actors in the process, and how to reflect the polycentricity of governance domains within the required governance dialogues (Reynolds and Horton, 2020). It has been suggested, as part of this engagement effort, that the adoption of processes of responsible innovation, such as anticipation, reflection and engagement by researchers during their work could help reposition SAI into the wider process of climate change social appraisal (Stilgoe et al., 2013), allowing the active practice of responsible innovation to contribute to the development of more authoritative assessments of SAI during the governance process (Low and Buck, 2020).

The inclusion of varied publics has been shown not only to improve the innovation process (Genus and Stirling, 2018) but, in the case of SAI, it has been suggested, it would generate new knowledge about how the technique can affect vulnerability and resilience to climate change on community and regional scales (Buck, 2018). It is suggested, then, as recommended to the US government (Parthasarathy et al., 2010), that opportunities to engage citizens in the evolution of any planning should be considered a key part of the process.

It is unclear how the international community might agree, set and stabilise, over the long-term, how much SAI to undertake, if it were ever decided to deploy the technique (Honegger, 2018). Neither is it clear how this process, and the outcomes of the decisions taken, could balance the individual interests of nation-states with the global need to reduce temperatures (Honegger, 2020).

It is also unclear how the required scale and speed of deployment might be achieved, and it is suggested that incentives, in terms of new financial and policy options which do not yet exist, may be required (Florin, 2020).

Table 2 - Summary of potential strengths, weaknesses and risks of SAI

STRENGTHS	WEAKNESSES	RISKS
High potential for effective planetary cooling.	Although research suggests delivery is technically feasible, the detail of the delivery mechanisms is unresolved.	Debate about and research on SAI may further delay or diminish efforts to reduce greenhouse gas emissions.
The financial costs of deployment compared to other climate-altering techniques are likely to be very low.	Currently there is no clarity about governance.	Which particles to use is not resolved. Some proposed SAI particles may reduce atmospheric ozone, others may enhance it. Some candidate aerosols may cause harm as they drop out of the stratosphere.
Studies of volcanic eruptions and climate models provide some insights into the likely effects of a SAI project.	It is not yet clear how the climate might respond to the large-scale forcing of SAI. For example, there is a potential for changes in precipitation patterns.	A potential for geo-political tensions arising from R&D and planned or actual deployments by a state or group of states.
No restructuring of global infrastructures or energy supply systems would be required.	Research funding for SAI has been limited and fragmented.	Climate termination shock, giving rise to a rapid increase in temperatures, may arise if there were an abrupt termination.
Cooling effects of a deployment may be evenly distributed globally.	Secondary effects are uncertain, for example, on plant growth rates.	Climate risks for some regions could be increased by changes in weather systems.
A deployment could rapidly cool the climate in a controlled way – i.e., it may be possible to cool the global climate within 1-year.	Limited numbers of people and institutions have knowledge about SAI, and it is often framed as socially unacceptable.	Ocean acidification would continue unabated (unless it were addressed by other means).

How SAI might be integrated alongside the Sustainable Development Goals (SDGs) is uncertain. The potentially uneven results of SAI use across regions and with regard to climate parameters such as precipitation, as discussed above may, in conjunction with other potential risks such as the termination effect, conceivably negatively affect delivery of some of the SDGs (Honegger et al., 2018). The literature summarised by Honegger et al. (2018) identifies potential risks including the delivery of Clean Water and Sanitation, Good Health and Well-being and Peace, Justice and Strong Institutions and, Life on Land. An accurate assessment of relative risks to the SDGs is not yet possible and, importantly, they should also be weighed against the potential benefits of a well governed, successful use of SAI which would limit the impact of climate change on some SDGs, including Climate Action, Life on Land, Life Below Water, Peace, Justice and Strong Institutions, Reduced Inequalities, Sustainable Cities and Communities and Good Health and Wellbeing (Honegger, 2018).

Deployment effects of SAI on the SDGs may also have wider socio-political implications, including economic and cultural impacts, opportunity costs and political tensions (Schneider, 2019).

If SAI were ever deployed it would be expected to have global and transboundary impacts, meaning international governance would be essential and, additional transboundary governance may also be required to address non global issues that may arise between countries.

Whilst several current instruments do have traction on SAI, none comprehensively address the full range of governance issues. Section II explores these instruments. Prior to this, a summary of the identified strengths, weaknesses and risks of SAI explored above is provided in table 2.

SECTION II : Governance Instruments

Introduction

There has been considerable generic debate about the governance of SAI over the past decade. This section briefly reviews existing legal instruments and some key non-binding principles or codes of conduct. The purpose of this is to highlight the most important provisions, for example, the Convention on Biological Diversity (CBD) but not to analyse them in depth. Hubert, (2020), Reynolds (2018), Scott (2013 and 2015) and Redgwell (2011) have produced in-depth descriptions of international law and governance relevant to climate-altering techniques, including SAI for those who wish to explore further.

General norms of international law

Customary law obligations require that states ensure that activities undertaken within their jurisdiction do not significantly harm or damage the environment of other states or regions beyond the limits of their national jurisdiction (UNCHE, 1972). This principle requires states to use all means at their disposal to avoid causing significant damage to the environment of another state. Any use of SAI that caused global or transboundary harm would then likely breach international law. However, this might be frustrated if there were any ambiguity regarding the attribution of any harm that may occur following a SAI exercise. For a comprehensive review of the general principles and norms of customary international law as they apply to SAI, see Hubert (2020).

The Convention on Biodiversity (CBD)

The 1992 CBD, with 168 Parties has three main goals:

- to conserve biological diversity;
- the sustainable use of biodiversity; and,
- the fair and equitable sharing of benefits arising from genetic resources.

The CBD is one of the few conventions to have discussed approaches to climate-altering directly. The initial focus was on ocean fertilisation activities (decision IX/16 C) (CBD, 2008), then, in 2010, the CBD invited Parties and other Governments, as well as relevant organisations and processes to consider its guidance (X/33(8)(w)) that '*no climate-related geo-engineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts.....*' (CBD, 2010). It should be noted, however, that the CBD recommendation did not include small-scale scientific research studies undertaken in controlled settings that would help identify the potential impacts on the environment. Subsequently, the Conference of Parties (COPs) XI and XIII reaffirmed this decision.

In 2016, at the 13th Conference of Parties additional guidance was agreed in Decision XIII/4 which states that '*more transdisciplinary research and sharing of knowledge among appropriate institutions is needed in order to better understand the impacts of climate-related climate engineering on biodiversity and* *ecosystem functions and services, socio-economic, cultural and ethical issues and regulatory options'* (CBD, 2012).

Whilst the CBD position appears strong and sends a governance signal it is not binding, and country participation is not universal (it excludes the US) and it only relates to the conservation of biodiversity and the sustainable use of biological resources. The CBD's own Technical Series 66 publication states "*The 2010 CBD decision on geoengineering is not legally binding. However, the decision is important for a global governance framework because of the consensus of the 193 Parties it represents and the political signal it sends*." (CBD, 2012). The CBD evocation of the Precautionary Principle may, however, be an important demonstration of international law's willingness to take such measures in time. However, the limitations of the CBD also highlight that individual extant protocols and conventions, as currently constructed, could only form an incomplete basis for global regulation (Hubert, 2020, Redgwell, 2011), which forms an important element of governance, because they each apply to discrete, specific topics and issues whereas SAI would operate at scale, across treaty boundaries (Hubert, 2020).

Vienna Convention on the Protection of the Ozone Layer and the 1987 Montreal Protocol

The 1985 Vienna Convention on the Protection of the Ozone Layer (UNEP, 1985) and the 1987 Montreal Protocol (UNEP, 1987), which have been ratified by 197 states, aim to protect against depletion of the ozone layer. Given that the injection of aerosols and, in particular, sulphates may deplete stratospheric ozone, they may both be applicable to SAI. However, it is at this stage unclear whether or to what extent the ozone layer might be damaged by SAI (Keith, 2018), hence the scope of their applicability to SAI is currently unclear.

Environmental Modification Convention (ENMOD)

The 1977 ENMOD (UN, 1977), formally the 1976 Convention on the Prohibition of Military and Other Hostile Use of Environmental Modification Techniques, prohibits the intentional use of environmental modification by one party against another for hostile purposes, and completely bans the use of weather warfare, activities which have previously been undertaken by the US during the Vietnam War (Hersh, 1972). ENMOD is not expected to be applicable to SAI given it is generally considered not to be usable as a weapon (Rayner, 2017). The Convention has limited reach - having been signed by 73 countries - leaving many non-signatory countries free to act, including France, a permanent member of the United Nations (UN) Security Council.

The Convention on Long-Range Transboundary Air Pollution (CLRTAP)

CLRTAP (1979) entered into force in 1983. It is implemented by the European Monitoring and Evaluation Programme, under the direction of the UN Economic Commission for Europe (UNECE). The Convention covers 22 pollutants, the majority of which are pesticides and insecticides. Currently there are only 51 signatories and as such the convention suffers from the same coverage problem as ENMOD. In addition, neither sulphates nor other possible SAI aerosols are currently listed as prohibited pollutants. Further, the Convention defines transboundary air pollution as '*air pollution whose physical origin is situated wholly or in part within the area under the national jurisdiction of one* *state and which has adverse effects in the area under the jurisdiction of another state at such a distance that it is not generally possible to distinguish the contribution of individual emission sources or groups of sources*.' (CLRTAB, 1979). Given that if SAI were deployed, it may or may not be possible to identify the sources of the particles (although it should be recognised that this could be a complex task even if possible) so the Convention may, as drafted, be difficult to apply. Given the Convention is aimed at protecting against pollutants, this creates a paradox in that SAI may not be polluting, and may or may not be considered to be a pollutant in the context of its ameliorating the effects of anthropogenic GHGs, in themselves considered as pollutants, although not listed in the Convention.

London Convention 1972 and the 1996 London Protocol

Known as the London Convention, the Convention on the Prevention of Marine Pollution by Dumping of Wastes or Other Matter was adopted in 1972 and came into force in 1975 (LC, 1972). The London Protocol 1996 came into force in 2006 (LP, 1996). The two instruments operate in parallel and when the Protocol was adopted, parties agreed no further amendments would be made to the Convention. The Protocol directly addresses SRM (as well as CDR techniques) and it is evolving in the context of debates about marine relevant approaches to altering the climate. The key measure is Article 3.1 which requires parties to "…*apply a precautionary approach to environmental protection from dumping of wastes or other matter*…" and this article is amended by Annex 4 to include the placement of matter for marine 'geoengineering' (a term used to describe the effects of deploying climate-altering techniques) activities. The Parties' decision to amend the Protocol in response to a potential climate-altering technique demonstrates that, were SAI to lead to potentially damaging substances entering the oceans, the Parties may be willing to exercise power to regulate SAI research or deployment.

UN Framework Convention on Climate Change (UNFCCC)

Adopted in 1992 the UNFCCC provides an overarching framework to intergovernmental efforts to tackle climate change (UNFCCC, 1992) and it may play a role in the global governance of climate-altering techniques such as SAI (Reynolds, 2019). However, what that role might be is unclear at this time. Three key elements of the Convention in this context are:

- Preamble, Para. 21 - "*Affirming that responses to climate change should be coordinated with social and economic development in an integrated manner with a view to avoiding adverse impacts on the latter, taking into full account the legitimate priority needs of developing countries for the achievement of sustained economic growth and the eradication of poverty*".
- Article 2 - "*The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner*."
- Article 4(1)(d) - "*Promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests and oceans as well as other*

terrestrial, coastal and marine ecosystems".

Articles 2 and 4 above are referenced in the context of the moral hazard concern that SAI, if deployed, may offset efforts to reduce GHG emissions.

The Paris Agreement 2015

Adopted in December 2015 the Paris Agreement is an agreement within the UNFCCC. The key purpose of the Agreement is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C. In an analysis of the Agreement, Craik and Burns (2016) have suggested that whilst SAI would not come under the auspices of the Agreement, it could potentially provide the procedural instruments and mechanisms to help satisfy demands for transparency, provide a forum for public debate about SAI deployment, potentially define market mechanisms to fund any future deployment and create a structure for monitoring and verification.

Research governance

Currently, no researchers are arguing in favour of deploying SAI and their work is focused on gaining a better understanding of the potential of SAI and its effects, predominantly through modelling and laboratory-based research. Some are also considering undertaking a very small-scale experiment to advance understanding of stratosphere aerosols that could be relevant to SAI. Such research is currently being governed through normal research protocols of institutions and professional bodies. However, SAI research is controversial (Stilgoe, 2015), and it gives rise to many questions. This is, in part, encouraging some to promote the idea of a voluntary code of conduct for SAI research.

The Solar Radiation Management Governance Initiative (SRMGI, 2019), an international Non Governmental Organisation driven project working to expand the global conversation about the governance of SRM research, has noted the following key questions for the governance of SAI research (SRMGI, 2019):

- Who decides if research proceeds, and what should be researched?
- Who pays for the research? Who benefits?
- What ensures that research is conducted in a transparent manner, and that all results are shared openly?
- How can the different research priorities of different groups be heard?
- What can be done to make sure that SRM research does not distract public and politicians from the task of cutting emissions of GHGs?

Whilst uncertainty is unlikely to ever be entirely resolved (Stirling, 2008, see Blue and Davidson (2021) for an overview of uncertainty in technology and innovation), further research may help reduce some uncertainty, easing some of the governance challenges described (Stilgoe, 2015). Addressing this research need is a governance challenge in its own right, for example, it is unclear how knowledge gaps will be identified, research agenda set and funding will be secured and provided to appropriate researchers.

In time, SAI research may deliver a small perturbation of the climate, resulting, in effect in an application of SAI with uncertain, difficult to predict effects and risks (Robock, 2009). Where the research/application governance boundary lies, is unresolved and it has been questioned whether there should be any delineation between the two or not, or whether the evolution of the technique from modelling and laboratory research, through to large-scale deployment should be treated as a continuum for governance purposes (SRMGI, 2011 and Parker, 2014). Parson and Keith (2013) have suggested that a measurement of the cooling effect in watts per square meter of field work would be appropriate. Other measures, such as some form of metric of social response, have also been proposed (Sugiyama, 2017). If a delineation point is required, it is uncertain what that might be and who might decide on it and monitor and verify.

In the light of the complex issues associated with SAI research, several non-binding codes of conduct have been developed by those active in SAI and other approaches to altering the climate, such as the Oxford Principles (Rayner et al., 2009), the Asilomar Principles for Research into Climate Engineering Techniques (Asilomar, 2010) and the Code of Conduct for Responsible Geoengineering Research (Hubert, 2017). These principles or codes all recognise that transparency in decision making, public participation, and open publication of research results are key to ensuring maximum public engagement with, and confidence in, the governance of SAI research (and climate-altering approaches more broadly). However, given they are voluntary and have no forfeiture available researchers may not choose to follow the recommendations.

Assessments

Internationally sanctioned or recognised technical assessments of SAI may prove a useful tool through which to reduce uncertainties about the technique (Florin, 2020). However, who might undertake such assessments remains uncertain and, it may be true that the debate around these technologies remains too immature to even secure an agreement to generate knowledge about the technique.

The IPCC is dedicated to providing objective, peer reviewed scientific information to inform the scientific basis of anthropogenic climate change and its risks (IPCC, 2013). Whilst IPCC is not therefore likely to be a direct participant in governance dialogues, it may play an important role, through its assessments of the latest science, in framing and informing debates about the technique. To date IPCC reports have paid only limited attention to SAI and SRM more generally, having addressed the issue briefly in the 5th Assessment Report, including the Summary for Policy Makers (IPCC, 2014). However, the IPCC has been tasked to capture global knowledge on SRM techniques in their 6th Assessment Report, and this may play an important role in the future. The UN Environment Assembly (UNEA), the UN Environment Programme's (UNEP) governing body may also play a role in the evolution of SAI assessments. For example, it has already discussed 'geoengineering' when, in March 2019, Switzerland tabled a resolution, co-sponsored by Burkina Faso, Federated States of Micronesia, Georgia, Liechtenstein, Mali, Mexico, Niger, and Senegal, titled '*Geoengineering and its Governance*' (UNEA, 2019). The objective of the resolution was to request that the Executive Director of UNEP produce an assessment of geoengineering technologies, which would have included SAI, to kickstart an international learning process. However, following some iteration, the resolution was withdrawn

(Hubert, 2020).

The *'geoengineering resolution'* tabled at the UNEA may not have been successful, however, it does provide an example of how international institutions might spark initial multilateral conversations about SAI and how it might be governed (for a discussion of associated issues, see Corry and McLaren (2021). It may also have sent a message that some countries on the frontlines of climate change do want an international discussion and a learning and awareness-raising process about climate-altering technologies, including SAI, its risks, potential benefits, and governance needs. Such processes could, potentially, be important steps of governance that include both regulatory issues, but also processes of inclusive participation and decision making.

Other fora or processes

In addition to those discussed above, other UN bodies that may be involved, in due course, in the governance of SAI include: the UN General Assembly, the UN Security Council, the UN Development Programme (UNDP), the International Law Commission (ILC), the High-level Political Forum on Sustainable Development (HLPF), the UN Educational, Scientific and Cultural Organisation (UNESCO) and The World Meteorological Organization (WMO). For a review of how these bodies may engage in the future see Hubert (2020). Other intergovernmental organisations (IGOs) that address economic, social, peace and security areas may also play a role in the evolving governance of SAI. As many IGOs have the ability to make rules and exercise power within their member countries they have become essential actors in the international community and may provide a mechanism through which SAI governance can play out.

Other actors who may participate in SAI governance processes in due course include nation states, regional bodies such as the African Union and the European Union, research groups, civic society organisations, independent non-governmental organisations and commercial interests and publics.

Conclusions

SAI has been described and its technical readiness, current research, applicable governance frameworks, and other socio-political considerations explored. Modelling suggests that SAI could be very efficient at reducing global temperatures and globally aggregated risks of climate change at low cost. No other proposed climate-altering techniques have these characteristics. However, SAI also has risks and there are important uncertainties that require further investigation. Currently, there are no measures, other than soft power, that would stop either researchers or states from taking forward field trials or climate scale deployments. Given the identified risks it is suggested that early discussions about how these technologies might be governed is required.

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Summarised information about the techniques and their governance is available in the
C2G Policy Brief: Stratospheric Aerosol Injection and its Governance

This briefing is based on the latest literature and has been subject to independent expert review.
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