Scientific Advice Mechanism
to the European Commission

December 2024

SAPEA evidence review report

Solar radiation modification

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Foreword

In August 2023, the College of Commissioners asked the Group of Chief Scientific Advisors to produce a Scientific Opinion on the complex issue of solar radiation modification (SRM). The aim is for the Advisors' policy recommendations to contribute to defining the EU's position in international discussions on SRM, as well as informing any future planning for research programmes and decisions on EU financial instruments.

SAPEA was asked to undertake a comprehensive evidence review, which informs the Scientific Opinion of the Advisors. To draft this evidence review report, SAPEA has assembled an outstanding working group of European experts from a variety of academic disciplines, backgrounds and countries. The evidence review has been coordinated by Academia Europaea, acting as the Lead Academy on behalf of SAPEA.

We would like to thank everyone involved and express our sincere gratitude to those who have contributed directly to the report, above all, the members of the working group. We particularly acknowledge the commitment and hard work of the two co-chairs, Johannes Quaas and Benjamin Sovacool, whose leadership has been pivotal.

Professor Marja Makarow, President of Academia Europaea

Professor Paolo Papale, Class Chair Exact Sciences, Academia Europaea

Professor Stefan Constantinescu, President of the SAPEA Board

Preface

Solar radiation modification is an exceedingly controversial topic in political debates, society at large, and, perhaps consequently, the scientific literature reviewed and synthesised in this Report. Given the working group's role in informing the Scientific Opinion and policy recommendations of the Group of Chief Scientific Advisors, it has been very aware of the potential significance and impact of this report. The working group has met ten times over eight months, with many rounds of review and revision of drafts, often over weekends or late at night, in what has been a very open and inclusive, but also intensive, approach to writing the report.

Extensive debate, with cogent argument and counterargument, reflected both the diversity of perspectives and membership of the group. But is also necessarily selective in that those who work on SRM are a self-selected group of experts who tend to be concerned about climate change and find SRM worthwhile and legitimate to engage with, whether as an object of hope or worry, or both. All within the working group have agreed that the full richness and multiplicity of views in the published literature, as well as diverse interpretations of such literature, should be presented in this report. We as chairs also recognise that the literature itself remains partial, and is not exempt from the inevitable institutional and historical contingencies and hierarchies that suffuse all scientific and scholarly work, where SRM is certainly no exception.

Fundamental issues of contention where diverse and often opposite views exist in the literature and among group members include:

- the nature and (un-)knowability of risks versus benefits of researching, developing and potentially using SRM
- the limitations of modelling in capturing real world conditions under which SRM might be developed and deployed
- fundamental limitations on being able to generate policy-relevant evidence about planetary-scale impacts of SRM, without -- or even with -- risky planetary scale experimentation
- the multidimensional justice concerns raised by SRM
- the extent, given world politics, to which SRM if deployed could ever be governed in an effective, constant and fair manner globally over protracted timescales
- the potential for research into SRM to deter or delay mitigation in this critical decade

The latter point was particularly controversial, as some members of the working group perform the very research others consider should be prohibited.

We note that the bulk of published peer-reviewed literature tends to be generated by those engaging in SRM research, predominantly modelling. However, we have drawn on a wide range of literature from across all relevant disciplines. We also include learning from historical precedent or real-world policy and societal developments, both of which can help to shed light on contested perspectives on risks versus benefits associated with SRM. As required in an evidence review report, all sources of evidence are cited and in the public domain.

We hope and believe that this evidence review report conveys the arguments and ideas within the published literature and evidence base that are relevant for the Group of Chief Scientific Advisors and any other reader to come to useful conclusions about the technical aspects of SRM, research on SRM, and governance of SRM, as requested in the scoping paper.

We would like to thank all working group members and SAPEA's professional support team, in particular Louise Edwards, for their dedication and hard work in completing this report within a concise timeframe, together with the experts who reviewed the report.

Professor Johannes Quaas, co-chair

Professor Benjamin Sovacool, co-chair

Members of the working group

- Johannes Quaas, Leipzig University, Germany (co-chair)
- Benjamin Sovacool, Boston University, United States; University of Sussex, United Kingdom; Aarhus University, Denmark (co-chair)
- Roberto Cantoni, IQS School of Management, Universitat Ramón Llull, Spain
- Gabriel Chiodo, ETH Zurich, Switzerland
- Olaf Corry, University of Leeds, United Kingdom
- Ilias Fountoulakis, Academy of Athens, Greece
- Oliver Geden, German Institute for International and Security Affairs (SWP), Germany
- Marco Grasso, Università degli Studi di Milano-Bicocca, Italy
- Aarti Gupta, Wageningen University, Netherlands
- Clare Heyward, UiT: The Arctic University of Norway, Norway
- Hannele Korhonen, Finnish Meteorological Institute, Finland
- Ulrike Lohmann, ETH Zurich, Switzerland
- Axel Michaelowa, University of Zurich, Switzerland; Perspectives Climate Research, Germany
- Andreas Oschlies, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
- Florian Rabitz, Kaunas University of Technology, Lithuania; Vilnius University, Lithuania
- Herman Russchenberg, Delft University of Technology, Netherlands
- Trude Storelvmo, University of Oslo, Norway
- Katalin Sulyok, Eötvös Loránd University, Hungary
- Massimo Tavoni, Politecnico di Milano, Italy; Euromediterranean Center on Climate Change (CMCC), Italy
- Simone Tilmes, University Corporation for Atmospheric Research, United States

The above experts were identified with the support of:

- Academia Europaea (Cardiff hub)
- Academy of Athens
- acatech, Germany
- Hungarian Academy of Sciences
- Swiss Academies of Arts and Sciences

Executive summary

Background

According to the IPCC's most recent Sixth Assessment Report (AR6), the current speed and scale of global emissions reductions is insufficient to meet the Paris Agreement goal of keeping the increase in the global average temperature to well below 2°C above pre-industrial levels, and even below 1.5°C. Strategies to limit warming from greenhouse gases are gaining more attention: one of these is solar radiation modification (SRM). SRM is a deliberate and potentially large-scale intervention in the Earth's climatic system, with the aim of temporarily or permanently reducing some of the impacts of elevated greenhouse gas concentrations.

The Group of Chief Scientific Advisors to the European Commission has been asked to provide a Scientific Opinion on research and potential deployment of SRM, with policy recommendations, focusing on the following questions:

> How to address the risks and opportunities associated with research on Solar Radiation Modification and with its potential deployment? What are the options for a governance system for research and potential deployment taking into account different SRM technologies and their scale?1

As mandated, SAPEA assembled an interdisciplinary working group of independent European experts to write this evidence review report -- a detailed review of the current scientific knowledge on SRM -- which the Group of Chief Scientific Advisors used to inform its Scientific Opinion and policy recommendations.

As we underscored in our Preface, there are divergent and sometimes opposite perspectives on some aspects related to SRM present in the scientific literature. In particular, there are starkly diverging stances on how to translate the main body of knowledge about SRM based on climate model experiments to realistic conditions since models rely on assumptions about technical and political conditions.

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[1] See scoping paper: https://research-and-innovation.ec.europa.eu/system/files/2023-08/Scoping_paper_SRM.pdf

This report is divided into two main parts:

- Firstly, it defines SRM and describes the main SRM technology options, and the status of knowledge about them. It examines the potential physical effects, impacts and side-effects of SRM. It then looks at the main technological requirements and prerequisites.
- Secondly, it considers the main actors involved in SRM, public and expert perceptions. It then considers justice and ethical considerations, defines different types of feasibility and required conditions. Lastly, it covers governance, legal issues and policy design.

The report concludes with a set of evidence-based policy options that could be considered by the Group of Chief Scientific Advisors when producing its policy recommendations.

Definitions

'SRM' is an umbrella term for technologies that would reflect sunlight back into space, or a related technology that may allow more infrared radiation to escape into space, thereby creating a net cooling effect on the Earth’s climate. SRM would aim to reduce the energy imbalance from anthropogenic activities that will lead to warming, by reducing absorbed solar radiation.

SRM technology options

SRM technology options include:

- **Stratospheric aerosol injection (SAI).** This is the most widely considered SRM technique. Climate models suggest that extensive global cooling is achievable using SAI. This is similar to observed surface cooling after a large volcanic eruption. However, uncertainties in required amounts of aerosols for achieving planetary scale impacts and deployment strategies are still considerable. Neither technology nor appropriate governance frameworks for aerosol deployment are ready; it is also debated which aerosol types might result in the smallest side-effects and whether appropriate governance frameworks are practically realisable. Abrupt phase-in or phase out of SAI can lead to large and rapid global climate impacts, while unequal injections between hemispheres can lead to uneven distribution of these impacts.
- **Cloud brightening (CB).** Clouds play a crucial role in regulating the Earth's radiative energy balance. Intentional CB aims to mitigate warming by increasing the reflectivity of shallow low-level liquid clouds. Research has largely addressed marine environments, especially subtropical stratocumulus clouds that already reflect a large amount of solar radiation. Even more so than for SAI, significant uncertainties, due to empirical parameterisation of crucial processes and coarse model resolutions, limit the credibility of model-based evidence on the efficacy of CB. There are significant technological challenges to address before CB could be operationally deployed.

- **Cirrus cloud thinning (CCT) and mixed-phase cloud thinning (MCT).** The scientific basis for CCT is much less robust still than for CB; yet more uncertain is the feasibility of MCT.[2] It is unclear whether either CCT or MCT have the potential for global cooling. The main reason to consider them is that they act in the terrestrial, rather than solar, radiation spectrum, and thus in principle could better counteract some aspects of greenhouse gas forcing. However, deployment technology is embryonic.
- **Surface brightening.** This aims to increase the surface albedo. Based on modelling studies, surface whitening is unlikely to be able to counteract global warming at large scales. Deployment techniques are comparatively straightforward at local scales, but not developed for large scales.
- **Space mirrors.** Shielding incoming solar radiation using space mirrors has been explored, based on a range of strategies. Simulations of the radiative effects of space mirrors in climate models support their potentially cooling effect. However, all studies so far conclude that the technology is far from being available, and that such a method would be very expensive.

General rationales for SRM research and deployment

Research into SRM and its governance involves one or multiple future scenarios that carry assumptions about how and why SRM may be pursued and by whom (the 'rationale' for SRM). Most rationales for researching and using SRM appeal to achieving specific climate targets and to reduce climate risks. Other rationales that are explored in the literature include: optimising overall costs of climate action; competition between countries or groups seeking to develop SRM; private incentives or gains; or protecting certain ingrained or privileged ways of life otherwise threatened by decarbonisation.

A risk-risk framework has been suggested to assess the potential benefits vs the side-effects and risks, comparing a future climate with and without SRM. These depend strongly on the SRM and future emission scenario chosen for comparison, rationale and assumed creation of governance institutions to ensure benefits and avoid harms or injustices:

- A global SRM scenario could be to reduce the global mean temperature; SRM could be devised to slow the rate of warming, to counteract warming at varying degrees, to maintain the current global mean temperature or set a different one.
- A variant could be temporally confined deployment, such as over decades, so-called 'peak shaving' in the case of a global overshoot of temperature targets such as those set in the Paris Agreement. This scenario presupposes strong mitigation and carbon dioxide removal efforts in addition to SRM.
- Another scenario is regional deployment, for example, targeting the Arctic or the Great Barrier Reef, or meeting differing climatic preferences in specific regions of the world. Another variant

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[2] CCT and MCT are not SRM in a strict sense as they target terrestrial (long-wave) radiation.

of regional climate engineering could be limited in time (possibly via cloud brightening or cirrus cloud thinning), although the feasibility of this is very uncertain.

Research on SRMs is often divided into 'indoor (modelling and laboratory studies) and 'outdoor'. Currently all of SRM research from the physical science perspective is based on indoor experiments, based on numerical modelling (climate modelling), or in a controlled environment (laboratory). Modelling evidence allows for a detailed evaluation of many of the risks and possible benefits of SRM from a physical science perspective.

Objections to SRM research or deployment

- **Governance challenges.** Daunting governance challenges are envisioned for SRM approaches that would run over long timespans and with planetary scale impacts, such as SAI.
- **Regional impacts.** SRM could exacerbate or overcompensate climate changes, especially at regional scales. These regional impacts strongly depend on how SRM would be applied. On balance, some consider that the risks introduced by SRM could be difficult to manage in practice.
- **Moral hazard.** Given international commitments to mitigation and the wider context of climate politics, considerable attention should be paid to the problem of deterring climate mitigation or 'moral hazard' that can be raised by SRM research. The presentation of SRM as a 'solution' to dangerous climate change may be used by certain actors to advocate for reduced or deferred efforts to implement mitigation of emissions that are already agreed in international targets, or otherwise hamper the needed acceleration of further or faster mitigation activities, for example by displacing emissions cuts in integrated model scenarios or legitimating larger 'residual' emissions.
- **Global acceptance.** It is challenging to identify what level of SRM deployment, if any, would be globally accepted. Climate modelling tools are imperfect and are thus not able to anticipate all the physical and environmental consequences of SRM deployment, nor any of the political and societal prerequisites and implications. Uncertainties are significant in predicting exact cooling potential, as well as regional climate impacts, and social and geopolitical complications could lead to abuse or rule out more beneficial strategies. Model scenarios of deployment of SRM are experiments and do not generally consider the required social and political conditions.
- **Observational evidence.** Observational evidence about aspects of SRM mechanisms comes from imperfect analogues, such as volcanic eruptions and ship-tracks, as well as the consequences of recent sulphur regulations. but are not guides to the politics of intentional global deployment of SRM, especially over long timescales.
- **Outdoor research activities.** Outdoor research activities on SRM have been the source of real-world controversy, including engineering and process tests, even if undertaken at small scale. Most planned outdoor experiments have thus far faced opposition and have been postponed or cancelled by researchers themselves or not authorised by public authorities.

For these reasons, early governance of research has been advocated strongly in the literature. Some of the most often-raised concerns about SRM research, besides the 'moral hazard', are that it would be hard or impossible to govern justly on a global scale, and that research on SRMs may create its own momentum or design lock-in, prejudicing future decisions about deployment. This is commonly known as the 'slippery slope' argument. Decisions on even indoor SRM research may have implications for future decisions on governance and possible deployment. However, research may also increase reluctance to conduct SRM, or close off certain technical avenues as infeasible or unwanted.

In considering visions and narratives underpinning rationales for SRM, the evidence suggests that disagreements about governance choices have been driven not only by different political aims and different preferences for institutional location and timings of research or potential deployment, but also by clashing underlying understandings of risk, what makes for valid and secure knowledge about the present and future, how local priorities and cultures decode and interpret climate science, and what future world development scenarios are considered possible and acceptable. Different ways of seeing SRM in terms of physical representations, and views on politics and authority and moral choices, drive wholly different evaluations of the desirability and feasibility of SRM.

Risks that are associated with a large-scale deployment scenario, including existential risks, are not necessarily fully predictable, even with systematic, global research efforts. Several members of the working group stress that there are likely epistemic limits to the degree to which scientific research, including field trials, can reduce the deep uncertainties associated with potential future global deployment

Weighing SRM risks and possible benefits

SRM has both intended and unintended impacts. Models have shown that SRM techniques, specifically SAI, have the potential to exert effective radiative forcing of a large enough magnitude to counteract greenhouse gas forcings. With this, SRM can prevent further global warming and has the potential to reduce various related impacts, including floods, heatwaves, sea-level rise, hurricanes, and melting of glaciers. However, SRM does not address the direct impacts of elevated greenhouse gas concentrations, such as ocean acidification and vegetation fertilisation. SRM would have regionally and temporally diverse impacts on surface temperature. SRM also acts differently on the hydrological cycle compared to greenhouse gas forcings; at balanced temperatures, precipitation on average is reduced. Multiple other potential effects also have to be considered.

One of the risks of all SRM methods in the case of global deployment is the need for a long-term commitment, which may cover decades to many centuries, requiring sustained applications not to risk a termination effect. Future projections of greenhouse gas concentrations and the required duration of SRM deployment are uncertain and relate to the rationale for deploying SRM in the first place, as well as prevailing political landscapes, levels of emission reductions and carbon dioxide removal.

Presently, there is no methodological basis for the systematic comparison of the risks associated with SRM and risks associated with climate change, both in the absence and in the hypothetical presence of SRM. There is thus currently little way of holistically accounting the relative benefits of SRM deployment and of non-deployment on all aspects of climate change, including human dimensions such as the diversity of social, economic, political and environmental issues. SRM deployment has environmental and social transboundary side-effects, with the potential to spark inter-state conflicts and trigger international litigation. Moreover, climate change and SRM all create considerable conceptual as well as empirical challenges for comparative risk assessment and related methodologies.

SRM has been studied so far mostly in climate models, by which not all effects and impacts of climate change and of SRM can be fully anticipated. Satellite monitoring technologies to detect and quantify SRM via SAI, CB and CCT/MCT mostly exist, but some such instruments are not yet on operational European satellites. The technological readiness level for the implementation of SRM is currently very low, as is readiness in terms of governance architectures that could safely and inclusively manage a global deployment

Actor networks, interest groups, and stakeholder/public perceptions

Public awareness and understanding of SRM remains very low. Much of the public knows nothing at all or very little about it. Public opinion is, at best, nascent at present and is likely to continue to evolve.

Understanding of the public perception of SRM is overly focused on a handful of western countries, namely the United Kingdom, the United States, and Germany. Perspectives of the Global South have been neglected, though this is slowly changing. The few studies that facilitate a comparison of Global North and Global South perspectives suggest that publics in Global South may be more willing to countenance SRM approaches -- yet this evidence has to be contrasted with opposition to SRM expressed by Global South decision-makers, such as the African Group of Environmental Ministers and the Government of Mexico, which have expressed opposition to SRM deployment (see below).

Key themes in public perceptions literature include concerns over moral hazard and 'messing with nature', and of the perceived unnaturalness of SRM. Climate change harms and exposure emerge as a potential reason for supporting SRM. SRM is, however, found to be less preferable than other climate options, such as emissions reductions strategies or carbon dioxide removal. Publics express a need to establish fair regulation of SRM and to distribute benefits and costs in a fair manner. The need to inform and consult citizens prior to development and use is also stressed.

SRM has attracted limited private investment, relative to funding for emissions-reductions technologies or carbon dioxide remova, although a commercial start-up is now undertaking activities in the western USA and another venture capital-funded start-up based in Israel is pursuing a proprietary approach, developing aerosols for SRM to patent, prompting worries about both 'rogue' actors and non-public, ungoverned and commercialised dynamics driving SRM development. There are concerns about motivations for private involvement in SRM. Some non-governmental groups have vocally opposed SRM on grounds of the unacceptability of risks. Some environmental non-governmental groups cautiously support SRM research, with some providing direct grant funding and garnering support e.g. among youth groups and researchers in the Global South, while others are generally against SRM. National scientific bodies in the US and the UK have endorsed SRM research under certain conditions. Several groups of academics have signed open letters, though they differ in either favouring or opposing an international non-use agreement on solar geoengineering, and in terms of calling for the need for an improved scientific basis, or, in turn, for governing or restricting certain kinds of research.

In 2023, Mexico became the first country to announce its intention to ban outdoor experimentation relating to SRM over its territory. African environment ministers have called for a non-use mechanism on SRM.

Considerations of ethics and justice

There is extensive literature on ethical and justice aspects of SRM as a climate policy option, and how these shape both debates about research and deployment as well as its desirability. They include ethics, distributive justice, procedural justice, recognitional justice, and rectificatory justice.

There is some literature claiming an ethical obligation to research SRM, on the grounds that it may significantly reduce climate impacts, especially for the poorest nations though so far many of the most vulnerable nations, including African countries, have recently called for a non-use mechanism on SRM at the United Nations Environment Assembly debate on SRM, where primarily the US and Saudi Arabia opposed governance of research and non-use agreement wording.

A risk-risk framing argues that side-effects and risks should be carefully assessed and compared to impacts of climate change without SRM, acknowledging that the outcomes of such assessments will depend significantly on scenarios chosen and are contested, especially from within the recognitional justice literature.

Any given SRM technology could raise issues of distributive justice to the extent that it affects entitlements to socially important goods, both material and non-material, both across the world and across generations.

There are concerns that consideration of SRM, even at the research stage, may deter or undermine already insufficient efforts in climate mitigation ('moral hazard'). Such a phenomenon is challenging to explore empirically, showing ambiguous results. Evidence where future carbon removal promises to facilitate continued emissions or slows emissions cuts e.g. in company or country offsetting may provide an indication of similar risks with future prospects of SRM.

Any given SRM technology could also raise issues of recognitional and procedural justice in the course of its development or use. A risk is that SRM might be implemented by elites such as large corporations, political authorities or the financial system. One way to minimise this may possibly be to ensure that procedural justice and legitimacy are built into governance of SRM research, especially in the context of unjust power structures and historical injustices such as colonialism or fracturing liberal world order.

Attention to issues of procedural justice and legitimacy also allow ethical concerns to be given appropriate consideration but may clash with optimised designs assumed in model experiments.

A means of remedying injustices is often perceived as an essential part of any governance system for SRMs, but there is little literature on how such a scheme would realistically look, how to comply with existing international and customary laws, or which principles for rectification should or could be realistically chosen.

Feasibility enablers and constraints of SRM

Conditions of feasibility consist of geophysical, ecological, technological, economic, social and institutional conditions for acceptable or desirable change.

- **Economic feasibility.** This includes direct and indirect costs, and benefits-costs. Recent studies indicate that SAI may be more expensive, less easy to implement and to realise than initially envisaged. Accounting for the uncertainty around the feasibility, effectiveness and consequences of SRM, the main outcome of existing assessments indicates the need for more detailed understanding of SRM. At state level, self-interested strategies from countries with varying preferences for cooling may lead to detrimental economic effects nationally or globally. Overall, SRM may affect economic incentives, including for the urgency and depth of mitigation efforts and arguments about climate finance and adaptation, and thus have global repercussions for international climate agreements.

- **Institutional feasibility.** The role of current institutions depends on what requirements these should fulfil and what role SRM is envisaged to play in tackling climate change. There are several scenarios for the development of SRM institutions, each assuming different functions, objects and agents involved at the international level. In all cases, the legitimacy of governance is considered important for equity but also stability of any SRM deployment. SRM development, especially potential global and long-term deployment, may pose challenges to democratic mechanisms of representation, accountability and control, all of which are currently absent or weak at the global level. Public awareness of the threat posed by climate change and of the features and objectives of SRM, as well as public engagement, may influence institutional constraints, to the extent decision-makers respond to public pressure. Another factor relates to interest and pressure groups, in particular carbon intensive industries, and non-governmental organisations (NGOs), especially environmental ones (ENGOs).
- **Political, security and geopolitical risks.** SRM poses extensive risks of these types. One risk would be a technology race, or new technology ending up in the hands of actors who could become hostile to one another, or that SRM research or deployment becomes militarised. Security risks include critical infrastructures that either require military protection or logistics, disinformation campaigns and geopolitical competition or mistrust around capabilities of deployments and or detection. Not much is known about how induced climatic changes can or will be interpreted by different countries and actors, and how 'national security' might be politically linked to climate. A growing literature assesses the possible interactions with other existing or future geopolitical rivalries and tensions. Climate modelling uses assumptions on these to assess SRM.

Governance dimensions, legal issues, policy design

Governance can aim to be supportive or restrictive for SRM. A diversity of proposed models of international decision-making around SRM exists in the literature. The challenges of governing SRM research are different for different 'rationales' and are likely to be distinct for different SRM technologies, given the potential risks and benefits of technology development or eventual deployment. The largest governance challenges are envisioned for techniques requiring large-scale deployment to be effective with planetary scale impacts, such as SAI.

Indoor SRM research enjoys significant legal protection at the international and European levels, as well as at the level of EU member states. Modelling studies on SRM use the same or similar tools, approaches and questions as climate research in a broader sense (e.g. studying climate impacts of volcanic eruptions). Nevertheless, there is debate about potential restrictions or creation of additional oversight mechanisms for indoor SRM research. In the case of outdoor research, different considerations apply due to the potential physical impacts. While outdoor research enjoys, in principle, similar legal protection (for instance in the context of the principle of the freedom of scientific research), studies suggest that the associated impacts and risks should be assessed, managed, and where appropriate avoided, in line with or beyond existing legal and regulatory provisions on environmental protection, at international, European, and national levels.

A central challenge is how to realise an effective SRM research oversight and governance framework aligned with EU climate and environmental policy objectives. A consideration could be the need to demarcate between laboratory research, field research, technology development and deployment. Another consideration might be to include the political and ethics effects of research in guidance and coordination efforts. Identifying the potential knowledge contribution as well as limitations for each research activity would require a critical-constructive interdisciplinary research design at project and programme levels. Additional considerations include whether public oversight should and can be achieved over specific types of private research, nationally and internationally, and how to ensure transparency about who is doing what kind of research, funded by whom.

Potential future deployment scenarios raise their own governance challenges. A question is how to govern potential SRM deployment in a manner consistent with existing or additional international legal commitments, as well as with existing practices in regard to other, comparable types of activities. Anticipation of future decisions on potential SRM use or its deterrence should consider the EU's existing climate policy goals, as well as existing international obligations and the possibility of a need to develop new international institutions, modify existing agreements and significant shifts regarding the risks of climate change and SRM in the future. Governance options for potential SRM deployment need to take into account wider aims of EU environmental diplomacy, particularly its climate policy goals centred around emission reductions and adaptation and its foundational commitments to effective multilateralism and the precautionary principle. Several members of the expert group emphasise that there is no legal precedent to suggest that large-scale SRM deployment could ever be consistent with the precautionary principle.

An international regime for the controlled, regulated global deployment of SRM has to consider management of the 'free-driver' problem, whereby a single actor (state or non-state, commercial or philanthropic), or a small group might initiate deployment without multilateral authorisation and outside of effective international oversight.

Even though there is no specific international treaty governing SRM activities, there are several customary law and treaty law obligations which pose binding requirements for the (usually restrictive) governance of SRM research and deployment. Reflecting the widespread possible impact of SRM, relevant legal limits of SRM research and deployment follow from a number of specialised fields, including the law of the sea, protection of the atmosphere, environmental law, and human rights law. Relevant legal obligations include the no-harm principle under customary international law; the obligation to cooperate on impact assessment; international treaties, such as the Convention on Biological Diversity, UNCLOS, LRTAP, and the Aarhus Convention; human rights safeguards, such as the right to science, and rights of the child; the principle of intergenerational equity and human rights obligations owed to future generations; the precautionary principle; relevant international soft law documents, and relevant rules of EU law. Several members of the expert group note that a wide range of treaty amendments would be necessary in order to prevent an international SRM deployment regime from generating legal inconsistencies and norm collisions. SRM technologies would likely lead to transboundary harm, and hence their use may breach the customary law obligation not to cause significant transboundary environmental harm.

Some note the importance of weighing the potential downsides of a restrictive position insofar that it could lead to growing US hegemony in SRM research, assessment, information and capability, which could exacerbate the risk of unilateral action, while others point to extensive precedence in international law in designing prohibitive regimes to curb such unilateral actions.

Policy options on SRM research

- The EU could unilaterally decide that funding research on SRM, possibly with a focus on indoor research, is a priority, given the ubiquitous uncertainties and lack of understanding of SRM effects.
- The EU could unilaterally abstain from funding SRM research, given various concerns around mitigation deterrence.
- Any SRM research funded by the EU could aim to establish governance standards (e.g. open access to data, pre-registration of outdoor experiments, disclosure of funding, prior informed consent of impacted communities, public engagement and deliberation around research agendas and priorities etc.) and encourage practice approaches that other public and private funders may wish to follow. The EU could require a pass-on mechanism in which outdoor SRM research above a certain scale at an institution that receives EU funding must comply with these governance standards. Funding programmes and mechanisms could span a broad variety of disciplines and could include provisions encouraging collaboration or meaningful engagement with researchers and stakeholders from the Global South and Indigenous Peoples.
- Any EU-based SRM research could commit not to undertake outdoor activities beyond a certain scale or commit to avoiding controversial 'indoor' research practices such as inserting SRM in Integrated Assessment Models that treat SRM as a substitutable for emissions cuts. Such a commitment would require careful weighing of the cost to scientific gains and the risks it might alleviate and would need to be re-evaluated at regular intervals. Outdoor SRM

activities, even at lesser magnitudes, should meet specific requirements regarding scientific merit, political, environmental, and human impact assessments, demonstration of no significant harm, and public engagement and deliberation.
- The EU could consider negotiating an international agreement relating to outdoor SAI research, or convening the space in which such discussions could occur, including refined definitions and specific conditions on what activities would be included or excluded in a regulatory or coordination regime. It could include a permitting process, specifying the process that would permit research of high scientific and policy relevance, with low environmental and political risk. However, a ban on process-oriented field experiments would hamper fundamental understanding of aerosols, cloud processes, and how they interact with climate.
- The EU could endorse or support the establishment of an international public repository or registry for research proposals, ongoing research, research funding, and research findings, potentially to be established under a new or an existing international institution e.g. the World Climate Research Programme or the United Nations Environment Programme, to provide for multilateral coordination, oversight and transparency. However, both options proved controversial at the failed UNEA-6 negotiations on SRM in Nairobi in February 2024.
- The EU could consider regulating or prohibiting patenting and intellectual property protection for any potential technology development relating to SRM, with a view to preventing undue accumulation of intellectual property in private hands or other sources of pursuit of SRM not driven by the public good.
- The EU could periodically call for proposals from European research groups to conduct a scientific and societal review, with the participation of relevant stakeholders from diverse backgrounds. The EU could likewise support such reviews by the appropriate international institutions.

Policy options on SRM deployment

- The EU could facilitate international dialogues on SRM, including in the context of the overlapping mandates of UNFCCC, UNEP, WMO, UNCBD, Montreal Protocol and others. The EU could also promote adopting a standalone treaty on SRM. The EU could commit to refraining from unilateral SRM deployment. With a view to likely transboundary harmful side-effects, the EU could prioritise developing a global SRM governance regime that promotes non-use or prevents causing transboundary harm through SRM.
- The EU could commit to subjecting potential SRM deployment decisions within the sovereign rights of its member states to informed, multilateral and participatory decision-making processes and encourage other governments to do likewise.
- The EU could prohibit any forms of SRM deployment aimed at global temperature modification within the territory of its member states. It could review the needs for this prohibition at 4-5-year intervals. It could link such a commitment to the multilateral decision processes referred to (above) and coordinate with international partners on this.
- There are a wide range of design options for a permanent ban or moratorium on SRM deployment. International norms can shape state or non-state actor behaviour by defining widely-shared standards of conduct. Widespread embrace of a non-use norm could address the challenges of compelling powerful actors to adhere to its restrictions.

- The EU could institute citizen assemblies including representatives from different societal sectors, to initiate debate on SRM (with or without binding value). The geographical scale on which assemblies would be organised could be regional, national, or continental, or there could be assemblies on several scales at the same time.
- The EU could prohibit or seek to carefully develop guardrails for future 'cooling credits', or other similar attempts at monetisation, in the context of climate agreements or international products standards or trading platforms where the EU could carefully scrutinise whether fungibility between cooling agents and greenhouse gas emissions reductions or removals would increase the risk of mitigation deterrence.

Policy options on monitoring, capacity building and tool development

- The EU could put in place information procedures to ensure decision-makers involved in international and domestic decisions are adequately informed on the detection of SRM activities (including large field trials). This could make use of operational satellites handled by the EU or its states or organisations (e.g. ESA, EUMETSAT) and might extend to collaborations with similar agencies in allied and affiliated countries. An option beyond current capabilities would be a polar-orbiting Earth radiation budget instrument, to identify relevant radiative forcings and/or an instrument capable of identifying and monitoring stratospheric aerosol (e.g. a lidar), in addition to existing capability in such regards, if required, to detect smaller volumes of substances deployed in the stratosphere.
- The EU could develop or adapt and operationalise detection-attribution statistical or modelling tools for the different time horizons of deployment scenarios considered. This would allow the identification of effects and impacts of SRM from field campaigns, regional/intermittent or global deployment using known or identified SRM action, and a counterfactual situation without SRM. Besides funding the corresponding research and development within the EU, the EU could also support collaboration on such tools at the international level, including at the World Climate Research Programme.
- The EU could build on its efforts to develop digital twins of climate to develop scenarios for SRM, including involving interdisciplinary groups of experts and expertise such as atmospheric science, geopolitics, national and European security, political science, engineering, policy, and others, avoiding undue dominance of single disciplines. This could include both optimal and non-optimal scenarios, including regional deployments targeting specific climate mitigation aims and potential geopolitical dominance conflicts. It could also aim to identify some unintended side-effects e.g. via teleconnections and transboundary effects. The EU could seek to foster collaboration on scenario development at the international level.
- Choice of policy options requires careful consideration of the governance dimensions and legal issues raised by SRM, laid out in Chapter 7. Multiple design options exist in international law for a permanent or temporary moratorium on SRM deployment, should governments decide to pursue this option, also to address undesired unilateral use of SRM.

Chapter 1: Introduction

The Group of Chief Scientific Advisors to the European Commission has been asked to provide a Scientific Opinion, with policy recommendations, on the following questions:

> How to address the risks and opportunities associated with research on Solar Radiation Modification and with its potential deployment? What are the options for a governance system for research and potential deployment, taking into account different SRM technologies and their scale?3

SAPEA has assembled an interdisciplinary working group of Europe's top independent experts to write this evidence review report -- a detailed overview of the current scientific knowledge on the topic -- which the Group of Chief Scientific Advisors will use to inform their Scientific Opinion and policy recommendations.

Solar radiation modification (SRM)[4] is a deliberate and large-scale intervention in the Earth's climatic system, with the aim of reducing impacts of global warming. It attempts to offset the effects of elevated atmospheric greenhouse gases (GHG) from anthropogenetic emissions, by increasing the reflectivity of the Earth to absorb less incoming solar radiation. SRM is an umbrella term for technologies that would reflect more sunlight back into space, or allow more infrared radiation to escape into space, thereby creating a net cooling effect on the earth's climate. SRM technology options such as stratospheric aerosol injection or cloud modifications (brightening of low clouds or thinning of high clouds) that are discussed in the scientific literature are introduced and discussed in Chapter 2.

According to the IPCC's most recent Sixth Assessment Report (AR6), the current speed and scale of global emissions reductions is insufficient for meeting the Paris Agreement temperature goal of keeping the increase in the global average temperature to well below 2°C above pre-industrial levels, and even below 1.5°C. To reach the Paris Agreement's long-term temperature goal, global climate action needs to be accelerated over the next few decades and there are multiple, feasible and effective options available today to reduce CO2 emissions to net zero by 2050 and adapt to anthropogenic climate change. However, even among the most ambitious scenarios and modelled

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[3] See scoping paper: https://research-and-innovation.ec.europa.eu/system/files/2023-08/Scoping_paper_SRM.pdf

[4] In the literature, the term "solar radiation management" was or is used synonymously. Studies also used and still use the terms "geo-engineering", "climate engineering" or "climate intervention" (these terms sometimes also include carbon dioxide removal techniques).

pathways assessed in IPCC AR6 only a few manage to keep the temperature increase at or below 1.5°C throughout the century. Almost all of the scenarios in the most ambitious category show a temporary overshoot of 1.5°C, before coming back to this level after several decades and before the end of the century. The IPCC AR6 Synthesis Report states that it is now more likely than not that global warming will exceed 1.5°C between 2030 and 2035, even with swift GHG emission reductions (IPCC, 2023; Reisinger & Geden, 2023).

Therefore, alternative strategies to temporarily limit warming from GHGs are gaining more attention: one of these is SRM. Global climate model simulations demonstrate that SRM technology options employing stratospheric aerosols have the potential to rapidly cool global mean temperatures (see Modelling), similar to the observed global cooling after large volcanic eruptions (see Observational evidence). Models also show that the resulting cooling from global SRM would mitigate some adverse effects of climate change, such as extreme heatwaves and rainfall extremes, also reducing the melting of sea ice and sea-level rise (see Method-independent effects). This is the basis for the idea discussed in this report, namely that SRM may be considered as a measure to reduce some climate change impacts. This report further assesses the various potential side-effects and risks both at a scientific and technological level (Chapter 3) and at an ethical and governance level (Chapters 6 and 7).

It is evident from model simulations, observations (e.g. of the reaction to volcanic eruptions) and theoretical considerations that SRM would not result in a climate as expected with reduced or constant GHG concentrations and does not result in a perfect offset of regional changes e.g. temperature and precipitation, but instead would lead to under- or overcompensations depending on parameter, season and region, though a reduction in the magnitude of change across parameters and regions would appear to be theoretically possible given idealised model conditions for delivery and calibration of the intervention (Chapter 3). These regional impacts strongly depend on how SRM would be applied and on the underlying emission scenario being considered as a baseline. Alternative strategies are being developed in modelling studies to minimise their side-effects in model simulations (Chapter 2), but uncertainties remain large. Furthermore, SRM would only mask the increase in surface temperature from GHGs, and would require long-term applications until other mitigation measures are in effect. The impacts and risks therefore depend strongly on the future emission scenario, with fewer risks and side-effects of SRM combined with large mitigation efforts. Potential unintended side-effects of large-scale SRM application would include possible risks of sudden termination that would bring temperatures rapidly back to the global warming levels caused by the underlying GHG scenario being considered.

All research into SRM and its governance implicitly or explicitly involves one or multiple future scenarios with attendant assumptions about how and why it may be pursued and by whom (the 'rationale' for SRM). Most model scenarios are developed assuming the rationale of a global actor aiming to achieve specific climate targets. These include limiting possible harm due to warming at a global level (e.g. Kellogg & Schneider, 1974), provided there is an unwillingness or inability to sufficiently reduce greenhouse gas emissions (Crutzen, 2006). Especially in a scenario in which some imminent rapid, drastic climate change ("tipping points", Lenton et al, 2008; Lenton & Vaughan, 2009) may be occurring, deployment of SRM is envisaged as a "temporary" solution to reduce some amount of warming, thereby reducing risks.

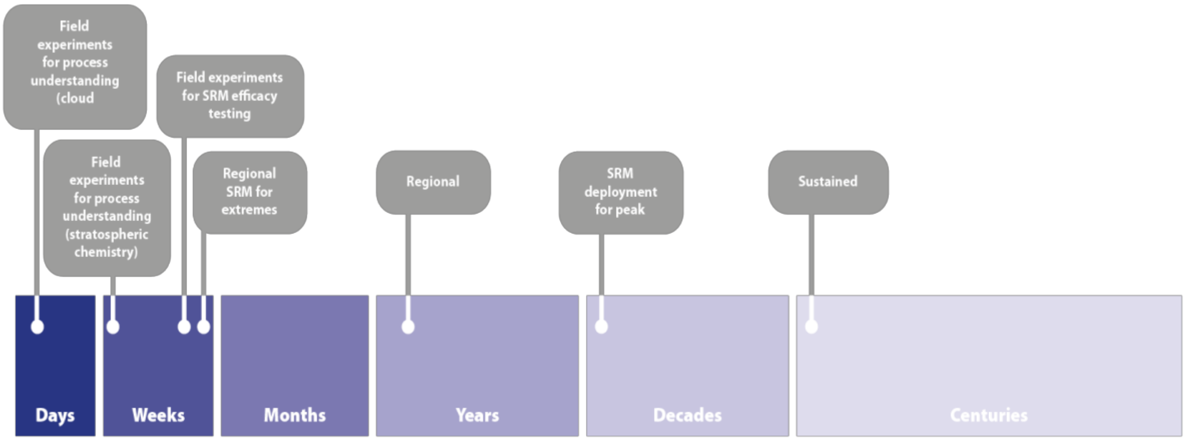

Figure 1. Temporal scales of SRM deployment and SRM outdoor research. The temporal scales go along with spatial scales. Field experiments are typically of order tens to a few hundreds of kilometres in extent (e.g. Seidel et al., 2014). Regional deployment is at sub-continental scales (e.g. Quaas et al., 2016). Peak-shaving or sustained deployments are global in extent. The temporal scale of SRM for peak shaving assumes net-zero greenhouse gas emissions are achieved in this timeframe.

Rationales may broadly be classified into different scales of SRM deployment:

- A global SRM scenario to limit the rise in global mean temperature, given a strong GHG forcing (Budyko, 1977; Crutzen, 2006; Kellogg & Schneider, 1974; Latham, 1990; Teller et al., 1996). SRM could be devised to counteract warming at varying degrees due to increasing greenhouse gases, or to maintain present-day or a different global mean temperature (as in the modelling scenarios described by Kravitz et al., 2015). Such scenarios are developed to understand the scientific processes of SRM in climate models. Large forcings of some of these scenarios help to separate a signal from the noise of climate variability.
- A variant is a temporally confined deployment (e.g. 'peak shaving', Hornigold 2021; Keith & MacMartin, 2015; Tilmes et al., 2016, 2020; Wigley, 2006) in terms of a global 'overshoot' framing, following internationally set temperature targets such as the Paris Agreement (Abatayo et al., 2020; Boucher, Lowe & Jones, 2009; Irvine et al., 2017), in combination with greenhouse gas emission reductions and/or carbon dioxide removal techniques. A regional, rather than global deployment, could target the Arctic (e.g. Bednarz et al., 2023a; Caldeira & Wood, 2008; Robock et al., 2008), the Great Barrier Reef (e.g. Sovacool et al., 2023), or aim to

account for different preferences in different world regions (Irvine et al., 2011; Kravitz et al., 2014, Rickels et al., 2020).

- A variant of regional climate engineering could be limited also in time (possibly via cloud brightening or cirrus cloud thinning), e.g. aiming to mitigate extreme events such as heatwaves. However, the feasibility is very uncertain, as suitable clouds for seeding may not be prevalent (e.g. Dipu et al., 2021).

Other rationales -- motives, interests and actors -- exist along with or besides those driven by a climate risk management rationale (Chapter 5). Some other rationales for developing or deploying SRM explored in the literature include: optimising overall costs of climate action (Belaia et al., 2021); pursuing multiple justice aims at different scales and in varying types of society, e.g. developing versus wealthy countries (Sovacool et al., 2022); seeking influence over and access to geoengineering knowledge (Lloyd & Oppenheimer, 2014); protecting certain 'ways of life' or existing societal models or specific interests or privileges perceived to be threatened by rapid decarbonisation (McLaren & Corry, 2023); financial incentives of private actors selling (or potential future trading of) 'cooling credits'; and ideological arguments in favour or against e.g. among think-tanks (Lloyd & Oppenheimer, 2014).

Research on SRMs can be divided into 'indoor' (e.g. modelling) and 'outdoor' (e.g. field experiments). Any research on SRM has implications for the perception of SRM (McLaren & Corry, 2021), but the prospect of outdoor research activities such as engineering and process tests, as well as field experiments, is especially so (see Research governance). The proposed outdoor research elements of two projects, SPICE (test site UK) and SCoPEx (test site Sweden) were cancelled. Academic researchers often profess a certain reluctance or ambivalence about the prospect of SRM (those discussed in this report) ever being used and maintain that mitigation of GHG emissions is the best strategy to avoid dangerous climate change. One of the oldest (Jamieson, 1996) and most often-raised concerns (Bodansky & Parker, 2021; McLaren, 2016a; Preston, 2013; Tsipras & Grant, 2022) about SRM research is that the prospect of developing SRM technologies will be used politically to justify delaying or reducing short- to medium-term efforts in mitigation scenarios ('moral hazard'). Another concern is that the beginning of research on SRMs might create its own momentum, leading to or pre-emptively shaping its eventual deployment ('slippery slope'). However, research may also result in increased reluctance to rely on SRM. A move to outdoor research activities is sometimes regarded as crossing an important threshold. For these and other reasons, early governance of field research and possible development of SRMs has been strongly advocated.

Even research on SRM is under debate. One of the fundamental reasons centres on the 'moral hazard' and 'slippery slope' arguments (Jamieson, 1996; McLaren, 2016a; Preston, 2013). 'Moral hazard' -- debating a possible way out of climate change consequences that does not require substantial changes in economic behaviour, including changes in energy supply -- might lead to reduced efforts in mitigation that addresses the root of climate change (mainly fossil fuel combustion). 'Slippery slope' -- investing in research and subsequently potentially small-scale deployments -- may lead to an ever-increasing expectation, normalisation and increasing magnitude and propensity for SRM deployment (or lock into certain models of it). In turn, research may also identify more risks and side-effects and diminish deployment options.

The EU's scoping paper on SRM[5] notes that the EU does not consider SRM as a solution, as it does not address the root cause of the problem, which is the increase in greenhouse gases in the atmosphere. It states, "Even if technically feasible and proven safe, it would provide only a temporary relief, not a cure". The EU has the objective to achieve climate neutrality by 2050 (*Climate Law*), reduction of GHG emissions by 55% by 2030 (*Fit for 55* legislative package) and adaptation to the climate change (*Adaptation Strategy*). The Commission and the member states are united in the scepticism about SRM, and the EU supported restrictions on geoengineering (including solar radiation modification) in the framework of the Convention on Biological Diversity. Nevertheless, a wide-ranging EU position on SRM is not developed.

The IPCCs recent assessment reports concluded that "modelling studies suggest that it is conceptually possible to achieve multiple climate policy goals by optimally designed SRM strategies" (AR6 WG1 Chapter 4, p.629) but concluded that SRM is beset with "large uncertainties and knowledge gaps as well as substantial risks and institutional and social constraints to deployment related to governance, ethics, and impacts on sustainable development" (SR15 SPM C.1.4 at SPM-12). The IPCC indicates that while some SRM techniques may be theoretically effective in reducing some climate hazards, the risks or benefits they pose are poorly understood and relevant rules, procedures and institutions (often referred to as 'governance') are weak or missing. The IPCC AR6 report also notes severe uncertainties associated with SRM and does not refer to SRM in its summary for policymakers.

Furthermore, the complexity of the climate system hampers prediction of the consequences of field experiments at scales that allow a detectable effect on the Earth energy budget and on surface climate, potentially violating precautionary principles. These points are sometimes even presented as arguments against research on SRM. However, much of SRM research in climate physics and chemistry that is short of deployment is almost indistinguishable from research on inadvertent climate change. A distinction can be made between modelling studies ('indoor' research) and field experiments ('outdoor' experiments). For the latter, the scale is an issue. Chapter 7 discusses such arguments.

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[5] Available at: https://scientificadvice.eu/advice/solar-radiation-modification/

In terms of broader visions and narratives underpinning rationales for SRM, research suggests that international diplomatic disagreements about governance choices have so far been driven, not only by different preferences for institutional location and timing (Möller, 2020), but by clashing underlying understandings of what makes for valid and secure knowledge about the future, how local priorities and cultures decode and interpret climate science, and what future world development scenarios are considered possible and acceptable (McLaren & Corry 2021a; Schenuit, Gilligan & Viswamohanan, 2021). Different ways of seeing SRM in terms of physical representations, politics and authority and moral choices drive wholly different evaluations of SRM and its desirability and feasibility (Oomen, 2021).

The effectiveness of SRM has not been widely tested with outdoor experiments (see Laboratory and field campaigns for cloud brightening). However, some observational constraints for SRM are available from imperfect analogues, such as volcanic eruptions and ship-tracks (see Observational evidence; Technical implementation and feasibility). Observations of these analogues greatly help to validate models, identify important processes in them and support uncertainty reductions. Much of SRM research from the physical science perspective is thus based on indoor experiments, done in a controlled environment (laboratory) and/or numerical model experiments.

Governance of SRM research does not emerge in a vacuum. It is influenced by many stakeholders that influence what Geels (2002) calls a socio-technical system, drawing on insights from sociology, institutional theory, and innovation studies. Elements of such a system include scientific research and technological inputs, infrastructures, and innovation dynamics (featured in Part 1 of this report) but also markets, regulations, norms, policies, organisations, and networks (featured in Part 2). Therefore, this report frequently uses this notion of a socio-technical system to structure the evidence for approaches to governance of SRM:

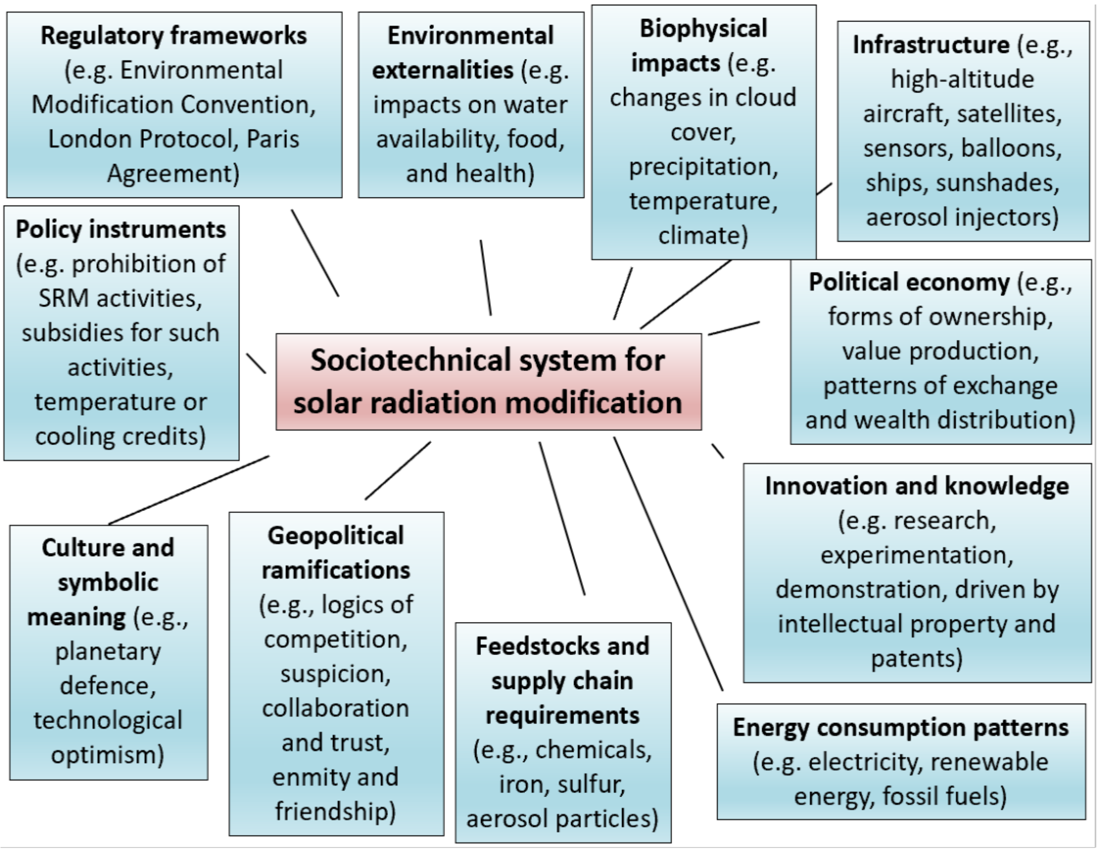


Figure 2. Visualising SRM as a sociotechnical system (Source: Authors). This system is composed of material and physical attributes such as infrastructure and technology but also non-technical aspects such as cultural norms, innovation patterns among the private sector, and policy instruments, to name a few. Each box represents one different sociotechnical domain which has the potential to shape the overall system for SRM, which in turn can shape back each domain. As such, the system is coevolutionary and dynamic.

A sociotechnical system of SRM includes hardware such as aircraft and aerosols but also patterns of innovation and knowledge such as experimental protocols, model parameters and simulations, and public opinion surveys. But it also includes regulatory frameworks and policy instruments seeking to restrict, govern, or enable and provide incentives for implementation of SRM, e.g. through cooling credits or subsidies, and prospective consideration of future environmental, social and justice-related impacts. A sociotechnical system includes flows of finance and investment as well as approaches to protecting intellectual property, aspects of which remain nascent or heavily contested or may be seen as undesirable for SRM. It includes energy resource needs (such as electricity) or material resource needs (such as feedstocks or chemicals). Lastly, it involves cultural and symbolic narratives and media discourses that people and institutions tell each other about SRM.

Part 1: Technological research, development and potential deployment

Chapter 2: Proposed solar radiation modification interventions

The Earth's radiation budget is intricately linked to climate change. At its core, the radiation budget represents the balance between incoming solar radiation and outgoing thermal radiation from Earth. Any anomalies or disruptions in this delicate balance lead to alterations in the Earth's climate.

Greenhouse gas emissions, primarily from human activities, have created anomalies in the energy budget, by intensifying the natural greenhouse effect. As greenhouse gases accumulate in the atmosphere, they trap more heat, resulting in an energy imbalance. Any imbalance in the radiation budget results in changes in ocean heat content and surface temperature, which in turn lead to feedback mechanisms that further amplify the surface warming (Forster et al., 2021; Hansen et al., 2005; Knutti & Hegerl., 2008). For instance, as the planet warms, polar ice melts, reducing surface reflectivity, which, in turn, leads to enhanced absorption of sunlight and exacerbates warming. Additionally, changes in cloud properties and water vapour levels contribute to feedback loops, intensifying the impact of radiation budget anomalies on climate (Forster et al., 2021). Understanding and quantifying these interactions between Earth's radiation budget and feedback mechanisms across different timescales is crucial for creating mitigation strategies and adaptation to climate change (Ramanathan & Feng, 2008). Solar radiation modification (SRM) aims to reduce the energy imbalance from anthropogenic activities that will lead to warming, by reducing incoming solar radiation (Lee et al., 2021a). SRM methods include a variety of techniques and are discussed as follows.

This chapter, as well as Chapter 3, are structured following the five main technology options discussed in the scientific literature. These are illustrated in Figure 3:

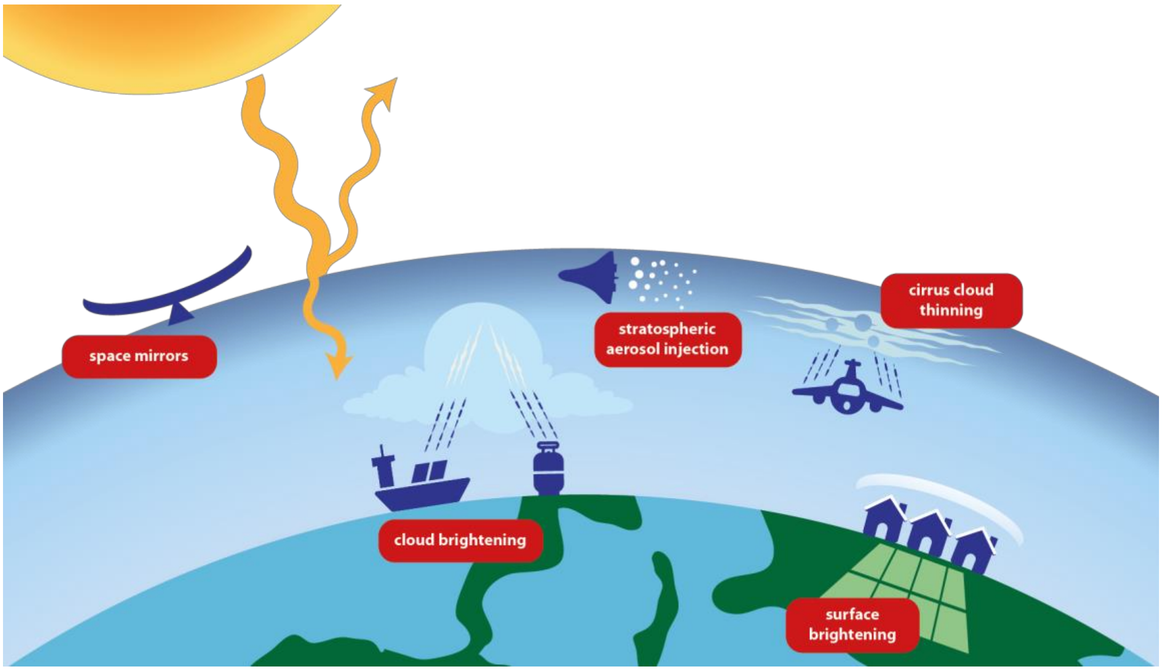


Figure 3. Technology options for SRM

Stratospheric aerosol injection (SAI)

Key messages

- The effectiveness of SAI has been extensively explored using numerous climate modelling studies. A general conclusion is that global cooling is in principle achievable (for impacts and effects, see Chapter 3). Uncertainties in required amounts and deployment strategies are still considerable. Significant uncertainties in climate model results exist due to the lack of sufficient complexity in many current climate models.
- Climate models are the only tools that can assess the full impact of long-term applications of SAI on climate. Regional climate impacts and changes in atmospheric composition, including ozone, can vary considerably depending on the details of the injection strategies and the scenario. Strategically placed injection locations can be adjusted to reduce undesirable impacts on climate.
- Interhemispheric uneven injections, and single point injections of SAI, can lead to large and uneven climate impacts.
- Observations of large volcanic eruptions for SAI can help to evaluate models and their ability to reproduce important processes related to stratospheric aerosol impacts on stratospheric composition and to reduce their uncertainty in terms of their simulated impacts on climate. Likewise, ship tracks can help to evaluate the effects of aerosols on clouds. However, both

volcanic eruptions and ship tracks are imperfect analogues due to their very different time scale, location, and potential material of injections.

- Technology for aerosol deployment is not ready. It is debated which aerosol type would be most suitable. Some alternative materials may be more efficient than sulphur and may have reduced or different side-effects. However, basic research and laboratory studies are still required.
- SAI masks the warming from increasing greenhouse gas concentrations. In the case of sudden termination, any masked warming would re-emerge within a few years.

Overview of method

The most widely considered SRM technique aimed at reducing the amount of absorbed solar radiation by the Earth system is via stratospheric aerosol injections. The basic idea behind SAI involves enhancing the stratospheric aerosol burden and thus its efficiency in reflecting solar radiation back to space. One of the suggestions is that this can be achieved by injecting the precursor gas sulphur dioxide (SO2) into the stratosphere, mimicking the effect of large volcanic eruptions. In the stratosphere, chemical and micro-physical processes quickly (within weeks) convert the injected SO2 gas into submicrometer sulphate aerosol particles (Crutzen, 2006). Carrying out the injection into the tropical stratosphere would maximise the residence time of the resulting aerosol particles (years) while minimising the required mass per degree cooling (Robock et al., 2008). This is due to the presence of large-scale ascending motion in the tropical stratosphere, and consequent export to high latitudes via the Brewer Dobson overturning circulation (Butchart et al., 2014). Most such modelling studies have considered SO2 or H2SO4 as injection material. However, the use of sulphur compounds for SAI has specific side-effects, including heating of the tropical lower stratosphere, which can lead to various changes in the atmospheric composition and climate (see Chapter 3 for a discussion). Recently, alternative strategies to sulphur-based SAI have been proposed to partly alleviate some of these side-effects for example due to reduced absorption of light and therefore the lower tropical stratospheric heating, such as ultra-fine particles from alternative materials, including titania, calcite and alumina (Pope et al., 2012). It has also been shown that some of these alternative materials, if injected at the optimal scattering size, may have smaller impacts on ozone (Weisenstein et al., 2015) or even enhance the ozone column, helping ozone recovery (Keith et al, 2016). However, research on non-sulphur-based SAI is still at its infancy, with very few laboratory and comprehensive modelling studies and thus the efficiency of these materials, their chemical reactivity, along with their side-effects on atmospheric circulation, atmospheric chemistry, and environmental impacts remain poorly understood.

Various different future modelling scenarios have been considered, for both SAI and solar dimming (see Space mirrors) approaches. A recent scenario by the Geoengineering Modeling Intercomparison Project (see Stratospheric aerosol injection) gradually increased SAI to reduce the radiative forcing, and thus the planetary energy imbalance, from high GHG emission scenarios (e.g. RCP8.5 or SSP5-8.5) to medium GHG emission scenarios (RCP4.5 or SSP2-4.5) (Kravitz et al., 2015). This scenario was performed by different Earth System Models, and SRM was applied to counter the planetary warming from unabated increasing GHG emissions. Recently, other scenarios of SAI have been formulated with the aim of limiting peak warming over the 21st century, to maintain global warming below certain thresholds (1.5 or 2°C, as mandated by the Paris Agreement) (MacMartin et al., 2018; Richter et al., 2022; Tilmes et al., 2020). These scenarios consider either an 'overshoot scenario' as a baseline, in which rapid mitigation and decarbonisation would only happen after 2040 or use a moderate SSP24.5 future GHG scenario (MacMartin et al., 2019; Richter et al., 2022). In the case of these overshoot scenarios, only one single Earth System Model per study has been used, which projected that global warming rapidly surpassed 2°C and even reached 3°C by 2060 with respect to 1850-1900 (Tilmes et al., 2016). Interventions using SAI could be devised to maintain global mean surface temperatures within the targets mandated by the Paris Agreement (2015), until GHG levels are sufficiently reduced. In practice, SAI in such scenarios would aim to effectively 'shave off' the peak of at least some climate impacts corresponding to warming exceeding (even if only temporarily) certain thresholds. A temporary intervention, which may need to be maintained for many decades or even centuries, would be intended to help prevent dangerous tipping-points, until GHG levels are sufficiently reduced. Most importantly, it could potentially be gradually phased out without a sudden termination shock for the Earth's climate (Lawrence et al., 2018; MacMartin et al., 2018; Tilmes et al., 2016; 2020). Alternative scenarios could also consider SAI to temporarily slow the rate of warming by gradually phasing them in, and later slowly phasing them out again; this would reduce climate change impacts as societies and ecosystems would have more time to adapt. All scenarios for SRM have one thing in common: they might allow society to 'buy time' with respect to planetary warming, but they would also come with a number of potential risks in both geo-physical and geo-political domains, as discussed later in this section.

Observational evidence

The effectiveness of SAI in achieving rapid cooling of global climate is evident after volcanic eruptions, which serve as a non-optimal "natural analogue" (Robock et al., 2000). For example, the eruption of Mount Pinatubo in 1991 (the last, and thus best-observed, eruption of this magnitude) injected about 20Tg of SO2 into the stratosphere and led to a global-mean surface cooling of about 0.3°C (Kremser et al., 2016; Thompson et al., 2009). In contrast to sporadically occurring volcanic eruptions at a single location, SAI would require continuous or periodic injections, potentially strategically placed at different locations to counter some of the effects of climate change. The effect of SAI on the climate system and its feedbacks would therefore be different from volcanic eruptions and can currently only be assessed using climate models.

Modelling

Effects of global SAI have been explored using Earth System Models and chemistry-climate models with different complexity to help to understand the physical response of the climate system to SAI. Early on, most SAI modelling studies were performed with single models, with different details of the scenario and application, and different impacts (Rasch et al., 2009). As a result, confidence in the results from such initial studies was limited. The Geoengineering Modeling Intercomparison Project has been a major contributor in coordinating experiments that allow multi-model comparison studies of the impacts of SAI on the climate system and advance the understanding of the importance of physical and feedback processes (Kravitz et al., 2013; Visioni et al., 2023b). Recently, the Chemistry-Climate Model Initiative has further prioritised an experiment to explore the effects of SAI, especially on stratospheric chemistry and dynamics (SPARC newsletter; Plummer et al., 2021). In order to explore the full impacts of the increased stratospheric aerosol burden on atmospheric composition (including ozone concentrations) and the feedbacks on climate, comprehensive Earth System Models are required that include fully interactive aerosol microphysics, chemistry, radiation, transport and dynamics in the stratosphere and troposphere, as well as the coupling to the land, ocean, and cryosphere. At the time of writing, only a few state-of-the-art models include most of these required capabilities (Pitari et al., 2014; Tilmes et al., 2022; Visioni et al., 2021). Multi-model comparisons indicate that models differ significantly in their outcomes, including the cooling potential with a specific amount of injection and effects on ozone, indicating that there are processes that have to be explored and model improvements are required to more precisely quantify the effects of SAI (Pitari et al., 2014; Tilmes et al., 2021; WMO2022). One large source of uncertainty between models is how well models simulate the time-evolving aerosol distribution with continuous aerosol injections, due to differences in stratospheric transport and aerosol microphysics.

Other injection strategies that have been recently investigated include the direct injection of H2SO4 vapour into the stratosphere (Pierce et al., 2010) and solid particles (Keith et al., 2016). These alternative materials have indeed shown potential to be effective at cooling climate, while also reducing side-effects compared to SO2. However, currently, global models have limited capability to simulate the chemical and climatic effects of aerosol injections of other solid materials like calcium carbonate, diamond or alumina, materials that may have different side-effects than sulphate, such as reduced stratospheric heating (Dykema et al., 2016), and potentially, also reduced ozone depletion (Keith et al., 2016; Weisenstein et al., 2015). The climatic impacts of these alternative materials may be different from sulphate injections (Pope et al., 2012), more closely resembling solar dimming scenarios. But there is very little laboratory data concerning the chemical reactivity of these materials under stratospheric conditions (Vattioni et al., 2023, 2024b), which presently limits our ability to accurately model the impacts of non-S based SAI on the ozone layer. Also, the microphysical interactions among these solid particles, including the scattering properties of complex structures arising from their agglomeration are still largely uncertain (Vattioni et al., 2024b). A thorough exploration of the potential of these strategies requires a concerted modelling and laboratory effort, to measure the reactivity of these materials under stratospheric conditions and refine the existing parameterisation of optical and chemical properties in global climate models.

In contrast to experiments that required interactive aerosol microphysics, simulations of prescribed stratospheric sulphate aerosols can be performed with much less complex Earth System Models (e.g. Schmidt et al., 2012). Around 15 models participated in the first GeoMIP experiments that required the models to apply global solar dimming to counter the radiative forcing of high (4xCO2) GHG future conditions (described above). While these experiments can help to understand the physical response of the climate system to solar dimming, they are unlikely to be representative of how SAI would be applied and what the outcomes are.

The impacts of SAI on the climate in model scenarios have been shown to strongly depend on how SAI is applied (WMO, 2022). The frequency, altitude, and latitude of the aerosol injections are very significant parameters that can change the effects of SAI (Bednarz et al, 2023a; Krishnamohan et al., 2019; Sun et al., 2023; Tilmes et al., 2017; Visioni et al., 2020; Zhao et al., 2021). The chemical composition of the injected aerosol particles, as well as their physical properties (e.g. their size, and their efficiency to interact with sunlight and terrestrial infrared radiation), also play an important role in their effectiveness in mitigating potential regional climatic changes (Dykema et al., 2016; Ferraro et al., 2015; Simpson et al., 2019; Weisenstein et al., 2015). The effectiveness decreases with increasing injection rate (Heckendorn et al., 2009; Niemeier & Timmreck, 2015; Visioni et al., 2021). This effect may be mitigated by directly injecting H2SO4 vapour, which would make it possible to optimally steer the size distribution of the aerosol particles towards optimal scattering (Benduhn et al., 2016; Pierce et al, 2010). Modelling studies show that H2SO4 may be more efficient than SO2 at cooling climate (per unit mass of injected material) (Vattioni et al., 2019), but the exact degree of efficiency is largely model dependent (Weisenstein et al., 2022). Also, H2SO4 injections do not prevent polar ozone depletion, nor tropical stratospheric heating (Weisenstein et al., 2022).

Injections of SO2 at one point at or close to the equator (similar to past large volcanic eruptions with large climate impacts) result in uneven cooling of surface temperatures with an overcooling in the tropics and less cooling in high latitudes, similar to global solar dimming experiments (Kravitz et al, 2014, and many others). In addition, injections of aerosols or their precursors in only one hemisphere result in shifts in the Intertropical Convergence Zone, and therefore potential droughts in the Sahel (Bednarz et al., 2023a, Haywood et al., 2013; Zhang et al, 2023). Stratospheric aerosol injection in different regions, altitudes and timings in the tropics and the use of different injection materials can result in very different changes in stratospheric ozone (WMO, 2022). In order to reduce some of the unintended effects of SAI, recent work has developed strategic applications of SAI that identified four stratospheric injection point locations using four fixed latitudes: 30N, 30S, 15N and 15S at a location between 1km and 5km above the tropopause (Kravitz et al., 2017; MacMartin et al., 2017; Richter et al., 2017; Tilmes et al., 2017). Injections in these four locations can be more easily modulated to produce an aerosol distribution that results in more equal surface cooling in the tropics and high latitudes. In addition, aerosol injections can be strategically placed to reduce the shift of the Intertropical Convergence Zone and minimise the risk of significant droughts in some regions (Kravitz et al., 2019). These studies coupled complex models to a feedback control algorithm that calculates the aerosol injection amount for the four injection locations in a way that the climate would be steadily nudged into the desired direction (MacMartin et al., 2017). This method was first applied to the Whole Atmosphere Community Climate Model, and two large ensemble simulations were performed with two different versions of this model (MacMartin et al., 2022; Richter et al., 2022; Tilmes et al., 2018; Vattioni et al., 2024). These and other model experiments provide a wealth of information to study the impacts of SAI on the climate and help to identify forced changes from SAI within the climate variability. Other modelling groups that have implemented the same approach, however, show somewhat different outcomes (Henry et al., 2023; Visioni et al., 2023b). Comparisons between different models indicate that reaching climate targets with feedback control has its limitations and requires further development, especially if other targets than near surface temperature may be considered (Lee et al., 2020). Despite advances in the formulation of stratospheric aerosol processes and the tremendous wealth of information gained from GeoMIP, there is still large model uncertainty on the effects of SAI, arising from imperfect representations of interactions between aerosols and radiation, transport and chemistry. Sub-grid scale processes including coagulation, condensation, turbulent mixing and dilution determine the evolution of the aerosol particles from the initial plume to the large-scale. Global climate models typically have a horizontal resolution too coarse (around 100km) to properly simulate these processes (Laakso et al., 2022). Also, uncertainties in the parameterisation of microphysical processes introduce uncertainty in the evolution of the aerosols' plume (Vattioni et al., 2024a). As a result, aerosol forcings associated with SAI including their spatial and temporal distribution are uncertain across models, impacting the accuracy of the simulated impacts.

Technical implementation

The efficacy of SAI depends on the details of the application (see above), the technical feasibility of the proposed application of each methodology, and the corresponding costs to be considered (e.g. Smith & Wagner., 2018). Although various technologies have been proposed for aerosol injection (e.g. balloons, rockets, guns, tethered hoses, jets), using aircraft currently seems to be the most cost-effective solution for SAI at altitudes of around 20km (Lockley et al., 2020; Moriyama et al., 2017; Smith & Wagner, 2018). However, aircraft that can loft the required amounts of material into the tropical stratosphere reaching at least 20km in altitude do not currently exist. For aerosol injection over the tropics, aircraft that will be able to fly at 20km, and loft and distribute up to around 15 tons of particulates have to be designed and constructed, which according to recent studies, is feasible (Bingaman et al., 2020; Smith, 2020; Smith & Wagner, 2018). Although SAI remains inexpensive relative to other interventions and solutions (e.g. using space mirrors or applying marine cloud brightening techniques to achieve similar results would be much more expensive), Smith (2020) estimated the cost to compensate for GHG-driven temperature increase at about $18billionyr^−1^ per degree Celsius of warming avoided (in 2020 USD) while others estimated substantial larger costs ranging from $34billion to $107billionyr^−1^ (Niemeier & Tilmes, 2017, Robock, 2020). In a previous study, Moriyama et al (2017) estimated the annual cost for a cooling of 2 W m-^2^ via SAI at $10billion yr^−1^. Thus, an effective SAI programme would require international efforts, with the contribution of large national economies. Although many previous modelling studies assumed higher altitude injections of around 25km instead of 20km, since injections are more efficient at higher altitudes (English et al., 2012; Niemeier et al., 2011; Smith et al., 2022b; Tilmes et al., 2017; Zhao et al., 2021), costs, complexity and operational risk would be substantially higher for deployment at 25km instead of 20km (Smith et al., 2022b). For such high altitudes, rockets, jet-hybrid rockets or guns (such as light-gas guns) would be more promising, and potentially successful solutions instead of aircraft (Lockley et al., 2020). Smith et al (2022a) proposed that subpolar deployment could also be effective, and thus implemented instead of global SAI, which could be achieved at much lower altitudes in these regions with respect to the tropics and would present fewer aeronautical challenges. Although existing aircraft are again not suitable for large-scale implementation of sub-polar SAI, the overall cost is estimated to be one-third of the cost for global SAI. Solar lofting options have been suggested by Gao et al (2021). These would include black carbon (a highly absorbent aerosol) in addition to sulphur and only require injections into the upper troposphere since the heating for black carbon would result in a self-lofting of particles into the stratosphere. However, this method has not been studied in much detail.

Implementation of SAI would also require accurate and continuous monitoring of the levels of stratospheric aerosols, the atmospheric composition in general, and other environmental parameters. Continuous monitoring of the evolution of the stratospheric aerosol layer would be crucial to determine optimal periods and positions for aerosol injections. Monitoring of other parameters would be necessary to detect, with the highest possible spatial and temporal precision, atmospheric and environmental perturbations that may be related to the SAI. As discussed in Satellite observations and monitoring, satellite missions that are planned for the near future will be able to provide information for stratospheric aerosols with sufficient accuracy. However, monitoring of other atmospheric and environmental parameters may be insufficient since many satellite missions that are used for this purpose will be terminated in the following years.

Cloud brightening (CB)

Key messages

- The scientific foundation supporting cloud brightening is significantly less robust compared to that for SAI, due to substantial uncertainties in the understanding of aerosol-cloud-radiation interactions and mixed assessment of efficacy and impacts from observational analogues and modelling studies. It remains uncertain where and when clouds could be brightened, and, if so, by how much.
- Climate models with parameterised aerosol-cloud-radiation effects suggest that substantial cooling at a global scale is in principle achievable, albeit with strong regional pattern of the forcing.
- Significant technological and methodological challenges remain before CB could be operationally deployed.
- The short lifetime of injected particles could, in principle, allow deployment of CB for limited periods and regions.

Overview of method

Intentional cloud brightening aims to mitigate global or regional warming by increasing the reflectivity of shallow low-level liquid clouds. The rationale behind targeting clouds for SRM lies in their crucial role in regulating Earth's radiative energy balance through two primary mechanisms. Firstly, they scatter and reflect incoming solar radiation, impeding a portion of it from reaching the Earth's surface. Secondly, clouds influence the emission of terrestrial (mostly thermal) radiation to space (i.e. they exert a greenhouse effect). In the case of shallow low-level clouds, the former impact tends to dominate, resulting in a net cooling effect on the climate. In principle the cloud greenhouse effect could be targeted in radiation modification. This is discussed in Cirrus cloud thinning.

CB proposes to further strengthen the cooling effect by introducing hygroscopic aerosol particles into regions characterised by persistent low-level cloud cover (Latham, 1990). A subset of aerosol particles can serve as cloud condensation nuclei (CCN) during the formation of cloud droplets, influencing the droplet size distribution -- a key determinant of a cloud's reflective and, more broadly, radiative properties. With an equivalent total cloud water content, an increased number of droplets (generated from additional nuclei) leads to an elevated surface area and a cloud that reflects more light (Twomey, 1977). Changes in droplet distribution can further impact the cloud's horizontal coverage or the water content in the cloud column, further altering its radiative properties (Albrecht, 1989). The cumulative effect of these changes is typically manifested as an increase in cloud albedo, leading to a greater reflection of solar radiation back into space. It should be noted, however, that large uncertainties remain regarding the intricate interaction between aerosols and cloud properties (IPCC, 2021) and hence the magnitude of the albedo effect from cloud seeding.

Since the albedo effect tends to saturate at high CCN concentrations, CB endeavours would be most effective in pristine areas. Thus far, research has almost exclusively addressed marine environments, where shallow clouds are abundant, where the minimal human influence ensures low background CCN concentrations, and where the background albedo is very low. Hence, this SRM approach is commonly referred to as marine cloud brightening (marine CB), a concept first proposed by Latham (1990). Identified through satellite and model studies, the west coasts of California, tropical South America, and Southern Africa emerge as promising seeding areas for marine CB (Jones et al, 2009; Korhonen et al., 2010; Partanen et al., 2012). The seeding itself could be done with e.g. sea salt produced from sea water (Latham et al., 2008) or chemicals (Fawzy et al., 2020). Sea water is the most studied method and offers an inexhaustible source of hygroscopic sea spray particles. Marine CB envisions the injection of seawater droplets into the atmosphere, resulting in the evaporation of these droplets and the creation of sea spray CCN typically in the range of 0.1µm-0.3µm in diameter (although even smaller particles could be more efficient, as suggested by Rollins et al, 2014). Moreover, these sea spray particles themselves would reflect solar radiation even in areas without cloud cover (Ahlm et al., 2017; Partanen et al., 2012), so the broader term marine sky brightening is also sometimes used (Lawrence et al., 2018). The significance of the cooling effect, whether directly from cloud-free areas (referred to as the direct radiative effect) or through cloud brightening (indirect radiative effect), hinges on various factors inherent to the marine CB deployment strategy and technology. These include considerations such as seeding location and time, the size of the injected sea spray particles, and the injection rate, all of which collectively influence the relative impact of the two cooling mechanisms (e.g. Mahfouz et al., 2023; Partanen et al., 2012).

Tropospheric aerosol, including sea spray, has a lifetime of the order of days, so that the radiative effect of seeding clouds is regionally and temporally confined. SRM restricted in space and/or time is thus conceivable. It has been proposed that marine cloud or sky brightening could be deployed to safeguard specific vulnerable ecosystems or climate components, such as coral reefs (Hernandez-Jaramillo et al., 2023) or Arctic sea ice (Latham et al., 2014), or to prevent climate tipping points (Hirasawa et al, 2023), mitigate hurricane strength (Goddard et al., 2022) or alleviate extreme weather events (Aswathy et al., 2015; Zhang et al., 2023). However, the effectiveness of marine CB for many of these purposes remains uncertain: Duffey et al (2023) highlight the uncertainty for polar regions and Hirasawa et al (2023) conclude that while marine CB might be able to mitigate many tipping element impacts, in specific regions it could even worsen certain impacts.

Although CB would be less effective over land, there are reasons to be interested in this as well, in particular considering terrestrial CB to mitigate climate change regionally, or to mitigate climate- and weather extremes only (Quaas et al., 2016). However, such considerations have to consider possible detrimental effects outside the target regions (Dipu et al., 2021) and imperfect attribution (see also Modelling tools).

Observational evidence

Real-world phenomena such as ship tracks, where particulates from ship exhaust alter cloud reflectivity, indirectly support the CB concept (Ackerman et al., 2000; Diamond et al., 2020). Similar cloud tracks have been observed from degassing volcanoes (Yuan et al., 2011) or industrial complexes (Toll et al., 2019). However, these analogues provide a mixed picture on climate impact, underscoring the complex nature of cloud-aerosol interactions. In specific conditions, ship emissions may even reduce cloud albedo, with the direction and magnitude of the response contingent on mesoscale cloud structure, humidity profile, and cloud top height (Chen et al., 2012).

Partly because of this, dedicated CB experiments have been proposed (e.g. Latham et al., 2012; Wood et al., 2017; see also Laboratory and field campaigns). The Australian Reef Restoration and Adaptation Program Cooling and Shading field experiments since 2021 have injected sea spray into the boundary layer using the effervescent technique (Harrison, 2024). Thus far, only one peer-reviewed study has been published on the results of these experiments, focusing on whether evaporative cooling prevents the vertical dispersion of sea spray aerosol (Hernandez-Jaramillo et al., 2023); hence, no peer-reviewed evidence on the impact of cloud reflectivity from these field experiments is currently available. Some insights can however be gained also from the summer 2011 E-PEACE campaign which examined the impact of controlled emissions of smoke particles and sodium chloride salt particles on marine stratocumulus clouds (Russell et al., 2013). Despite differences from proposed CB aerosols, submicron smoke particles effectively modified cloud albedo when emitted close to the ocean surface. In contrast, larger salt particles released above the cloud base acted as giant cloud condensation nuclei, enhancing precipitation. It should be noted, however, that neither of the E-PEACE experiments are a direct analogue of CB.

Model-based evidence

The significant general uncertainties surrounding aerosol-cloud interactions also limit the credibility of model-based evidence regarding the efficacy of CB. Furthermore, modelling studies of CB suffer from uncertainty in cloud process representation. Many of the relevant aerosol-cloud interactions occur on much smaller spatial scales (down to micrometres) than those resolved by global models (around 100 kilometres) or limited scale cloud-resolving and large eddy models (from tens of metres to a couple of kilometres). As a result, both local and regional impacts of CB are uncertain in all models, with impacts on predicted cloud changes and planetary cooling. For instance, in a study by Stjern et al (2018), nine global models participating in GeoMIP were compared, revealing a wide range of -0.6 to -2.5Wm-2 for simulated effective radiative forcing in response to a prescribed 50% increase in cloud droplet concentration over global oceans. The strongest of these values would almost entirely balance the current anthropogenic climate forcing (+2.7Wm-2; Forster et al, 2021). This variation was partly attributed to significant disparities in cloud location and representation among the models. Most other studies have relied on a single model, further complicating efforts to reach a consensus on CB efficacy and climate impacts as the models differ considerably from each other in their description of aerosol-cloud interactions (ranging from fixed cloud droplet concentration values to explicit seeding emissions), transport, and deposition (e.g. Korhonen et al., 2010; Rasch et al., 2009). Moreover, diverse seeding strategies employed in published studies, such as targeting all oceans, only tropical and subtropical oceans, or specifically the most persistent marine stratocumulus regions, add further complexity to comparisons (e.g. Alterskjær et al., 2013; Jones et al., 2009; Korhonen et al., 2010; Partanen et al., 2012; Rasch et al., 2009).

Cloud resolving and large eddy models often predict lower efficacy compared to global models. Firstly, global models tend to underestimate CCN gradients, missing certain circulation and dynamical feedbacks, as well as the patchiness of cloud albedo fields (Glassmeier et al., 2021; Wang et al., 2011). Secondly, limited area models capture cooling from sea spray evaporation, which they predict to delay dispersion and subject droplets to higher scavenging (Maalick et al., 2014). However, the initial results from the Australian Reef Restoration and Adaptation Program Cooling and Shading field campaign suggest limited evidence that negative buoyancy, induced by evaporation, significantly suppresses vertical mixing (Hernandez-Jaramillo et al., 2023). The authors attribute this to the small sea spray aerosol size in the field experiments, requiring several orders of magnitude lower flow rates to generate the desired aerosol injection rate compared to earlier assumptions in many model studies. At the same time, it should be noted that the field experiments featured an over-representation of unstable and slightly unstable conditions compared to average summer daytime conditions in the study region (Hernandez-Jaramillo et al., 2023), and that under such unstable conditions plumes rise more steeply.

Technical implementation and feasibility

A system deployed for marine CB would need to be able to function at sea for long periods of time and produce CCN at a sufficient rate, over a wide enough area, to deliver the required degree of cooling (Latham et al., 2012). Technically the spraying could be executed, for instance, using specialised autonomous sea water spraying vessels propelled by wind power (Salter et al., 2008). Given the short atmospheric lifetime of tropospheric sea spray, achieving substantial and consistent coverage across major oceanic areas with persistent cloud cover would necessitate a substantial fleet of such vessels; however, precise estimates of the fleet's size and associated costs remain uncertain due to the technology still being in its developmental phase. Ahlm et al (2017) have previously estimated that, to attain a cooling effect of 1°C, an annual injection rate on the order of hundreds of teragrams per year would be required; however, Hernandez-Jaramillo et al (2023) suggest that recent technological advancements could lower the required injection rate by several orders of magnitude compared to previous theoretical estimates (e.g. Maalick et al., 2014; Salter et al., 2008) due to smaller injected particle size. In addition, recent research has proposed the use of unmanned aerial vehicles (UAVs) for the delivery of industrially manufactured NaCl particles to marine clouds (Claudel et al., 2024). The authors argue that since this airborne approach relies on an existing platform and a fairly developed supply chain, it has a higher technology readiness level than vessels spraying from the sea surface. The main technological challenge is developing an energy efficient spraying system capable of generating particles of the optimal size in required quantities (Fawzy et al., 2020). The National Academies of Sciences, Engineering, and Medicine (2021) SRM report highlights notable progress in engineering spray nozzles, tested both in laboratory settings and outdoors in Australia (Hernandez-Jaramillo et al., 2023), with promising particle numbers for scaling up, but the technology would still need a lot of development before it could be applicable in an operational setting. Beyond the technical challenges in deployment, addressing issues such as targeting suitable meteorological conditions (seeding location and timing), optimal particle composition and size, and minimising adverse environmental effects requires resolution (Lawrence et al., 2018).

Scientific uncertainty

Overall, the scientific foundation supporting CB is significantly less robust compared to that for SAI. For example, the National Academies of Sciences, Engineering, and Medicine report (2021) summarises a number of sources of uncertainty regarding CB and concludes that "there is high uncertainty regarding where and when cloud albedo can be modified by addition of particles and, if so, by how much". As mentioned above, significant uncertainties remain even in the basic understanding of aerosol-cloud interactions and cloud dynamics. Despite decades of experimental and model-based study and an abundance of literature in this domain, the most recent IPCC report (2021) finds that the uncertainty range for aerosol-cloud interactions is by far the widest out of all contributors to the current effective radiative forcing estimate. Furthermore, global climate models struggle to accurately capture observed cloud fields and properties, contributing to a significant source of uncertainty in climate studies (Lauer and Hamilton, 2013). This limits their credibility as tools for reliable information on CB's regional and global climate impacts.

It can be expected that the magnitude, and sometimes even the sign, of cloud reflectivity change following CCN injection would depend on intricate cloud adjustments and feedbacks. For example, in certain conditions additional aerosol can lead to *decreased* reflectivity due to cloud evaporation driven by entrainment of dry air, adding complexity to predicting outcomes (Ackerman et al., 2004; Bretherton et al., 2007; Toll et al., 2019). Further process uncertainties in the CCN seeding response stem from e.g. saturation effects of cloud reflectivity change at high CCN concentrations, uncertainties in background CCN sources and sinks, negative buoyancy from evaporating sea spray aerosol, and varying turbulent updrafts. In addition, microphysical and dynamical effects that impact CB efficiency vary between locations and in time (Wang et al., 2011). Marine low clouds also exhibit uneven distribution and intermittent patterns, and taken together, this means that a cooling impact from CB is likely possible to achieve only in specific areas and times. This sporadic influence may result in climate alterations in distant regions (teleconnections) with varied side-effects not fully understood.

Direct, quantitative verification and monitoring of CB efficacy could prove challenging due to the highly varying nature of atmospheric conditions. Differentiating between natural variability in cloud properties and changes induced by increased aerosol concentration is often difficult, especially over short time periods. Verification on a local scale could be attempted via in situ measurements of changes e.g. in cloud droplet number concentrations and size before and after aerosol injections. Over larger areas, satellite observations of changes in e.g. cloud albedo and the effective radius of cloud droplets could provide valuable data both for verification and monitoring (see Satellite observations and monitoring). Statistical analysis of long-term satellite data offers the most feasible approach for continuous global-scale monitoring, although it too is complicated by ongoing climate change which impacts the background atmospheric conditions and cloud properties.

In summary, while CB has theoretical potential to cool the global climate, its scientific basis is less solid than that of sulphate aerosol injection SAI, mainly due to significant uncertainties in our understanding of aerosol-cloud-radiation interactions. Furthermore, observational analogues and models offer mixed assessments of CB's effectiveness and its impact on climate. There are also significant technological challenges to address before CB could be operationally deployed, including issues related to targeting suitable seeding conditions, optimal properties of seeding particles and minimising environmental side-effects. The short lifetime of injected particles could, in principle, allow for temporary deployment in specific regions to target e.g. climate and weather extremes; yet the efficacy of CB and potential for adverse effects outside these areas remain possible caveats.

Cirrus cloud thinning (CCT)

Key messages

- The scientific basis for cirrus cloud thinning (CCT) is more mature than for mixed-phase cloud thinning (MCT), but large uncertainties -- substantially larger than the uncertainties for CB -- still remain regarding the feasibility of both methods.
- CCT and MCT are not SRM in a strict sense as they target terrestrial (long-wave) radiation. They thus act in the same radiation spectrum as greenhouse gas forcing.
- For both CCT and MCT, the deployment technology is not advanced.
- CCT and MCT are reversible on timescales of days to weeks, and may in principle be deployed confined to regions and confined in time.

Overview of method

Cirrus cloud thinning (CCT) was originally put forward by Mitchell and Finnegan (2009), and is based on a global climate model study by Lohmann et al (2008) evaluating the difference in the top-of-the-atmosphere (TOA) radiation balance for cirrus clouds forming either purely by heterogeneous ice nucleation on ice nucleating particles (INPs), such as mineral dust, or purely by the homogeneous freezing of solution droplets, like sulphuric acid. Because there are much fewer INPs in the upper troposphere than solution droplets, the ice crystal number concentration is lower in heterogeneously formed cirrus clouds. A lower ice crystal concentration typically means larger ice crystals, which can sediment faster, hence reducing the ice water content, lifetime and the optical depth of these cirrus clouds. They thus reflect less shortwave radiation back to space. Simultaneously, and importantly for the idea of CCT, the longwave cloud radiative effect (the cloud greenhouse effect) of these clouds is reduced, due to their lower optical depth. In addition, heterogeneous ice nucleation occurs at lower ice supersaturations and higher temperatures than homogeneous ice nucleation, causing them to emit more longwave radiation to space and keep less in the Earth-atmosphere system. As for cirrus the impact on the cloud greenhouse effect is larger than on the cloud brightness, due to the cold temperature and thin optical depth of this type of clouds, the net impact is smaller (less negative) net cloud radiative effect. The study of Lohmann et al (2008) quantified the global mean effect at --2Wm-2, sufficient in principle to counterbalance much of the current anthropogenic radiative forcing.

In locations where cirrus clouds are formed by homogeneous nucleation, injections of INPs could lead to cirrus clouds formed by heterogeneous nucleation instead, with implications as described above, and thereby cause a negative radiative forcing (Storelvmo et al,. 2013; Storelvmo & Herger, 2014). However, if the background cirrus clouds are already formed by heterogeneous nucleation, the cirrus clouds would form on more INPs and become optically thicker instead, thus leading to an "overseeding" and a positive radiative forcing instead (Gasparini & Lohmann, 2016; Gasparini et al., 2017; Penner et al., 2015; Storelvmo et al., 2013; Storelvmo & Herger, 2014; Tully et al., 2022). In such locations, CCT will not work as intended.

Mixed-phase cloud thinning (MCT) is based on weather modification ideas. Mixed-phase clouds that consist of both cloud droplets and ice crystals are thermodynamically unstable because the saturation water vapour pressure over ice is less than that over supercooled liquid water. Hence ice crystals can grow at the expense of cloud droplets if the environmental water vapour pressure drops below water saturation. This so-called Wegener-Bergeron-Findeisen (WBF) process (Bergeron, 1935; Findeisen, 1938; Wegener, 1911) can lead to glaciation of supercooled clouds and, subsequently, precipitation. If INPs are introduced in mixed-phase clouds, they can trigger the WBF process and thereby reduce cloud optical depths and/or lifetimes. In most locations, MPCs have a net cooling effect due to their relatively large negative SCRE, and a reduction of their water content or lifetime would thus lead to a warming. However, in regions and seasons with large solar zenith angles (i.e. in the high latitudes in polar winters of both hemispheres), the decreased cloud greenhouse effect dominates and MCT would have a cooling effect.

Observational evidence

For CCT, there is satellite-based evidence that a considerable fraction of cirrus clouds in the present climate is formed through homogeneous freezing and therefore in principle susceptible to seeding (Mitchell et al, 2018). This result is, however, not consistent with analysis of aircraft observations combined with modelling results (Froyd et al., 2022). However, there are no well-established natural analogues for CCT that convincingly demonstrate its feasibility. For the WBF process, on which MCT relies, potential analogues are so-called hole-punch clouds (Heymsfield et al., 2011) and glaciogenic cloud seeding (Bruintjes et al., 1999; French et al, 2018; Henneberger et al., 2023; Rauber et al., 2019; Tessendorf et al., 2012) on small scales. There is also preliminary evidence that suggests that certain industrial emissions contain INPs which can glaciate MPCs downstream and lead to cloud thinning and even their removal through INP-induced snowfall (Toll et al., 2024).

Modelling capabilities

Both CCT and MCT can be studied with general circulation models (Gasparini & Lohmann, 2016; Gasparini et al., 2017; Penner et al., 2015; Storelvmo et al., 2013; Storelvmo & Herger, 2014; Tully et al, 2022, Villaneuva et al,. 2022) and high-resolution regional models (Gruber et al,. 2019). The latter modelling tools tend to have better representation of clouds due to their higher resolution and sometimes also more sophisticated process representation, but they cannot give insights on the effects of CCT and MCT on global climate. This requires general circulation models, which often suffer from coarse resolution and parameterised cloud process representation. For CCT, large uncertainties remain in the current understanding of cirrus formation (homogeneous vs heterogeneous nucleation) in the present-day climate (Cziczo et al., 2013; Gryspeerdt et al., 2018; Krämer et al., 2016; Mitchell et al., 2016, 2018; Sourdeval et al., 2018) and uncertainty in the microphysics (e.g. Gasparini and Lohmann, 2016; Gasparini et al., 2020; Tully et al., 2022, 2023), which limits confidence in current modelling capabilities. For MCT, significantly less research has been conducted than for CCT, and consequently uncertainties are even larger, for example with respect to the WBF process and its parameterisation in models (e.g. ; Omanovic et al., 2024; Storelvmo et al., 2008).

Technical implementation and feasibility

Modelling evidence suggests that both CCT and MCT would be most effective in the high latitudes and winter season of both hemispheres. One of the reasons is that in such conditions, the impact of thinning on cloud brightness is particularly small compared to the reduction of the cloud greenhouse effect. For CCT, the optimal seeding concentrations have been simulated to be on the order of 10L-1 (Storelvmo et al., 2013) and the suggested seeding agent is Bismuth triiodide (BiI3, Mitchell & Finnegan, 2009). This equates to a relatively modest total amount of seeding material, compared to CB and SAI, due to the limited susceptible areas and seasons and relatively low required mass injection rates. For MCT, silver iodide or dust would be possible seeding agents, but there is insufficient evidence up to now regarding what seeding concentrations would yield the most desirable effect. For both MCT and CCT, seeding would target the troposphere exclusively, corresponding to approximately the lowest 8km of the atmosphere for the latitudes in question.

However, according to the NAS (2021) report, "it would be premature to explore technical feasibility and costs of CCT (which are likely to be less of a challenge than for SAI owing to the lower altitudes and smaller payloads required)". This statement is still valid today. It is rooted in the considerable uncertainty that remains regarding how cirrus and mixed-phase clouds will respond to seeding, and whether appreciable cooling could in fact be achieved. In particular, MCT research is in its infancy and not yet at a state where an evaluation of technical implementation and feasibility would be meaningful.

Scientific uncertainty

The NAS (2021) report states that CCT is the least well understood of the three methods this report explored (SAI, CB, CCT) especially because "models do not necessarily represent relevant cirrus processes correctly, including capturing the prevalence of homogeneous versus heterogeneous freezing". The same holds for MCT because of challenges in representing the partitioning of liquid water vs ice (e.g. Kay et al., 2026), heterogeneous freezing and the WBF process.

Surface brightening

Key messages

- According to modelling studies, surface whitening is unlikely to be able to counteract global warming at large scales.
- Deployment techniques are comparatively straightforward at local scales and not developed for large scales.

Summary

Surface whitening effects are essentially local and have, e.g. in settlements in the Mediterranean, already been applied for many centuries. Surface whitening aims at increasing the surface albedo, very similar to CB over the oceans. Applications, but not necessarily impacts, are directly tied to fixed coordinates at the surface of the planet. Surface whitening could thereby offer higher regional flexibility than most other SRM approaches. Proposals for surface whitening on land include urban albedo enhancement, growing crops that reflect more sunlight, and desert albedo geoengineering (Irvine et al., 2011; Seneviratne et al., 2018). Urban albedo modification, e.g. via albedo increases of roofing or paving, may reduce the urban heat island effect and help improving air quality in cities (Pomerantz et al., 1999; Taha et al., 1999), but has very limited global impacts because of the small suitable area, estimated as much smaller than 1% of the Earth's surface. Albedo modification in agricultural regions could be achieved by growing selected or genetically modified crops with a higher albedo or different growth periods, or possibly by no-till farming that would allow relatively bright crops residue to remain on the soil surface. Desert albedo modification has been proposed as covering large desert areas, sometimes deemed of little societal or ecological value, with a highly reflective material. Surface brightening has also been considered for glaciers during the melting seasons, but here the intention is a local cooling to protect the respective glacier rather than an immediate impact on climate.

Idealised modelling indicates a general regional cooling potential of all surface whitening approaches (Seneviratne et al., 2018). Because of the small areas involved, impacts on evaporation and precipitation are small for urban and crop albedo management. Desert areas are mostly in the subtropics and, though they have little potential for further local reductions in evaporation, are often key elements of atmospheric circulation patterns like monsoon systems. By reducing local surface temperatures, desert albedo modification has, in models, been found to reduce monsoon circulation and associated precipitation over large areas (Irvine et al., 2011; Crook et al., 2015).

Proposals for surface brightening of the ocean and sea ice include the deployment of small reflecting glass spheres (Field et al., 2018) or foams (Evans et al., 2010) or the generation of long-lived microbubbles in the surface layer of the ocean (Seitz, 2011). Such proposals have so far been put forward mostly with respect to Arctic Sea ice protection. Pumping seawater onto the ice to enhance ice growth and seasonal sea ice cover has also been proposed (Zampieri & Goessling, 2019). Via the ice-albedo feedback, the melting of sea ice is regarded as one of the important drivers of the observed polar amplification, and via possible 'tipping points' in relation to the release of methane from Arctic permafrost or sub-seafloor gas hydrates, mitigating polar amplification might be of global climatic relevance (Lenton, 2012). Model studies confirmed the substantial local cooling during deployment but yet little potential for mitigating global warming (Zampieri & Goessling, 2019). They also, however, indicate the possibility of enhanced northward heat transport with subsurface ocean currents (Mengis et al., 2016), in line with other approaches for regional Arctic SRM (Tilmes et al., 2014).

Space mirrors

Key messages

- In climate model simulations, the effect of space mirrors in terms of solar dimming shows a cooling effect.
- All studies so far conclude that the technology is very far from available, and that such a method would be very expensive.
- Shielding incoming solar radiation by space mirrors has been suggested in several conceptual studies over the past decades, proposing a range of strategies and typically with a focus on the engineering part. But overall, the topic of space-based SRM is on the periphery of discussions about SRM.

Summary

Proposals can be characterised along three main dimensions. The first dimension is the location, with mirrors, screens, or other intervening materials placed either in a Lower Earth Orbit (LEO), a Geosynchronous Orbit (GEO), or further away, e.g. at one of the 5 quasi-stable meta-regions known as Lagrange points -- points where the gravitational pull of Earth and sun broadly cancel one another. Of these Lagrange points, nearly all studies focus on L1, the intervening location between Earth and sun that is about 1.5million kilometres away from Earth, or four times the distance to the Moon. Although LEO or GEO would potentially be more convenient (and cheaper) locations, downsides of the following kind have led to a preference for L1 as a potential location: the heightened potential for collisions with key satellite infrastructure, creation of a transient shadow over the Earth's surface, and the inability to maintain a fixed relative position to the Earth to have a uniform cooling effect (Baum et al., 2022; Bewick et al., 2013; Keith et al., 2020; Kennedy et al., 2013; McInnes, 2010). The second dimension addresses active or passive operations. Given that L1 is not a region of true stability, any sunshade placed there would, without external intervention, eventually drift out of ideal position -- potentially in as little as a few years. Accordingly, there are ‘passive’ proposals that would use relatively cheap materials and just replace them if they drift out of position, or else make use of alternate Lagrange points at L4 or L5 which, although not directly between Earth and Sun and thus less than optimal for shading purposes, offer the benefit of passive stability (e.g. Struck, 2007). These contrast with the ‘active’ proposals which entail the use of self-propulsion technology in some form, to maintain the orientation and altitude of the sunshade, or its constituent objects. The third dimension relates to the mass of the proposals, specifically whether a large sunshade would be used versus hundreds of thousands of smaller objects working in unison. The primary benefit of the 'low mass' approach is stated to be the ability to avoid the costs and challenges of manufacturing, launching, and possibly having to repair such a large object -- having many identical components offers built-in redundancies in case some should fail or be impacted by an event like a solar wind or solar storm, strong radiation fields or micrometeoroids. On the flip side, for a 'low mass' approach to be viable, there would need to be coordination, for instance through sensors, to keep the components in position relative to one another (e.g. Matloff et al., 2014; Ellery, 2017). For this reason, such "low mass" proposals also tend to be more "high tech", to use the terminology of Keith et al (2020).

The amount of material to be placed in space is enormous, raising questions about launch energy demands, and thus costs and the related environmental and (societal) impacts. Some investigators therefore considered using the moon as feedstock source and launchpad, at times invoking such efforts as part of a future "moon economy" (Bromley et al., 2023; Bewick et al., 2012; IRS & Airbus, 2020; Rozen et al., 2024; Szapudi, 2023;). Such endeavours would necessarily give rise to novel questions regarding governance, legal frameworks, and environmental protection, for instance, the applicability of international treaties such as the Outer Space Treaty of 1967 which establishes outer space as "the province of all mankind", and institutions such as the United Nations Commission on Peaceful Uses of Outer Space (Bodansky, 1996; Keith et al., 2020).

The implementation of space mirrors would be significantly more expensive than SAI, with the estimated cost for research, development, and deployment ranging from $1trillion to $20trillion (Baum et al., 2022; Maheswaran et al., 2022; Pearson et al., 2006;). Furthermore, there are many technical constraints and risks (e.g. uncertain results, costly and difficult maintenance and repair if needed; Baum et al., 2022).

Space mirrors in LEO or GEO are close enough to Earth that effects such as transient shading as well as uneven cooling can be expected, which could impact wildlife on land and in the ocean, renewable energy production, societies, and human experience in general. There are modelling studies that examine the effects of a more space mirror-specific approach (Irvine et al., 2010; Lunt et al., 2008). These studies reveal the regional disparities in the potential cooling effects between polar and equatorial regions, whereby temperatures would decrease more strongly in the tropics. A subsequent modelling exercise by Sánchez and McInnes (2015) thus examined how the use of "out-of-plane sinusoidal motion", in which the space mirror would be slightly out of sync with the Earth, could diminish the strength of regional or seasonal variations.

There has been little modelling of space mirrors in a near-Earth orbit and that would result in regional shadow effects over only part of the Earth's sun-lit surface area. Solar eclipses may serve as a natural analogue, and recent observational evidence indicates that current cloud models would have difficulties simulating tropospheric impacts and cloud feedbacks (Trees et al., 2024).

Chapter 3: Effects, impacts, and side-effects of solar radiation modification

Method-independent effects

Key messages

- SRM techniques, specifically SAI but also CB, have the potential to exert an effective radiative forcing of magnitude large enough to counteract greenhouse gas forcings in model scenarios for next decades to centuries.
- SRM methods do not address the direct impacts of elevated GHG concentrations, like ocean acidification and land fertilisation
- SRM would have regionally diverse impacts on temperature, not perfectly counteracting global warming patterns. It would largely mitigate hot temperature extremes, but to a lesser extent temperature changes at night and in winter.
- SRM acts differently on the hydrological cycle compared to GHG forcings. At balanced temperature, precipitation on average is reduced, however larger regional changes may occur depending on the application strategies and amount of application.
- Multiple other effects have to be considered, such as potential changes to plant growth and crops, reduction and droughts, which can differ between regions.

The relationship between cumulative greenhouse gas emissions and global warming has been a cornerstone of climate science and climate politics. Specifically, since the Paris Agreement (UNFCCC, 2015) efforts have focused on reducing emissions to limit temperature rise and on reaching net zero emissions to stabilise global mean temperature. The net-zero target is underpinned by an essentially linear relationship between cumulative CO2 emissions and global warming termed 'transient climate response to cumulative emissions' (Allen et al., 2009). It implies that net-zero CO2 emissions are essential and that arresting global warming does not require net-zero emissions for non-CO2 GHGs, because their lifetime in the atmosphere is considerably shorter than that of CO2 (Allen et al., 2022). SRM introduces a disruptive element by decoupling the link between emissions and warming.

Other disruptive impacts of SRM arise from different spatial patterns of SRM and CO2 forcing that lead to an 'artificial' climate with different circulation patterns and a different hydrological cycle, compared to a climate with the same effective radiative forcing but without SRM (control climate), most intensively studied for the case of SAI (Robock et al., 2008). The intensity and extent of such deviations from 'control' climate depend on the intensity and spatial patterns of SRM-induced cooling (Reynolds et al., 2016; Ricke et al., 2023). Adding matter to the environment associated with SRM (e.g. sulphur dioxide considered for SAI) poses direct risks (e.g. acid rain, Irvine et al., 2016). Ocean acidification is sometimes considered as "the other CO2 problem" (Doney et al., 2009) and generally not mitigated by SRM. Modelling studies suggest that SRM-induced cooling can lead to a significant lowering of atmospheric CO2 via reduced respiration in soils, elevated solubility of CO2 in colder surface waters (Keller et al., 2014; Tjiputra et al., 2016) and -- in the case of SAI, CB and CT -- enhanced photosynthesis at enhanced diffuse-to-direct fraction of solar radiation (Mercado et al., 2009). However, the effects of elevated solubility and reduced atmospheric pCO2 act against each other and, in models, result in a slight reduction in oceanic CO2 uptake and hence a slight mitigation of ocean acidification (Jin et al., 2022).

CO2 directly affects plant metabolism through its role in photosynthesis. Elevated CO2 concentrations due to climatic changes are therefore expected to increase leaf photosynthetic rates. Nevertheless, the degree to which increased CO2 levels will result in increased photosynthesis rates is unclear, given that the stimulation of photosynthesis by CO2 also depends on factors such as water and nutrient availability, and leaf temperature (Dusenge et al., 2019; Zhu et al., 2017). While SRM would not directly affect the CO2 levels, it might affect the canopy's ability to uptake CO2. For example, reduced carbon gain under the combined conditions of elevated CO2 levels and low vapour-pressure deficit (the latter is often concurrent with increased diffuse radiation (Cirino et al., 2014)) has been reported in several studies (e.g. Norby et al., 2005; Ainsworth & Long, 2005; Urban et al., 2014). This reduced carbon gain is usually attributed to a relatively closed stomatal aperture (Heath, 1998) and/or enhanced non-photochemical quenching of absorbed solar radiation energy (Erice et al., 2007) under such conditions.

Besides intended and unintended impacts of SRM, listed below, one of the largest risks of all SRM methods in the case of sustained, global deployment is the long-term commitment after start, which may cover decades to multi-centuries (Baur et al., 2023). If SRM would be applied to significantly mask the increase of global surface temperatures due to elevated GHG concentrations in the atmosphere (or to provide additional cooling), the amount of required SRM would have to be adjusted continuously, following the rate of change in climate forcing in consequence of rising GHG concentrations in the atmosphere. However, projections of the evolution of GHG concentrations in the future and therefore the required duration of SRM deployment are also uncertain and with this the impacts. These uncertainties are based on the political landscape and the human system response to future climate change under SRM regarding emissions reductions and potential CDR applications (Chapter 6). The potential lack of ambition to mitigate after SRM has been started could lead to continued use of fossil fuel emissions. On the other hand, ambitions to phase out SRM may provide incentives for intensified emissions reductions and deployment of CDR.

Another uncertainty lies in the uncertainty of climate feedbacks. It is possible that some climate tipping points may have already been reached or initiated at the time a potential SRM application would be started. Feedbacks like large methane emissions due to the thawing of permafrost or submarine gas hydrates, or other unexpected releases of greenhouse gases may result in much higher GHG concentrations than projected. The larger the application of SRM the larger the risk of a termination, including short-term termination (interruption by just a few months or a couple of years) or a complete termination. Short-term termination may not have very drastic impacts on the climate and the environment, depending on the application. Long-term terminations could be much more harmful than climate change itself (Trisos et al., 2018), since all masking of warming due to SRM would be reverted relatively abruptly, within less than a decade. The pattern of rapid warming resulting from sudden termination of SRM is robust, while the effects on regional hydroclimate and land ecosystems are more uncertain (Jones et al., 2013) Generally, the longer the SRM has been deployed and the larger the underlying GHG emissions, the larger the potential termination shock. However, the risks of termination may be potentially prevented by concurrent strong GHG emission reduction (McCusker et al. 2014) as well as precautionary and political measures (Parker & Irvine, 2018).

Effects from stratospheric aerosol injection

This section not only covers stratospheric aerosol injection (SAI) but also highlights the effects of space mirrors, referred to here as solar dimming (SD).

SAI cannot perfectly revert changes from elevated atmospheric GHG concentrations, and residual climate change is expected compared to present-day (or, more generally, control-climate) conditions. The impacts of SAI compared to historical conditions strongly depend on the details of the considered SAI applications and are often strongly model-dependent. Differences in the impacts in part scale with the required amount of SAI application, depending on the assumed future baseline scenario and the desired temperature target. For example, in order to reach the same temperature targets, a future climate with a high GHG trajectory requires more SAI than a climate that includes strong mitigation efforts. In addition, the details of impacts (desired and undesired) depend on the details of the injection strategy (outlined in Modelling). Strategically-chosen injections have been shown in model simulations to reduce some unintended side-effects, like a relative overcooling of the low latitudes or a strong shift in the ITCZ. As shown in Haywood et al (2013), asymmetric forcings from volcanically induced stratospheric aerosol injections in one hemisphere have shown significant impacts on the surface climate.

Multi-model comparison experiments have been used to identify robust impacts (see Modelling). In addition, single-model large ensemble experiments (GLENS and ARISE) have been performed to explore the detectability of climate impacts that help attribution studies (e.g. Barnes et al, 2022). However, disagreements are especially found for regional and local impacts, but even at the global level. For example, models describe a factor of two uncertainty in the required amount of SAI needed to reach a specific amount of cooling (WMO, 2022). These uncertainties stem from differences in aerosol microphysics, details in the radiative response, and climate adjustments and feedbacks. Furthermore, models have very different climate sensitivities, which results in different projected warming for specific CO2 concentrations. Even for a given scenario, some models may need more injections of aerosols than others. In addition, different models require hemispherically uneven injections that can also result in different climate impacts, particularly with regard to regional impacts, for example, changes in the Asian summer monsoon (Henry et al, 2023). Based on these caveats, intended and unintended consequences are only described qualitatively.

Intended impacts of SAI compared to a climate without SAI and elevated GHGs

Intended impacts of SAI include effects that are directly targeted by SAI application, which may include radiative forcing, global and regional surface temperature, precipitation and sea ice (Lee et al., 2020), and even crops (Clark et al., 2023). Most SAI and SD studies so far have aimed to either reach specific radiative forcings or surface temperature targets. Intended impacts may also include those impacts that are mitigated compared to the impacts from future GHG concentrations or other climate forcers (including tropospheric aerosol).

All current ESM studies agree that SAI and SD are able to globally cool or sustain near-surface temperatures with increasing atmospheric GHG concentrations. Large uncertainties exist in how much cooling can be achieved with a certain amount of injection (as described above). The validity of this process is supported by the fact that all ESMs show a cooling of global surface temperatures after large volcanic eruptions supported by observations. Many climate impacts are related to changes in near-surface temperature. Keeping temperatures close to the present-day or control-climate conditions using SAI has been shown to significantly reduce uncertainties in the projected run-away climate impacts simply based on the fact that humanity has not experienced or observed temperature increases outside the historical range that comes with many unknown conditions, including potentially reaching tipping points (IPCC AR6 WG1 Chapter 1).

Related to sustaining near-global surface temperatures, SAI would result in various other desired impacts, including the reduction of increasing heat waves and extreme temperatures (Tye et al., 2022, Ji et al., 2018), reduction of extreme weather events and tropical cyclones (Jones et al., 2017), sustaining Arctic sea ice (e.g. Tilmes et al., 2016), potentially sustaining Greenland ice sheets (Moore et al., 2019), slowing sea-level rise (Moore et al, 2010, Yue et al., 2023), delaying West Antarctic Ice Sheet collapse (Sutter et al., 2023) and slowing or reversing the potential shutdown of the Atlantic meridional overturning circulation (AMOC, Fasullo et al., 2018; 2023; Xie et al., 2022). Most of these changes would address future conditions compared to elevated-CO2 scenarios without SAI and are strongly dependent on the injection strategy (Lee et al., 2020) as well as model-dependent (Fasullo & Richter, 2023).

The projected increase in the recurrence and intensity of droughts and heatwaves in the future could have detrimental impacts on vegetation, agriculture, drinking water scarcity, and food security (Miralles et al., 2019). Drought can be either due to decreased rainfall (caused by decreasing temperatures or changed circulation patterns) or due to increased evapotranspiration (caused by increasing temperatures). In the future, more droughts induced by decreased rainfall are projected under SAI, and more droughts due to decreased potential evapotranspiration are projected under climate warming (Coughlan de Perez et al., 2022). According to the findings of recent studies (Dagon & Schrag, 2017; Odoulami et al., 2020, Tye et al., 2022) SAI would reduce the number of consecutive dry days and the frequency of heatwaves, and thus the likelihood of drought (Abiodun et al., 2021).

Extreme precipitation events are mitigated by SAI due to reductions in tropospheric temperatures and increased atmospheric stability (Kravitz et al., 2015; Tilmes et al., 2013) and reduced evaporation (Niemeier et al., 2013). The resulting flooding from extreme precipitation events would therefore decrease, due to the implementation of SAI (Ji et al., 2018; Tew et al., 2023). According to Tew et al (2023), SAI would lower flood risk in many parts of the world with respect to high-emission scenario (RCP 8.5). However, studies focused on regional impacts of SAI are more uncertain and are, for example not sufficient for robust basin-scale assessment and flood control policy formulation.

Side effects and other impacts

This section lists side-effects or impacts, that could be either beneficial or detrimental, which may also depend on region and season. It considers, unless otherwise stated, a comparison between present-day conditions and a climate with SAI and elevated atmospheric concentrations of GHGs. Robock

(2020) has summarised a list of benefits and risks or concerns that include physical and biological climate systems, human impacts, aesthetics, unknowns, governance and ethics. Here, we focus on the physical, as well as societal and ecosystem impacts. Further aspects are addressed in Chapter 5.

Surface temperatures

Disparities in the effectiveness at the regional level have been identified, with both SAI and SD 'overcooling' the tropics, and 'undercooling' the NH high latitudes (Kravitz et al., 2012, Visioni et al., 2021). However, more recent targeted model applications with strategically placed injections of aerosol can reach a significant cooling close to desired near-surface temperature levels in the global mean and mostly remove interhemispheric and pole-to-equator temperature gradients (Tilmes et al., 2018). A prominent feature of regional surface temperature response to SAI in models is a strong wintertime warming of Northern Eurasia (e.g. Banerjee et al., 2021; Jones et al., 2022). A similar albeit weaker continental warming has also been observed after large volcanic eruptions (Stenchikov et al., 2002) although not conclusively (Polvani et al., 2019) and is the result of a strengthening in the stratospheric polar vortex, induced by the heating of the lower tropics stratosphere. This regional pattern has been found in multiple models employing S-based SAI (e.g. Jones et al., 2023; Visioni et al., 2021) and even for some alternative materials, such as titania and black carbon (Jones et al., 2016). Conversely, SD does not lead to this NH continental warming. Outcomes may be different for other materials that are not strongly sunlight- and infrared-absorbing and thus not conducive to stratospheric heating (Dykema et al., 2016). In addition, the injection location plays a crucial role: SAI can result in uneven changes in surface temperatures, for example, if aerosols are injected at the equator, or other single locations (Bednarz et al., 2023b). Symmetric injections in both hemispheres can also result in uneven cooling compared to present-day conditions since other feedbacks like the AMOC response interact (Fasullo & Richter, 2023). With regard to the seasonality and diurnal cycle of near-surface temperatures, it has been shown that SAI does not perfectly offset the effects of increased GHG concentrations. The reasons are that SAI and SD are only effective during daylight and not at night, therefore showing a relatively smaller cooling effect in particular in winter at high latitudes (Govindasamy & Caldeira, 2000; Curry et al., 2014).

Model simulations of SAI also reveal alterations in the amplitude of the seasonal cycle at high latitudes (Zarnetske et al., 2021). These changes influence the seasonal cycle of snow depth and sea ice, with implications for the environment and ecology. The dynamical effects of aerosol-induced stratospheric heating and seasonal sunlight variations contribute to these shifts, highlighting the interconnected nature of climate responses to SAI (Zarnetske et al., 2021).

Hydrological cycle

Although SAI would prevent increasing heatwaves and other extreme weather events such as droughts and floods, many studies show that one of its most significant implications would be the slow-down of the hydrological cycle and the overall decrease in precipitation (Bala et al., 2008; Cheng et al., 2019; Ferraro & Griffiths, 2016; Ji et al., 2018; Niemeier et al., 2013; Tilmes et al., 2012; Tilmes et al., 2020), which occurs because solar forcing drives changes in global mean evaporation more effectively than CO2 forcing of a similar magnitude (Bala et al., 2008). Irvine and Keith (2020) showed that reductions in global precipitation can be prevented by only applying half the amount of SAI and therefore aiming for warmer temperature targets. In addition to the reduction of the hydrological cycle, stratospheric aerosol injection in one hemisphere (for example, after volcanic eruptions) can significantly change precipitation patterns due to the shift in the ITZC, impacting the rainfall of millions of people in the tropics and causing droughts in the Sahel (Haywood et al., 2013; Iles & Hegerl, 2015; Trenberth & Dai, 2007). Strategically placed injection locations applying SAI may help to mitigate this problem, however much more research is needed to identify the limits of strategic injections with regard to impacts.

Strategically placed aerosol injections can still lead to large regional changes in rainfall. Simpson et al (2019) showed that a very large SAI application to counter a high forcing GHG scenarios could result in a 50% chance of the shut-down of the Indian summer monsoon and may only slightly improve reductions in precipitation in regions over the Amazon. In contrast, smaller SAI applications using a similar strategy did not support this result (Henry et al., 2023). In summary, details of changes in regional rainfall strongly depend on the amount of SAI applied and also on details of the injection strategy, and even for the same strategy, the estimates of different models for the regional effects in precipitation and their magnitude vary (Kravitz et al., 2021; Laakso et al., 2023; Ricke et al., 2023). Different models can show different magnitudes and even different signs of rainfall changes over them. A single model study (Obahoundje et al., 2023) showed that decreased precipitation over specific African regions would increase droughts with a potential negative impact to the local population, although in other regions, precipitation would increase. Another study, (Alamou et al., 2022) showed that the number and the intensity of the drought events in western Africa would decrease under SAI with respect to RCP8.5 in 2030-2049.

Stratospheric ozone

The WMO2022 report has assessed the effects of SAI and SD on stratospheric composition, including ozone, and dynamics. Their conclusions were based on very few and often single-model studies using sulphate aerosol. In general, the continuous injection of sulphate aerosol precursors into the tropical stratosphere results in both dynamical and chemical changes. Sulphate aerosols absorb both the solar and terrestrial infrared radiation and therefore result in a warming of the tropical lower stratosphere. The changes in stratospheric temperature have consequences for the stratospheric dynamics, resulting in an acceleration of the Brewer-Dobson circulation above the injection location, a strengthening of the polar vortex, and a weakening of the sub-tropical jet streams (e.g. Banerjee et al., 2021; Wunderlin et al., 2024). In addition, the heating of the tropical tropopause causes an increase in water vapour in the stratosphere, which has implications for chemistry and climate (e.g. Visoni et al., 2017). Chemical changes are the result of heterogeneous chemical reactions that increase and decrease ozone depending on the location (Tilmes et al., 2009). Increased aerosol surface area density results in a delay of the ozone hole recovery in the Southern winter over Antarctica. Increased heterogeneous reactions in the tropics and mid-latitudes result in positive changes in ozone in the middle stratosphere, due to suppression of the NOx chemical cycle (Tilmes et al., 2022). In addition, the heating from stratospheric aerosol accelerates the deep branch of the Brewer-Dobson circulation; the combined effect of both dynamical and chemical processes results, in general, is an increase in ozone concentrations in the tropics and potentially in mid-to-high latitudes through enhanced transport of ozone from the tropics to high latitudes (Bednarz et al., 2023c; Tilmes et al., 2022; Vattioni et al., 2019; Wunderlin et al., 2024).

The effect of SAI on future ozone would be in addition to changes driven by future climate conditions and, therefore strongly depend on the specific future scenario as well as the details of the strategy in terms of injection location, timing, and material used. Without SAI, total column ozone is expected to recover globally after the successful phase-out of chlorofluorocarbons and various other halogen components. The ozone hole in austral spring is expected to recover by the mid-21st century. The future Total Column Ozone (TCO) evolution in other parts of the world strongly depends on the future GHG scenario. A warmer climate will result in a so-called super-recovery of TCO, which means that TCO will increase above pre-ozone hole values. Both the increase and decrease of TCO, especially in the Northern Hemisphere, have implications for surface ultra-violet radiation (UV-B; see below). If SAI were applied using sulphate aerosol, an initial reduction in TCO is expected for a few years, but model results show changes that are within historical values. A later start of SAI has a smaller effect on TCO in high latitudes. On the other hand, SAI is somewhat effective in countering the super recovery of ozone in the NH high-latitudes. However, some models indicate that SAI could further increase TCO. Using alternative materials such as calcite and alumina would not imply ozone depletion, but even increase (instead of decrease) global ozone burdens (Keith et al., 2016), while also offering stronger cooling efficiency (Weisenstein et al., 2015). However, there is a great degree of uncertainty concerning the heterogenous chemistry on the surface of these materials. As a result, we have very limited knowledge of how they would behave under stratospheric conditions and thus, their effects on the ozone layer are uncertain and can only be constrained with more laboratory data (Vattioni et al., 2023; 2024b).

Tropospheric ozone and air quality

SAI would further impact tropospheric air quality through various paths, with direct health and environmental consequences (Tracy et al., 2022). The injection of aerosols in the stratosphere would impact photochemistry, as well as dry and wet deposition (Moch et al., 2023; Visioni et al., 2019,). A limited number of studies that are focused on the impact of SAI on tropospheric chemistry and air quality are currently available (Eastham et al, 2018a; Moch et al, 2023; Xia et al, 2017;), and with few exceptions (e.g. Visioni et al., 2017), interactive photochemistry is commonly not included in climate modelling studies, or represented by simple schemes (Tracy et al., 2022). The delay in the stratospheric ozone hole recovery over Antarctica (see above) would increase the UV-B radiation that enters the troposphere in those regions. On the other hand, a potential super-recovery of ozone, especially in the NH mid- and high latitudes, would decrease UV-B radiation. Changes in UV-B radiation would impact the rate of photochemical reactions in the troposphere (e.g. Huynh & McNeill, 2024; Jacob, 2000; Madronich et al., 2018). Eastham et al (2018b) performed a sensitivity study using a chemistry transport model and showed that for a scenario assuming sufficient SAI to offset 1°C of surface warming in 2040, there would be a decrease in tropospheric ozone with respect to RCP6 that would be the most important health impact from SAI. Xia et al (2017) estimated that surface ozone would, on average, decrease globally due to SAI, mainly due to reduced net transport of stratospheric ozone into the troposphere over mid and high latitudes. They also estimated a small increase over the tropics. Changes in tropospheric photochemistry, similar to stratospheric ozone, are dependent on the method and the conditions of the SAI (Bednarz et al., 2023c). In a more recent study, Moch et al (2023) investigated how the long-term chemical feedbacks from sulphate SAI would alter its impacts. Compared to earlier works, they additionally examined the oxidative capacity of the troposphere. They found that sulphate SAI can increase the tropospheric oxidative capacity by 9%, which would result in a decreasing lifetime of methane. Feedbacks involving tropospheric chemistry could have noticeable impacts on the effectiveness of SAI. As discussed in Moch et al, (2023), these impacts vary with regionally and seasonally. For example, they estimated that over mid-latitudes, chemical feedbacks enhance the wintertime decline in radiative forcing from SAI by around 20% but decrease the summertime effect by around 10%. Aerosol concentration in the troposphere would not only be affected by the sedimenting sulphate particles. Eastham et al (2018b) estimated that SAI would result in increased levels of the PM2.5 particles, mainly due to lower temperatures and decreased rainfall with respect to unmitigated climate change. Nevertheless, SAI would suppress increases in the levels of dust and smoke aerosol particles that are expected, due to unmitigated climate change (Tracy et al., 2022)

Changes in surface solar radiation and the diffuse-to-direct radiation ratio

Injection of sulphate and other aerosols into the stratosphere would increase the relative contribution of the diffuse component in total solar radiation that reaches the Earth's surface (Xia et al.,2016). This change in the distribution of light would negatively impact solar energy production (Moriarty & Honnery, 2022; Smith et al., 2017) but could favour vegetative ecosystems (e.g. Fan et al, 2021; Proctor et al., 2018; Tracy et al., 2022; Trisos et al., 2018). An effort to quantify the changes in the contribution of the diffuse and direct components in the total solar radiation reaching the Earth's surface due to sulphate aerosols has been performed in a few studies. The decreased intensity of the direct beam has been measured after volcanic eruptions (e.g. Garrison, 1995; Olmo et al., 1999; Wendler, 1984). For example, at Fairbanks, Alaska, the volcanic cloud that travelled from Mexico resulted in an overall decrease of 5% in global radiation, a decrease in the direct beam of 24.8%, and an increase in the ratio of diffuse to global radiation of 76%, during the period 15th November 1982--31st May 1983, relative to clear day data. Madronich et al (2018) estimated the differences in effective UV doses and PAR for the RCP 8.5 scenario, with and without SAI, for northern high latitudes (70°N) and sub-tropics (30°N). For March, under the SAI scenario, they found a substantial reduction, of the order of 20-30%, in UV doses and a reduction of the order of around 10% (at 30°N) and around 40% (at 70°N) in PAR. The results of Madronich et al, (2018) show that SAI would result in a shift in spectral composition toward longer wavelengths as small aerosol particles attenuate shorter wavelengths more effectively relative to longer wavelengths. They also reported a large increase in the diffuse to direct ratio, which at local noon doubles at 30°N and increases by about an order of magnitude at 70°N. In another modelling study. Smith et al (2017) estimated that SAI using sulphate aerosols could result in a decrease of 1.3Wm-2 in the global mean downwelling surface solar radiation with respect to RCP4.5 until the end of the century, while the corresponding difference for the direct irradiance was over 25Wm-2.

Materials with different refracting indices (and subsequently with different scattering efficiency) have been proposed as alternatives to sulphate aerosols (Dykema et al., 2016) (see above). By using solid aerosols with higher refractive index relative to sulphate, comparable shortwave radiative forcing to sulphate aerosols can be achieved, with less stratospheric heating (Dykema et al., 2016). Further investigation is, however, necessary to quantify how these aerosol species would impact the direct and diffuse components of solar radiation. SD would have no impact on the diffuse-to-direct solar radiation ratio since it would practically lower the solar constant by 2-4% (Bhowmick et al., 2021; Lunt, 2013;) before the solar beam enters the atmosphere.

Dry deposition of ozone impacts vegetative systems because ozone that is deposited into the plant's stomata can damage plant tissues and prevent their growth (Clifton et al., 2020). SAI would affect tropospheric ozone differently over different regions of the world through various paths, and it would result in increased or decreased levels, respectively, regionally (Moch et al., 2023; Xia et al., 2017). Globally, tropospheric ozone is projected to decrease under SAI scenarios with respect to moderate RCP scenarios without SAI (Eastham et al., 2018; Xia et al., 2017), with potential positive impacts on the uptake of CO2 by plants and plant growth. Nevertheless, further research is necessary to identify the potential effects of SAI on surface ozone and on the health of plants (Tracy et al., 2022)

Carbon cycle changes

One of the key metrics of interest for a comprehensive assessment of the impacts of SRM on the Climate System is the effects on the carbon cycle and associated climate responses. To properly simulate the global carbon cycle and the potential impacts of SRM, ESMs need to interactively couple all processes from the aerosol formation (e.g. for SAI) all the way to the accurate simulation of land and ocean carbon pools, exchange fluxes between the individual systems, i.e. land-atmosphere, ocean-atmosphere and land-ocean, including dynamic ecosystems. While much progress has been achieved in terms of the simulation of atmospheric processes governing the effects of SAI (Visioni et al., 2023), the representation of carbon cycle processes and their multi-scale interactions in ESMs is still limited (Kravitz et al., 2015). Many modelling studies that evaluated the effects of SRM on the carbon cycle involved models without an interactive carbon cycle, with prescribed atmospheric carbon concentrations (Kravitz et al, 2015), or models with limited representation of ecological impacts (Zarnetske et al., 2021). Despite the missing feedback between the carbon cycle and time-evolving climate, many of these studies have provided useful insights concerning the wide-scale environmental effects of SRM and the related effects on ecosystems (e.g. Dagon et al., 2019; Jin et al., 2022).

Compared to a high-greenhouse gas (GHG) scenario, SRM via SAI and SD would impact the carbon cycle by (1) alteration of sunlight (diffuse vs direct radiation), environmental factors such as (2) temperature, precipitation, soil moisture, and ocean circulation, and lastly, indirect effects via (3) atmospheric chemistry (e.g. ozone depletion and resulting changes in UV exposure). The overall effects of SRM on the carbon cycle, when compared to a scenario without SRM, are contingent on the changes in individual factors and the interactions among them. Alterations in sunlight resulting from solar radiation modification (SRM) play a direct role in influencing the carbon cycle. Specifically, SAI is expected to decrease the sunlight reaching the Earth's surface while concurrently increasing the fraction of sunlight that is diffuse. These changes in quantity and quality of sunlight produce contrasting effects on land plant photosynthesis. Reductions in photosynthetically active radiation

(PAR) alone would decrease photosynthesis. However, the increase in diffuse light is more effective in reaching light-limited leaves within plant canopies, resulting in what is known as the 'diffuse-radiation' fertilisation effect (Mercado et al., 2009). Model simulations consistently show that SAI would reduce atmospheric CO2 concentrations (Cao et al., 2017; Jin et al., 2022; Muri et al., 2018; Sonntag et al., 2018), with land sinks playing a primary role, due to enhanced CO2 uptake by the terrestrial biosphere (e.g. Jin et al., 2022; Sonntag et al., 2018). The enhanced uptake is primarily due to a SRM-induced surface cooling, a consequent decrease in terrestrial gross primary production (GPP), as well as reductions in vegetation and soil respiration (Jin et al., 2022). Models generally suggest that vegetation carbon storage increases (Lee et al., 2021b). Conversely, there is larger uncertainty concerning the effects of SRM on net primary production (NPP), with the sign of NPP changes differing widely between models (Glienke et al., 2015; IPCC-AR6 Chapter 5), depending on the inclusion of interactive nitrogen cycle in the land model components of these ESMs. Generally, ESMs that incorporate the terrestrial nitrogen cycle indicate a less pronounced decrease in atmospheric CO2 due to solar radiation management (SRM) compared to models that do not consider the nitrogen cycle. This is primarily due to nitrogen limitation, which results in a less effective terrestrial carbon sink. One comprehensive ESM study compared the effects of climate engineering and carbon dioxide removal methods, including SAI, afforestation, and ocean alkalinisation (Sonntag et al., 2018). This comparative analysis highlights the significance of feedbacks in CE effects and emphasises the importance of normalisations for comparability among methods (Sonntag et al, 2018). The results suggest that different CE methods may require varying efforts to achieve the same global warming reduction, adding nuance to the understanding of their effectiveness.

It has also been shown that the SRM may have sizable effects on the allowable CO2 emissions (Plazzotta et al., 2019). Based on output from GeoMIP experiments (Kravitz et al., 2015), this study showed that SRM could effectively reinforce global carbon uptake by up to 40 GtC ± 19 GtC, after 50 years of continuous SAI deployment (injecting 5 Mt/y of SO2, according to the "G4" scenario in GeoMIP). This is mostly due to the reinforcement of land carbon sinks by SAI. More specifically, declining temperatures affect ecosystem respiration and the land biosphere, thereby increasing carbon uptake; at the same time, cooling SSTs increase the solubility of CO2. This would mean that fifty years of SRM under this protocol would increase the allowable anthropogenic CO2 emissions by the same amount (40 ± 19 GtC). This increment represents approximately four years of global anthropogenic CO2 emissions at the current rate. However, the termination of SRM would be highly detrimental, as the ESMs employed in this study robustly predict a mean release of 8 ± 11 GtC back into the atmosphere 20 years after SRM cessation. A critical caveat is that models with an interactive nitrogen cycle show reduced effects of SRM on the carbon sink, suggesting that the effects of SRM on allowable CO2 emissions may not be robust and could largely depend on the specific details of the land model employed in the ESM. Taken together, SRM has the potential to temporarily increase the allowable CO2 emissions by enhancing global carbon uptake, but the uncertainties and potential negative consequences, particularly related to SRM termination, present significant risks. Additionally, the impact of SRM may be less pronounced in models that account for the interactive nitrogen cycle, suggesting that the findings from previous modelling studies may depend on specific model configurations.

While there is emerging evidence concerning the effects of SRM (and in particular SAI) on land carbon sinks, the effects on ocean sinks remain more uncertain (Cao, 2018). Some models report a minimal change in the marine contribution to the carbon sink (e.g. Jin et al, 2022; Sonntag et al, 2018), primarily due to compensating effects. On one hand, the decrease in atmospheric CO2 resulting from SRM tends to diminish ocean CO2 uptake due to the direct reduction in the air--sea CO2 gradient. On the other hand, the surface cooling effect induced by SRM tends to enhance oceanic CO2 absorption. These factors counteract each other, leading to a minimal alteration in global ocean carbon storage. However, the relative roles of ocean and land may depend on the sensitivity of the land carbon sink to changes in climate and CO2 (Sonntag et al., 2018); better constraints of the carbon uptake sensitivity may help reduce such uncertainty in the modelled SRM effects.

Despite advances in modelling capabilities, our understanding of the effects of SRM on the carbon cycle are limited by the following issues. First, ESMs and global models in general may lack the spatial resolution needed to capture regional variations in ecosystems and their responses to SAI. The complex interactions among various factors, such as temperature, precipitation, nutrient availability, and species composition, may not be fully understood or accurately represented in models. Models often make assumptions about how plants respond to altered environmental conditions, and these assumptions may not fully capture the diversity of plant physiological responses to changes induced by SAI. The models may not adequately represent feedback mechanisms between the carbon cycle and climate, introducing uncertainties in predicting how SAI would affect carbon sequestration. Lastly, models may simplify the representation of the aerosol forcings associated with SAI, including their spatial and temporal distribution, potentially impacting the accuracy of the modelled changes in radiation and consequently, in the modelled environmental effects on impacts on ecosystems. In summary, these studies collectively underscore the complex and interconnected nature of SAI and SD, with impacts on the carbon cycle, global climate, and ecosystems. While SAI shows potential in mitigating global warming symptoms, there is a consensus on the need for a comprehensive assessment, considering feedback, normalisations, and ecological implications to inform responsible implementation scenarios.

Impacts on societies and ecosystems

The potential effects on societies and especially ecosystems of SAI and SD are identified as a critical knowledge gap, with studies emphasising that the impacts and risks would vary based on the implementation scenario, geographic region and specific characteristics of ecosystems (Jiang et al., 2024). SAI implementation may prevent some of the consequences of climate change on societies and ecosystems (Lafferty, 2009; Lobell and Field, 2007; Mitchell et al, 2016) but it could also have unintended, and potentially unexpected, impacts (Irvine and Keith, 2020; Tracy et al, 2022; Trisos et al, 2018). Zarnetske et al (2020) recommend that SAI planning should consider protection of biodiversity hot-spots.

Various previous studies have discussed the effects of SAI on societal impacts, including water and food availability and health. One of the main positive effects of SAI implementation is projected be the decrease in the amount and the intensity of extreme heat events with respect to unmitigated scenarios (Irvine et al., 2019; Ji et al., 2018; Obahoundje et al., 2023) that would be beneficial for human physical and mental health (Ebi et al, 2021; Lisa et al, 2024; Meadows et al., 2024;). Prevention of increased temperatures due to SAI would also moderate increased animal infection rates and extension of the ranges of zoonotic infectors northward (Greenspan et al., 2017; Ogden & Gachon, 2019). Nevertheless, temperature variations due to SAI deployment could substantially increase malaria risk in Southern Asian and Western Africa countries and decrease the risk in high elevation Eastern African areas (e.g. Carlson et al., 2022).

The societies and the ecosystems would be affected directly by SAI-driven changes in air quality which, as discussed earlier in the document, are highly uncertain and need further investigation (Eastham et al., 2018; Li et al., 2021, 2020b; Tang et al., 2023). SAI (as well as climate change) would alter stratospheric ozone, as well as other factors (e.g. clouds and aerosols) that determine personal UV-B exposure (Baldermann et al., 2023; Bernhard et al., 2023). The sign and the magnitude of the potential UV-B changes vary greatly depending on the location of the injection, and the quantity and the duration of SAI (Bernhard et al., 2023) Thus, estimation of the potential health effects due to UV-B changes is highly uncertain.

Although SAI may increase the risk for extreme weather events and natural disasters locally (Butsch et al., 2023; Tong & Ebi, 2019), it is estimated that on average it would reduce natural disasters due to climate change (tropical cyclones, droughts, floods). The estimated impact depends strongly on the injection methodology (Irvine et al., 2019; Ji et al., 2018; Jones et al., 2017; Moore et al., 2015).

Production of energy from renewable sources will be key in the following years. Any change in the potential for energy production due to the implementation of SAI would have societal impacts through the availability of energy. Different studies report effects of different directions and magnitudes, that vary temporally and spatially, on the production of wind (Moriarty & Honnery, 2022; Wang et al., 2022), hydro (Alamou et al., 2022; Bhowmick et al., 2021; Sun et al., 2020a), and biomass (Alamou et al., 2022; Zarnetske et al., 2020) energy. SAI would likely have the largest negative impact on solar energy production relative to other SRM methods, mainly because of the reduction in the direct sunlight component (Baur et al., 2024). For example, Smith et al, (2017) estimated an average reduction of 5.9% over land in the average Concentrated Solar Plants (CSP) output, but generally smaller reduction for photovoltaic systems relative to RCP4.5.

Studies on crops and food production show that SAI can have a positive effects on crops in limiting heat stress and water stress (through relative humidity) with SAI and continued fertilisation from enhanced atmospheric CO2 concentrations (Clark et al., 2023; Fan et al, 2021; Xia et al, 2014; Zhan et al, 2019). However, some plants have been shown to benefit from increased CO2 more than others (e.g. Clark et al., 2023; Zhan et al., 2019). Also, changes in precipitation pattern and reductions of incoming solar radiation can counter some of the benefits depending on region and season (Kravitz 2021; Pongratz et al., 2012; Proctor J. et al., 2018). Other research has however argued that, by increasing diffuse radiation, SAI may rather enhance photosynthesis (Xia et al., 2016). Clark et al (2023) have assessed the changes in crops and calorie production under different future scenarios with and without SAI. They concluded that in terms of calorie production, some nations in high latitudes benefit more from unabated climate change, while others, in particular in the Tropics and the Global South would benefit much more from a cooler climate imposed by SAI applications. The results, as they note, highlights the challenge to define a 'globally optimal' strategy.

Light is the main source of energy for photosynthesis for plants and leaves and its spectrum as a source of information (Demarsy et al., 2018). The geometry of light propagation changes with respect to the proportion of diffuse and direct radiation, which subsequently changes the distribution of the energy that is available for photosynthesis for leaves and plants (URBAN et al., 2007). Shifts in the spectral composition of the incident radiation could affect plant physiology, photomorphogenesis and stress responses (D'Amico-Damião & Carvalho, 2018). For example, canopy can be also sensitive to changes in ultraviolet (UV) radiation (e.g. Yin & Ulm, 2017). However, the effect of diffuse solar radiation on canopy photosynthesis, a multilayered phenomenon that also depends on the characteristics of canopy and cannot be easily modelled (Durand et al., 2021). Experimentally testing the effects of long-term enhancements of diffuse radiation in plant canopies would provide the knowledge to better understand the consequences of SAI on their growth and productivity, which are currently uncertain, and would contribute significantly towards predicting the potential hazards of employing such a solution.

Changes in soil properties (Kibblewhite et al., 2007; Tjiputra et al., 2016), wet and dry deposition (Nam et al, 2008; Visioni et al., 2020), and the hydrological cycle (Dagon & Schrag, 2019; Krishnamohan & Bala, 2022; ; Sun et al., 2020; Tilmes et al., 2013; Tracy et al., 2022; Trisos et al., 2018) would also impact vegetation. Despite the uncertainties and the large spatial variability in the estimated impacts of SAI on vegetation, and subsequently in the food production from vegetative ecosystems and livestock, it is estimated that, on average, vegetation will be benefited from SAI, mainly through the reduction of temperature extremes, the increase in the diffuse component of the SSR, and the reduced deposition of ozone.

Combined impacts of acidification, changing temperatures, deoxygenation of phytoplankton and other processes are poorly constrained and make the estimation of the potential SAI impact on marine biomes and subsequently the marine food systems very uncertain (Krumhardt et al., 2017). Depending on the assumptions, different studies give different results. For example, according to (Lauvset et al., 2017) SAI would impact the ocean food system through the generation of a global decrease in ocean net primary production, while according to Zarnetske et al. (2021), SAI would reduce water stress and lead to increased primary production. According to other studies SAI may lead to a small increase in the ocean pH (Matthews et al., 2009) and prevent coral reef decline and coral bleaching events through the prevention of temperature changes (Hughes et al., 2012). Changes in ocean circulation and chemical cycling would also impact oceanic ecosystems and oceanic food stocks (e.g. Bijma et al., 2013; Lauvset et al., 2017; Lavaud et al., 2007). Severe sea ice melting that would impact marine and sea ice ecosystems will be also prevented due to the implementation of SAI (Wadhams & Munk, 2004).

Other social and ecological impacts are explored in Chapter 6, where geopolitical, security and weaponisation risks are summarised.

Impacts on biodiversity

Climate change poses a threat to biodiversity, as ongoing changes in large-scale temperature and precipitation patterns are reducing the availability of suitable habitats and altering the distribution of species, disrupting species interactions (Chen et al., 2011; Pinsky et al., 2013). If species cannot adapt to these rapid changes, the populations will decline, leading to biodiversity loss (Corlett et al., 2013; Schloss et al., 2012;). Human-driven climate change exacerbates these threats due to anthropogenic pressures, such as over-exploitation, habitat loss, fragmentation and degradation, introduction of non-native species, and pollution, greatly increasing the risk of species extinctions and local losses (Zarnetske et al., 2021). One proposed method to limit risks posed by climate change is SRM, with SAI being the most widely studied method. SRM has been shown in model studies to alleviate several climate-change-related impacts on biodiversity via reducing global mean temperatures (Trisos et al., 2018). However, SRM also poses potential unintended consequences on biodiversity, which are still poorly understood, as they generally vary by implementation scenario, anthropogenic climate effects, geographic region, ecosystem, community, population, and organisms (Zarnetske et al., 2021). For instance, it has been shown that rapid implementation of SAI can effectively reduce land species' climate velocities (the rate and direction of temperature shifts). However, its abrupt termination can result in extreme temperature velocities that are 2 to 4 times higher than both historical trends and future projections of unabated GHG emissions, without any SRM implementation (Trisos et al., 2018). This sudden change could severely impact biodiversity, especially for poorly dispersing species like corals and amphibians, which are vulnerable to climate change. Most notably, subtropical and northern temperate oceans, and much of North America, Africa and Eurasia would face the most significant increases in local extinction risk from the SRM termination-shock, as species fail to track faster moving climates in these regions. Also, SRM does not address ocean acidification caused by elevated atmospheric CO2, leaving marine biodiversity at risk. If SRM were terminated after being deployed for some time, the rapid and severe warming would likely cause more significant negative impacts on biodiversity and ecosystem services than gradual climate change, as it would reduce the opportunity for species adaptation through migration (Jones et al., 2013; McCusker et al., 2014; Trisos et al., 2018). Improperly designed SRM could harm global biodiversity hotspots more than the rapid rise in greenhouse gas concentrations (Trisos et al., 2018).

SRM's physical effects, such as reduced surface shortwave radiation and cooling, are unique and distinct from those caused by greenhouse gases, resulting in different ecological impacts. These include changes in organism physiology and morphology, genetic diversity, phenology, ecosystem processes, and biogeochemistry, as well as alterations in population dynamics, species range shifts, and community assembly (McCormack et al., 2016). Combining climate change mitigation with SRM in a peak-shaving scenario might reduce risks and potential harm to organisms and ecosystem processes (Zarnetske et al., 2021). However, this approach may still be insufficient in some regions to prevent serious ecological losses. For example, it might inefficiently mitigate Arctic permafrost thaw, leading to vegetation changes, biodiversity loss, and climate feedbacks through methane release. To manage these risks effectively, it would be desirable to consider biodiversity targets in SRM scenario development, with biodiversity hotspots (i.e. areas with the highest risk of losses and greatest endemic diversity) being the focal points for assessing such targets.

A more moderate approach to SRM implementation, such as inducing only a small degree of cooling or curtailing the rate of warming alongside emissions reduction efforts (e.g. Kosugi, 2013), could significantly reduce some of the adverse effects on ecosystems and biodiversity (MacMartin et al., 2014).

Effects from cloud brightening

Compared to SAI, radiative responses to CB are more localised, due to the short lifetime of tropospheric aerosols and their impacts on cloud properties (e.g. Hirasawa et al., 2023). In this section, we only address effects from cloud brightening that are different or occur in addition to those listed in Effects from stratospheric aerosol injection.

When assessing the impacts of CB, it is important to define the framework for comparison. Is it the present-day climate, a climate without emission reduction of GHGs or against one of the future emission scenarios such as the SSPs? CB does not address the cause of climate change; its intended impact is to lower the global or regional temperature. Only a few locations are suited for large scale deployment. These will experience a strong cooling, and via transport of energy and momentum through oceans and atmosphere lead to an uneven impact on temperature globally. The most pronounced cooling effects typically occur in areas directly under or near the modified clouds. Global climate modelling studies predict that CB can decrease the average global temperature with, however, significant regional temperature effects (Kravitz et al., 2013). The uncertainty of regional impacts is much larger than on global temperature. Areas where models consistently predict fairly strong temperature reductions include the northern high latitudes due to polar amplification, Antarctica and some low-latitude land areas (Stjern et al., 2008). As CB lowers the mean temperature, it will also slow down evaporation and decrease atmospheric water vapour content, similar to what is found for SAI, or even stronger (Niemeier et al., 2013).

Consequently, the warming-induced increase in global rainfall formation will be dampened, be it with an uneven regional distribution. Global models consistently show precipitation increases over low-latitude land (Australia, Africa, parts of South America) and decreases over ocean (Stjern et al., 2018). This is due to increased albedo over the oceans due to CB leading to downward motion and a subsequent rising motion over land. Models further show a tendency towards La Niña conditions (Stjern et al., 2018) and the possibility of a change of the Walker circulation (Alterskjaer et al., 2013; Niemeier et al., 2013). Effects on regional precipitation are much more uncertain than on global precipitation. For example, some models predict substantial precipitation decrease over Amazonia (Jones et al., 2009) leading to serious damage to the rainforest, while others project increased rainfall in the same region (Stjern et al., 2018). Differences between models are explained by, for example, differences in cloud amount, location and water content, but also by differences in cloud microphysics descriptions. The amount of sea salt as CCN may lead to increased salt deposition in coastal regions. The ecological impact of this is largely unknown and needs to be studied. At the seeded areas the incoming sunlight can be reduced by 30-50 watt per square metre, likely impacting sea surface temperature, mixing and marine ecosystems. Haywood et al (2023) show a range of potential effects:

- overcooling of the tropics and residual warming of middle and high latitudes
- changes in monsoon precipitation and increases in precipitation over Australia and the maritime continent
- increased sea-level rise around western Australia and the maritime continent

Effects from cloud thinning

This section lists such effects from cloud thinning (both cirrus cloud thinning, CCT, and mixed-phase cloud thinning, MCT) that are different from the effects listed for SAI, SD and CB. A key difference between the other schemes and CCT/MCT is that in cloud thinning, the terrestrial spectrum of radiation is targeted rather than the solar one. In consequence, these methods work best in polar winter because of the absence of sunlight. Also, the response of the hydrological cycle to CCT/MCT is resembling more the one in response to GHG increases (but opposite in sign) than the one in response to SRM.

CCT causes a decrease in mean global precipitation (Gasparini et al, 2020), but to a lesser extent than if the same cooling is achieved by SAI or CB (Kristjansson et al., 2015). Global modelling studies of CCT and MCT consistently show precipitation decreases in the polar regions, as expected since the largest temperature signal also occurs in this region (Gasparini et al., 2020; Villanueva et al., 2022). CCT and MCT are comparable to CB in the sense that the cooling would be spatially heterogeneous and could therefore induce significant atmospheric circulations and precipitation changes regionally. However, in contrast to CB, only a very limited number of studies have investigated this topic for CCT and MCT, making robust conclusions difficult at this point. Effects on regional precipitation are much more uncertain than on global precipitation. For example, there is a shift in the ITCZ in response to CCT in the CESM model, but not in the ECHAM model (Gasparini et al., 2020). Multi-model assessments would be beneficial to investigate spatial patterns in the precipitation change to a greater extent.

The question of which material(s) could be used for seeding for CCT and MCT is still open. Bismuth triiodide (BiI~3~) has been proposed for CCT by Mitchell and Finnegan (2009), but this was motivated by a desire to avoid effects on lower-lying clouds like MPCs, since BiI~3~ is only an efficient INP at relatively low (cirrus-like) temperatures. However, if appropriate regions and seasons for CCT are selected, the coincident additional seeding of MPCs would in fact be a co-benefit (Gruber et al, 2019) and not something to be avoided. In this respect, mineral dust, which can serve as an INP also in

MPCs, may be a more suitable seeding material candidate. Since dust is ubiquitous in the atmosphere (albeit at highly variable concentrations) this should also ease concerns related to toxicity or other harmful effects on ecosystems. However, the relatively large required mineral dust loading for efficient MCT (Villanueva et al., 2022) could be a concern. At present, no comprehensive assessment of the environmental impacts of CCT and MCT exists. Abrupt cessation of CCT and MCT is similar to abrupt cessation of CB or SAI, but less severe, because its magnitude is likely to be smaller due to its regional extent. It could, however, lead to rapid warming and associated ecological and societal challenges in polar regions. However, it could also be shut down very quickly if negative impacts were to arise, which could be viewed as an advantage.

Chapter 4: Technical and scientific requirements and prerequisites

Key messages

- SRM has been studied so far only in climate models. Models are not yet able to anticipate all effects and impacts of SRM and relevant processes (stratospheric composition and aerosol for SAI, and cloud-aerosol interactions for CB and CCT/MCT) are only coarsely integrated or still missing.
- Satellite monitoring technologies to detect and quantify SRM via SAI, CB and CCT/MCT exist, but some of such instruments not yet on operational European satellites.
- Technology readiness level for the implementation of SRM is currently very low.

Modelling tools

Climate modelling of SRM has its roots in the 1970s, when scientists began to theorise methods to artificially cool climate, at a time when computer modelling was still at its infancy. One such attempt was made by Budyko (1977), who first proposed deliberately modifying the sulphur content of jet fuel to produce an enhanced aerosol layer, via emissions of precursor gas (SO2). Two decades later, Lenton and Vaughan (1997) explored the impact of a range of climate geoengineering proposals, by using a simple analytical approach, including SRM against the conventional mitigation approach of large reductions in CO2 emissions. Another decade later, Crutzen (2006) conjectured that injecting a few Tg of sulphur per year into the stratosphere would be sufficient to offset the warming caused by tropospheric aerosol reductions due to air-pollution regulations. These first conceptual studies were based on a set of simple scaling assumptions, and yet laid the foundation for all the modelling efforts since the turn of the century (post-2000), which employed numerical models of increasing complexity, including the effects on multiple components of the climate system, such as vegetation (Govindasamy et al., 2002) and carbon cycle (Fyfe et al., 2013). Recently, more sophisticated numerical models have been used to study the effects of all various types of SRM strategies, including surface albedo modification and cloud seeding. These model studies have been coordinated by the Geoengineering

Modeling Intercomparison Project (GeoMIP) (Kravitz et al., 2015; Visioni et al., 2023). Other single modelling studies have produced large ensemble simulations, allowing in-depth impact assessments to be performed (Henry et al, 2023; Richter et al., 2023; Tilmes et al., 2018), including the level of detectability of SRM (Mamalakis et al., 2023) The large growth of modelling evidence over the past decade allows for a detailed evaluation of risks and benefits of SRM from a physical science perspective. While these models provide invaluable insights into the potential impacts on the Earth's climate system, societal implications of SRM are not considered in models, nor in any of the SRM scenarios.

Before SAI can be considered a viable option, an in-depth assessment of various aspects has to be performed (e.g. Kellogg & Schneider, 1974) that would ensure that SAI application would in general lead to improved conditions for societies and ecosystems, based on unbiased research performed by interdisciplinary and international scientists including minorities and researchers from developing countries. Both natural and societal criteria need to be considered that need to address various aspects of SAI application, and interdisciplinarity needs be reflexively practiced since it can potentially help keep problem framings open and subject to reflection, contestation, and revision; but "it can also make this harder, by reifying disciplinary outputs and occluding the processes that shape the production of knowledge" (Szerszynski & Galarraga, 2013).

The impact of SAI on the climate and resulting impacts is for the most part derived from model simulations using only a couple of comprehensive Earth System Models (Chapter 2). Many shortcomings still exist in terms of the complexity of the modelling systems themselves that still limits our understanding of processes important for assessing SAI approaches our ability to reach prescribed climate targets, and the understanding of the detectability of climate impacts. Furthermore, experiment or scenario design for climate intervention model experiments often lacks the consideration of economic and technical limitations and geopolitical considerations, including interactions with human systems. These shortcomings and limitations will also lead to shortcomings in our understanding on the climate impacts, which translates to impacts on both natural and human systems.

Tilmes et al. (2024, in revision) have outlined criteria to guide a comprehensive assessment process for SAI research, which includes technical and design requirements, detailed assessment criteria for response and impacts for SAI application, and the consideration of societal considerations. The technical and design requirements include technical and economical limitations, radiative cooling potential, ability to reach climate targets, monitoring detectability, and attribution. The assessment of responses and impacts includes large-scale and regional climate response and the impacts on the human and natural systems. Finally, the paper by Tilmes et al (2024) discusses the need to include societal considerations in such an assessment, including societal risks and the mitigation of risks through governance, and recommends the establishment of re-occurring assessments to be set into place to move important science forward and to inform policymakers on the status of the current research regularly.

Technical feasibility and limitations are often discussed as an afterthought of suggested SAI applications. However, details on technical and economic feasibility need to be included in the experimental (scenario) design. Technical feasibility has to be considered from the start when developing plausible SAI scenarios. For example, previous work has demonstrated that the deployment of SAI is technically possible using aircraft that can reach into the stratosphere (at around 20km altitude) and inject aerosols or their pre-cursors (Bingaman et al., 2020). However, there may be injection methods that are much more unlikely or costly to be either developed in time or able to inject a sufficient amount of aerosol to have a meaningful impact such as balloons (Smith & Wagner, 2018). Other methods that may be currently dismissed as viable options, for example, rockets, may be developed in the future as delivery platforms for large-scale applications. The consideration of economic and technical feasibility also needs to consider ranges of needed injection amounts based on different assumptions of climate sensitivity in models and differences in the strategies, including type of material, location, and timing.

Shortcomings and differences in the inclusion of physical processes and parameterisations in ESM that are important for SAI can lead to large differences in how much cooling can be achieved per injection amount (see Chapter 2). In recent decades, ESMs have focussed more on climate effects and less on chemistry and aerosol microphysics in the stratosphere due to a reduced focus on the ozone layer. However, stratospheric chemistry and dynamics play an important role in terms of climate impacts and predictability and are especially important to study the effects of SAI. Furthermore, SAI approaches require very detailed descriptions of aerosol formation, transport, removal, and its interactions with radiation and chemistry. A new focus on middle-atmospheric (stratospheric) processes for ESMs is required to develop more state-of-the-art models that are able to represent SAI and their impacts comprehensively. Detailed model assessments of stratospheric processes that were performed (CCMVal in 2010) have not been performed in the same detailed way since the previous assessment. These types of in-depth assessments would help identify many differences in models that can lead to differences in assessing the effects of SAI. For example, differences in stratospheric transport in models may lead to different aerosol distributions with SAI and therefore cooling effects that change the controllability of the climate in these models (Henry et al., 2023). To gain more confidence in the modelling of SAI impacts a focus research programme is needed that supports major improvements of stratospheric processes and aerosol-chemistry interactions in models. In addition, interactive chemistry modelling in the troposphere needs to be a focus of improvements in order to identify impacts on human health (including changes in UV, air pollution like ozone and pm2.5). In addition to the need to improve atmospheric modelling processes, improved coupling processes to other components, including ocean, ice, and land are needed for both climate change research and SAI. Many ESMs currently prescribe concentrations of CO2, nitrogen, and other processes like fire emissions. However, the carbon and nitrogen cycle may change differently in the future with or without SAI (see Chapter 2).

Furthermore, multi-model intercomparison projects are needed to, for example, evaluate comprehensive microphysical schemes based on observations e.g. after volcanic eruptions (SPARC Hung Tonga Activity) and can further reduce uncertainties in modelling the effects of SAI. These types of activities would also require observing systems that would focus more on stratospheric aerosol and chemistry, including continuously observing satellites that do not exist currently, and in-situ observations, as well as more direct observations after the occurrence of volcanic eruptions and pyrogenic thunderstorms (pyroCb) events that injection aerosols like black carbon and soot into the atmosphere. Volcanic eruptions and pyroCb can serve very well as natural tests for SAI and do not required artificial injection experiments at present to improve models.

Other model experiments have been designed that focus on evaluating differences in aerosol microphysics in models (Laakso et al., 2023, 2024), as well as prescribing stratospheric aerosols to understand differences in models regarding the effects of SAI on stratospheric dynamics and chemistry (Plummer et al., 2021). In addition to process-level studies, comprehensive model simulations are required to simulate policy-relevant scenarios that can be directly compared to future simulations without SAI, as performed by the GeoMIP community (Visioni et al., 2023). Impact-relevant simulations are required to understand climate impacts and effects on natural and human systems. Impact modelling is another important aspect. Impact models use output from ESMs to derive small-scale impacts over specific regions of interest (Menk et al., 2022). It is important to provide these impact assessment modellers with different potential future SAI scenarios based on multi-model results in order to perform comprehensive risk-to-risk assessments and with that identify the possible range of outcomes depending on the specific application of SAI. As outlined above, the impacts of SAI strongly depend on how SAI may be applied and are strongly model-dependent.

The representation of cloud processes in Earth system models is coarse and most processes are included only via parameterisations. This leads to large uncertainties in anticipating the effects of both CB and CCT (and even more so, MCT). A possible way forward is the application of high-resolution modelling that improve many long-standing problems in simulating clouds and the hydrological cycle more generally (Stevens et al, 2020). In Europe, pertinent development efforts are pursued for weather and seasonal prediction timescales (Bauer et al., 2021), and international efforts are undertaken towards operational kilometre-resolution climate models at global scale (Stevens et al., 2024).

Since still for the foreseeable future, global simulations at timescales of decades and longer will not reach resolutions that allow us to represent cloud-scale dynamics (i.e. large-eddy simulations with resolutions better than 100m), an option may be to learn, via machine-learning approaches, the effect of such processes from data (Schneider et al., 2017; Yuval & O'Gorman, 2020). However, the microphysical processes at the origin of the effects that are considered in CB and CCT/MCT will remain unsolved, and insights most likely have to come from observations and field campaigns (see Laboratory and field campaigns for cloud brightening).

A specific question is how to judge on the model quality. In essence, a climate model cannot be validated (Oreskes et al., 1994). A workaround is the consideration of models as 'fit for purpose' (Chen et al., 2021). However, in the context of SRM, there needs to be acceptance that a model is fit in this sense. All parties relating to an SRM deployment or even an experiment would need to agree on the fitness for purpose of a model so that sharing of costs for beneficial impacts as well as compensation payments for detrimental impacts could be decided upon (e.g. Quaas et al., 2016; Pfrommer et al, 2019). Not just atmospheric/climate effects should be anticipated, but also impacts need to be attributable (Chen et al., 2021). Subtle effects and teleconnections are expected for regional climate engineering, causing effects even far outside the target region (Dipu et al., 2021). In the early assessment by Kellogg and Schneider (1974), the postulation is to "establish conclusively cause and effect linkages", and a possible solution for assessment could be to establish a "formally assembled body of impartial experts".

Satellite observations and monitoring

Applying SRM solutions for the mitigation of climate change would demand global, accurate and continuous monitoring of the levels of stratospheric aerosols and/or clouds to:

- monitor the transferring, the dispersion, the transformation, and the removal rate of aerosol particles in the stratosphere
- optimise the timing, the frequency, and the locations of aerosol injections
- monitor the cloud extent and radiative properties in assessment of CB and CCT/MCT

In addition, monitoring of chemical components, especially in the stratosphere, would be needed to identify impacts on the ozone layer, and detailed information of climate impacts.

Information for the properties of stratospheric aerosols and chemistry can be retrieved using in-situ observations (e.g. samplers on balloons or aircraft), active (e.g. lidars) remote sensing from the Earth's surface, or satellite-based remote sensing platforms. In-situ observations can provide vertical profiles of details of properties such as the particle mass or number concentration (e.g. Todt et al, 2023) but provide only limited samples in space and time. Lidars can provide information for the vertical profile of optical properties such as the aerosol backscatter and extinction coefficients (e.g. Khaykin et al., 2017; Langenbach et al., 2019; Trickl et al., 2023; Vaughan et al., 2021). The first in-situ observations of stratospheric aerosols were performed in the early 1960s (Junge et al, 1961; Rosen, 1964). Systematic in-situ observations (e.g. Hofmann et al., 1975; Pinnick et al., 1976), as well as observations using lidars (e.g. Allen & Evans, 2003; Fernald et al., 1972; Schuster, 1970) began in the 1970s. The potential of spectroradiometric ground-based networks to monitor volcanic SO2 plumes has been discussed in the paper of Zerefos et al (2017). Ground-based radiometers and spectroradiometers can provide information for columnar SO2 and columnar aerosol optical properties, but they do not provide any information for their vertical distribution and aerosol properties like size distributions (Deshler et al, 2003). As for aerosols, cloud optical and microphysical properties can be monitored either using in-situ observations, or from the ground (using weather radars, lidars, infrared radiometers, sky-cameras), or from space (using instruments aboard satellite platforms). Lidars can provide information for the vertical profiles of cloud optical and microphysical properties over a specific location (e.g. Giannakaki et al., 2007), while cloud radars can provide similar information in two or three dimensions (e.g. Fielding et al., 2013; Maki et al., 2021). Infrared radiometers provide information for the columnar average optical and near-cloud-top microphysical properties of clouds (e.g. Nakajima & King, 1990; Platnick et al., 2017), and sky cameras can provide information for the cloud coverage and type. In many cases, synergies of different sensors have been used to retrieve more detailed information for clouds from the ground (e.g. Delanoë & Hogan, 2008).

Despite the progress in the technology of in-situ and lidar measurements since the 1970s, the only way to achieve continuous global monitoring of stratospheric aerosols is by using instruments aboard satellite platforms. Satellite-based measurements of stratospheric aerosols started in the late 1970s (e.g. Kent & McCormick, 1984; Mauldin III et al., 1985;). Cloud cover observations started in 1960 (Sylvain et al, 2023), while retrievals of cloud optical properties have been performed since the late 1970s (Goodman & Henderson-Sellers, 1988), in many cases by the same sensors that are used to retrieve aerosol optical properties. Currently, many passive sensors aboard satellites, including sensors onboard European satellites, can retrieve columnar aerosol and/or cloud properties from space providing global coverage, without however being able to discriminate between the tropospheric and stratospheric aerosol components or provide information for the distribution of microphysical cloud properties. Information for the vertical profiles of aerosol and cloud optical and microphysical properties can be currently retrieved by satellite instruments with particular characteristics that employ different techniques: (1) instruments that measure scattered radiation, (2) instruments that employ solar, lunar and stellar occultation techniques, and (3) instruments that use lidar techniques. Satellite-borne instruments that are currently in orbit and can provide information for stratospheric aerosol are described in the following.

Instruments that measure scattered radiation

The Ozone Mapping and Profiler Suite Limb Profiler (OMPS/LP) (Jaross et al., 2014) has been flying aboard the Suomi National Polar-orbiting Partnership (S-NPP) satellite since 2011, on a sun-synchronous polar orbit. It produces aerosol vertical profiles at a 1.6 km resolution over the entire sunlit globe, for altitudes 0-80km. The currently used aerosol extinction retrieval algorithm provides aerosol extinction profiles at 675nm (Chen et al., 2018, 2020; Loughman et al., 2018).

The Optical Spectrograph and InfraRed Imager System (OSIRIS) is mounted on the Odin satellite, which moves into a Sun-synchronous orbit at an altitude of around 600km. Since 2001 it measures vertical profiles of spectrally dispersed, limb scattered sunlight from the upper troposphere into the lower mesosphere. The measurements are used to retrieve vertical profiles of stratospheric aerosol extinction at 750nm (Bourassa et al., 2012). The instrument's orbit restricts observations to the Northern hemisphere in the months May to August, and the Southern hemisphere in the months November to February, and near global coverage is achieved only on the months adjoining the equinoxes.

Instruments that measure atmospheric chemistry important for stratospheric ozone

There are currently two main satellite instruments that have focused on the chemistry and dynamical processes in the stratosphere, with a particular emphasis on ozone and other relevant chemical tracers (Manney et al., 2009; 2022). The Atmospheric Chemistry Experiment (ACE) uses Fourier transform infrared spectroscopy of sunlight during sunrise and sunset. It provides ozone and other important trace gases (including chlorinated species) important to assess the evaluation and health of the ozone layer, mandated by the Montreal Protocol on Substances That Destroy the Ozone Layer. This instrument also detects the effects of volcanic eruptions on stratospheric chemistry and therefore relevant for understanding SAI processes. It is already 20 years old and does not have a replacement if it is to stop working. Likewise, the Microwave Limb Sounder (MLS) is measuring stratospheric constituencies. This instrument has a wider range in the horizontal than ACE but is not as detailed in scanning the vertical distribution of tracers in the stratosphere. As ACE, MLS is measuring a wealth of tracer important for assessing the evolution of the ozone layer and is at the end of its lifetime. There is not a replacement in sight, which would be critical to assess the effects of volcanoes and therefore SAI on the ozone layer.

Instruments that employ occultation techniques

The Stratospheric Aerosol and Gas Experiment III on the International Space Station (SAGE III/ISS) mission provides high-vertical resolution and nearly global observations of aerosols, as well as ozone, water vapour, nitrogen dioxide, and other trace gas species in the stratosphere and upper-troposphere. SAGE III/ISS was launched in 2017 and aims to extend the long-term Stratospheric Aerosol Measurement (SAM) and SAGE data record that begun in the 1970s (Cisewski et al., 2014). It makes sunrise and sunset occultation measurements and covers latitudes between 70° S and 70° N. SAGE III/ISS uses the algorithm described by (McCormick et al., 1979) and provides aerosol extinction at nine wavelengths (384.2, 448.5, 520.5, 601.6, 676.0, 756.0, 869.2, 1021.2, and 1544.0 nm) with a vertical resolution of 0.5 km for altitudes between the surface (or cloud top) to 45 km.

Instruments that employ lidar techniques

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite was launched in 2006 jointly by NASA and the French National Centre for Space Studies (CNES). It performs global profiling of aerosols and clouds in the troposphere and lower stratosphere (altitudes below 40km) with a very high vertical resolution of around 30 m below and a horizontal resolution of 335 m (Winker et al, 2009). CALIOP is a polarisation lidar that produces simultaneous coaligned pulses at 1064 and 532 nm. The identification of aerosol and cloud layers and the retrieval of cloud and aerosol optical and microphysical properties are achieved using a suite of algorithms that has been developed for that purpose (e.g. Omar et al., 2007, 2004).

Passive visible-infrared (VIS-IR) imagers

Such satellite sensors have been widely used in the past decades and are currently being used to retrieve information for cloud types and (columnar) cloud optical and microphysical properties (e.g. Stengel et al, 2017). In the following we provide additional information for three sensors that measure at high spatial resolution and their measurements are widely used for the retrieval of cloud optical properties.

Spinning Enhanced Visible and Infrared Imager (SEVIRI), on board the geostationary Meteosat Second Generation (MSG) satellites provides such information on fine spatial and temporal resolution. SEVIRI measures in eight InfraRed (IR) and four Visible and Near-InfraRed (VNIR) channels. It provides continuous imaging of the Earth with a baseline repeat cycle of 15 min, with an imaging sampling distance of 3km at the sub-satellite point for standard channels (Benas et al, 2017). Measurements from SEVIRI have been continuously available since 2004, and have been exploited to retrieve cloud optical properties such as cloud optical thickness, cloud type, etc.

Another passive imager that currently provides information for clouds is the Advanced Very High-Resolution Radiometer (AVHRR) aboard MetOp-A, that was launched in 2006, and is the Europe's first polar orbiting operational meteorological satellite system. AVHRR has been launched on different NOAA and EUMETSAT satellites since 1978 (Karlsson et al., 2023). It is a cross-track scanning system with five spectral bands that scans Earth twice a day with a spatial resolution of 1.1km. AVHRR measurements have been exploited to retrieve cloud optical and microphysical properties (e.g.; Karlsson et al., 2023; Kawamoto et al., 2001; Simpson & Gobat, 1996).

Measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the NASA's Terra and Aqua satellites are widely used to retrieve cloud optical properties (e.g. Platnick et al., 2015; 2017) as well as aerosol properties (Levy et al., 2013). MODIS measures in 36 bands, continuously since the beginning of the 21st century and acquires data at three spatial resolutions: 250m, 500m, and 1000m. Terra and Aqua orbit Earth with a frequency that results in two MODIS overpasses daily. Important additional information about both aerosols and clouds may come from multi-angle measurements, such as from the Multi-Angle Imaging Spectroradiometer (MISR, Moroney et al., 2002; Kahn et al., 2010) and from polarimeters such as the POLarization and Directionality of the Earth's Reflectances (POLDER) (Buriez et al., 1997; Deuzé et al., 2000; Hasekamp et al., 2019; Tanré et al., 2011).

Based on more than 40 years of extinction coefficient measurements from different sensors, the Global Space-based Stratospheric Aerosol Climatology (GloSSAC) (Kovilakam et al., 2020, 2023) has been constructed, and can be used to study stratospheric aerosols and their impact since 1979. The GloSSAC was developed to support the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). Measurements by the Stratospheric Aerosol and Gas Experiment (SAGE) series of instruments have been used for 1979-2005, while for the years after 2005 measurements from the Optical Spectrograph and InfraRed Imager System (OSIRIS) (Llewellyn et al., 2004) and the CALIPSO (Winker et al., 2009) have been exploited. Data from ground-based, air and balloon borne instruments, and other space instruments have been used to fill in key gaps in the dataset.

Measured aerosol extinction coefficient profiles are also available for the past by satellite sensors that do not operate any more. For example, the Global Ozone Monitoring by Occultation of Stars (GOMOS) instrument on board the Envisat satellite has provided the aerosol extinction profile at altitudes 10-40km for the period 2002-2012 (Sofieva et al., 2023). The Laser Doppler Instrument (ALADIN) aboard Aeolus satellite was the first high-spectral-resolution lidar (HSRL) in space. Aeolus was launched in 2018 and orbited in a sun-synchronous, dusk/dawn orbit, 320km above Earth, aiming to acquire profiles of Earth's wind on a global scale. Nevertheless, its measurements have been also used to derive aerosol optical properties (Flament et al., 2021; Gkikas et al., 2023; Rizos et al., 2023;). The Aeolus mission ended recently (July 2023).

The cloud Properties -- International Satellite Cloud Climatology Project (ISCCP) H-SERIES Climate Data Record (CDR) from NASA (Young et al, 2018) was established in 1982 as part of the World Climate Research Program (WCRP) and focuses on the distribution and variation of cloud radiative properties to improve understanding and modelling of the way clouds affect climate. It currently extends from 1983 to 2018 and has been created using data from different imaging radiometers aboard operational weather satellites (e.g. the Advanced Very High-Resolution Radiometer, AVHRR). Cloud information (cloud amount, cloud-top temperature, cloud-top pressure, cloud optical thickness, cloud water path, cloud phase, cloud type) is available on a 10 km grid on a 3-hourly temporal resolution on a global scale. Other cloud products such as the Earth Observing System (EOS) series satellite cloud products (references), the National Oceanic and Atmospheric Administration (NOAA) series satellite cloud products (references), the Cloud Detecting Satellite (CloudSat) cloud products (references), and other have been also created in the last decades by exploiting remote sensing information and are available for research.

As the term 'SRM' indicates, the concept targets the Earth radiation budget. The effectiveness of SRM thus has to be observable in Earth radiation budget (ERB) observations (e.g. Seidel et al., 2014). This is advantageous since ERB satellite observations are particularly stable for monitoring (e.g. the CERES instrument; Corbett & Loeb, 2015). An instrument like CERES will after a short time detect large-scale deployment of SRM in either method. Also, largescale field experiments are detectable but only if they have a substantial effect (Seidel et al, 2014). The main ERB instruments (CERES) are US-American. There will be an ERB instrument onboard the ESA-JAXA EarthCARE satellite for launch in 2024 (broadband radiometer, BBR), but EarthCARE is designed for a lifetime of only 3 years.

Recent and future missions

The Earth Cloud Aerosol and Radiation Explorer (EarthCARE) satellite mission that has been jointly organised by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) is expected to provide new, high-quality information on a high vertical resolution for aerosols and clouds, including stratospheric aerosol optical properties. Combined measurements from the different sensors aboard the EarthCARE (which is equipped with four instruments: a lidar, a radar, an imager and a broad-band radiometer) will allow to identify different aerosol species (Illingworth et al, 2015; Wehr et al., 2023). EarthCARE was launched in May 2024. EarthCARE will provide global coverage moving in a near-polar orbit at an altitude of 393km.

The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) satellite mission by the US National Aeronautics and Space Administration (NASA) has been launched very recently (February 2024). NASA-PACE will continue and advance observations of global ocean colour, biogeochemistry, and ecology, as well as the carbon cycle, aerosols and clouds. PACE will operate in a sun-synchronous, polar orbit about 675km above the Earth's surface and will orbit the Earth once every 98.3 minutes. The PACE mission will be equipped with an optical spectrometer (Ocean Color Instrument; OCI) and two polarimeters, the Spectro-polarimeter for Planetary Exploration (SPEXone) and the Hyper Angular Research Polarimeter (HARP2).[^1] By combining measurements from the three sensors, it will be possible to retrieve various optical properties of aerosols and clouds, as well as to characterise tropospheric and stratospheric aerosols (Hasekamp et al., 2019).

The 'multi-viewing, multi-channel, multi-polarization imaging'"' (3MI) instrument combines the information content from spectral resolution, angular distribution and polarisation (Marbach et al, 2018). This instrument will be operational on the European EUMETSAT satellite Metop Second Generation and thus will allow for monitoring of detailed properties of clouds and tropospheric aerosols.

Uncertainties and needs

Despite the significant progress in the stratospheric aerosol monitoring in the last two decades, changes of less than 20% in stratospheric AOD levels cannot be detected confidently (Kremser et al., 2016). Wrana et al (2021) estimated the size distribution of stratospheric aerosols using measurements from SAGE III and reported errors at the peak of the stratospheric aerosol layer, that on average, lie between 20 % and 25 % for the median radius and 5 % and 7 % for the mode width. (Tackett et al., 2023) discussed an updated algorithm to classify aerosol types from CALIOP and reported that one of the weaknesses of the algorithm is that mixtures of ash and sulphate aerosols can be misclassified as smoke. In general, the development of algorithms that synergistically exploit measurements from different sensors, more closure studies, and algorithm improvement are needed to achieve more accurate classification and retrieval of stratospheric aerosol properties (Wandinger et al., 2023). The use of polarimetric instruments in future satellite missions is expected to increase the accuracy in the measurements of stratospheric aerosol properties and could be a useful tool for the monitoring of injected aerosols (either due to volcanic eruptions or for SRM) (Mishchenko et al., 2019).

The detection and accurate parametrisation of multi-layered cloud is one of the biggest challenges, even for the most advanced imagers and sounders (Marchant et al., 2020). As for aerosols, synergistic approaches are necessary to improve the accuracy in the retrievals of cloud properties. Future missions of polarimetric satellite sensors and the use of novel techniques are also promising towards the improvement in the retrievals of cloud properties (Yuan et al., 2023).

Several satellites that can retrieve information on stratospheric composition (e.g. ACE, MLS) are currently operational (Manney et al., 2009; 2022; Santee et al., 2009). However, these satellite instruments have reached their lifetime and new satellites have not been launched, leading to a hiatus of stratospheric chemistry information in the near future.

Laboratory and field campaigns for cloud brightening

Many observational campaigns and opportunistic studies of unintended cloud adjustments (e.g. ship-tracks) were performed in the past to enhance our understanding of aerosol-cloud interaction, and its implication for climate and weather, but only a few experiments directly aiming at CB, most notably the recent work for the restoration of the Great Barrier Reef. Only global climate models can be used to assess the largescale impact of CB. The representation of clouds and aerosols in such models is however not sufficient, due to the incompatibility of temporal and spatial scales of cloud-aerosol processes and model resolutions. Climate models need to be augmented with high-resolution LES models to zoom in on smaller scale features, that in turn need knowledge about aerosol-cloud interaction processes obtained from parcel (box) models. As described in [NRC, 2015], models exhibit discrepancies among themselves and with observations of clouds, aerosols, and their interactions. To address these issues, the following specific studies are suggested:

- Conducting model studies designed to replicate field studies, especially controlled emission studies, can unveil specific reasons for discrepancies.
- Improving intercomparisons between climate models, utilising diverse treatments of aerosol microphysics (regarding type, amount, and altitude of aerosol emissions) would aid in

understanding the reasons behind climate simulation differences, reducing model uncertainties and improving projections of climate consequences.
- Comparing global-scale model formulations of aerosol, clouds, and aerosol dispersion in the sub-cloud layer with finer-scale models (LES, aerosol dynamics, and plume models) could be beneficial. This comparison challenges the simplified formulations in global models with the more detailed ones in fine-scale models.

Feingold et al, (2022; 2024) report on the state-of-the-art of CB and make recommendations for field campaigns and model studies:

- Laboratory work involving cloud chambers are needed to address knowledge gaps concerning activation, droplet growth, entrainment, cloud processing, collision-coalescence onset, and the potential impact of Giant CCNs.

While analogues to CB experiments, like effusive volcanoes and ship tracks, provide valuable insights into aerosol-cloud interactions, they are however only partially representative from CB. So-called *perturbation-oriented* field experiments are required to investigate and test components of CB, most notably:

- sea-spraying technology from an ocean-based platform, optimising particle size distribution to prevent excessive cloud water evaporation
- assessing vertical mixing and aerosol transport towards the cloud base under various meteorological conditions, and the impact of evaporative cooling on buoyancy
- employing aircraft, drones and remote sensing (ground-based and from space) for measuring microphysical properties in perturbed and unperturbed clouds
- conducting closure studies to compare observed drop concentrations with model predications, based on actual aerosol-size distribution and composition methods
- performing closure studies to assess how aerosol and cloud microphysical properties align with radiative properties measure directly
- including detailed modelling of the cloud system in perturbed and unperturbed regions to evaluate microphysical responses, cloud fraction adjustments, and radiative responses
- employing statistical sampling and analysis in atmospheric observations to represent a realistic range of conditions

Part 2: Actors and public perceptions, feasibility conditions and constraints, and options for multilevel governance

The reports by IPCC (2023) and to lesser extent, UNEP (2023) offer the most recent comprehensive global evidence-based review of some of the key aspects of SRM techniques and their governance. These reports stress the importance of mitigation of emissions and adaptation to human-induced climate change, but they also highlight the increasing interest concerning SRM as a possible supplementary strategy to alleviate certain impacts and prevent the global temperature from surpassing certain thresholds that are considered dangerous as they may lead to low-likelihood but high-risk rapid climate changes ("tipping-points"). The reports also highlight the model-based evidence showing theoretical efficiency of SRM methods in offsetting some of the effects of GHG, within years from initial deployment.

They also highlight the limitations of SRM, including side-effects such as potential change to the ozone layer (WMO, 2022), alterations of regional climate, and societal aspects such as exacerbation of power imbalances among nations. These reports emphasise the need for international scientific review and governance processes to assess the benefits, risks, uncertainties, and ethical considerations associated with SRM. The UNEP (2023) report provides recommendations concerning the need of governance for both small-scale outdoor experimentation and large-scale deployment of SRM, and the need of a broader framework for governing the stratosphere, including the impacts of SRM experiments. While SRMs may offer the capacity to reduce temperature increases globally or regionally, depending on the technology in question, these reports conclude that careful consideration of its impacts, risks, and governance mechanisms is paramount, even before any deployment of SRM.

Discussions around governance of SRM and the most appropriate approaches have generally employed the broad distinction between research activities and deployment (Bellamy et al., 2017; Bellamy & Healey, 2018; Pidgeon et al., 2013; Smith & Henly, 2021; Victor, 2008). Keith (2013) even proposes four different stages of work, from (i) theory and laboratory work based on climate models, up to (ii) very small-scale atmospheric experiments designed to test the theoretical conclusions reached via models and simulations; (iii) operationalisation of SRM projects on the smallest scale from which to gather empirical data for proceeding with subsequent gradual deployment; and (iv) gradual deployment, combined with other approaches to counter climate change. A longer development phase between (iii) smallest scale empirical tests to (iv) deployment, would be envisaged.

The distinction between research and deployment was inherited from an early desire of some researchers to propose, explore, and examine (in a modelling or laboratory-centred sense) potential SRM options. Such a distinction of "research" from "deployment" was intended to carve out a defined space in which research activities could be permitted to occur, with the caveat that this should not prejudice decisions on potential deployment.

Equally, this distinction has, in a sense, been motivated by the criticism and controversy which the (implicit) consideration of SRM has invited. Some have, for instance, invoked the possibility of a 'slippery slope' whereby funding and engaging in research could inevitably lead to deployment (Biermann et al., 2022; Callies, 2019; Pidgeon et al, 2013; Smith & Henly 2021; Tang, 2023). Potential triggering mechanisms that could trigger a slippery slope could include: increasingly severe climate impacts, or the unilateral deployment, e.g. by a rogue state or non-state actor (Grieger et al., 2019; Smith & Henly, 2021; Sovacool et al., 2023; Victor, 2008). Concerns over a possible slippery slope have also underpinned the criticisms from environmental NGOs and indigenous groups, most saliently, with regard to the SCoPEx project. Led by a team of researchers at Harvard University (in collaboration with the Swedish Space Agency), the project announced field trials wherein some of the components set to be used for future SAI activities would be tested -- notably, on Sámi lands (Oksanen, 2023). In the wake of substantial backlash, the experiment was at first postponed, and in March 2024, SCoPEx, as a solar geoengineering initiative, was abandoned. This makes it the latest project on SAI to be cancelled, following the SPICE trial in the United Kingdom. Partly lending credence to concerns over unilateral deployment by a non-state actor, the first (unauthorised) field trials on SAI are now underway -- not led by universities but rather commercial actors. The one that has garnered the most attention (and criticism) is a Silicon Valley-based start-up, Make Sunsets, which conducted trials in late 2022 in Baja

California, Mexico, without prior authorisation by the Mexican government. Mexico's subsequent response was to place a ban on future SAI activities on its territory, until some kind of international agreement is in place. Make Sunsets is currently undertaking activities in the western United States of America, prompting renewed discussion of the need for a more rigorous regulatory framework in the United States as well (Calma, 2023; De La Garza, 2023; Temple, 2022).

Accordingly, as attention to SRM has increased, critiques of the distinction between research and deployment have followed. McLaren and Corry (2021) stress that researching SRM is not neutral in relation to future deployment as it influences "the criteria and targets for their assessment; the scenarios in which they might be deployed; the publics which may support or oppose them; their political implications for other climate responses [including mitigation], and the international relations, governance mechanisms, (...) that are presumed in order to regulate them". Lock-in mechanisms, including cognitive lock-in of ideas and pathways is a widely recognised risk in ways that technical and social systems evolve (Cairns, 2016).

The literature also suggests that a licence for certain types of research (particularly if public funding is received) may establish implicitly the conditions for future deployment to occur (e.g. while there are questions whether enough can be learned about certain SRM options, SAI in particular, without full-scale deployment (Biermann et al 2022), some note that there are no-regret research endeavours which may reduce uncertainties without necessarily advancing toward deployment capability (Honegger et al., 2021; Hulme, 2014; Robock et al., 2010; UNEP, 2023).

Some literature that stresses the fact, that if more funding for research was available using large numerical models and observations (e.g. from erupting volcanoes) more confidence can be gained in our understanding of potential impacts. For example, the US government-funded NOAA Earth Radiation Budget programme focusses currently on improving the understanding of the background atmosphere, and on improving numerical models. It argues that funding does not need to imply any future deployment and in contrast could prevent it.

Meanwhile, others argue that 'research' versus 'deployment' matters less than the type of research that is undertaken, notably, whether 'indoor' or 'outdoor' (e.g. MacMartin & Kravitz, 2019; Smith, 2018). Some therefore argue that what constitutes a permissible experiment versus unreasonable deployment is a line "so blurry it is meaningless" (Smith & Henly, 2021). The question is here that the term 'permissible' is interpreted differently by different stakeholders. How to appropriately categorise 'research' for research governance purposes thus remains an open question: A new Horizon Europe project "Conditions for Responsible Research of SRM -- Analysis, Co-Creation, and Ethos" (Co-CREATE) is therefore examining the question of desirability against a broader array of scientific merit, physical and political risk and other values elicited in stakeholder deliberations to move away from simplistic dichotomies of field experiments versus non-experimental research (European Commission, 2023).

While giving due regard to the critiques discussed above, we discuss both governance of 'research' and 'deployment' in the current chapter for several reasons. First, it remains helpful for making clear differentiation in the scale and purposes of ongoing activities (e.g. MacMartin & Kravitz, 2019), offering a terminology for the discussion of such differences. Second, this distinction is reflected (even if implicitly) in the most discussed governance frameworks for SRM, even if only to underscore the need for governance to be in place before deployment occurs (Grieger et al., 2019; Oxford Geoengineering Programme, 2019). Third, such a distinction prevails in sense-making of experts (e.g. Bellamy et al, 2017) and public perceptions of SRM (Baum et al, 2024; Merk et al 2019).

Retaining this discussion is thus deemed appropriate to reflect the existing literature and to facilitate engagement and communication with policymakers and stakeholders. Giving due regard to criticisms, it should at the same time be recognised that this distinction is itself malleable and is, in effect, itself a tool of governance with potential risks including that it may exaggerate the separation of two activities that in practice are deeply linked. The distinction between research and deployment will be different for the different SRM methods, and also in view of regional versus global applications. At the same time, the analysis of governance options in Chapters 7 and 8 will distinguish, where appropriate, between laboratory-based (or 'indoor') research and 'outdoor' field experiments. For the former, fundamental norms on the freedom of scientific research likely stand in the way of regulatory interventions. Things are different for outdoor research, where potential environmental impacts give rise to different sets of considerations.

This part of the report proceeds as follows:

- Chapter 5 focuses on elements of the sociotechnical system such as actor networks and interest groups, community and social perceptions, and expert perceptions.
- Chapter 6 examines ethics and justice, economic, institutional, political and security feasibility aspects.
- Chapter 7 describes governance and legal issues relating to research, deployment, and international law.
- Chapter 8 of this report sets out a range of evidence-based options for policy that could be considered by the Group of Chief Scientific Advisors in drafting its Scientific Opinion and policy recommendations.

Chapter 5: Actor networks and interest groups, community and social perceptions, and expert perceptions

Key messages

- SRM has seen a variety of actor coalitions arise to support it, oppose, it or remain ambivalent, and these include state actors such as governments but also commercial actors, civil society groups, scientific bodies, and academic institutions.
- Social science research on public familiarity and social acceptance of SRM is large and growing, though dominated by Germany, the United Kingdom and United States.
- The public largely remains unfamiliar with SRM options and nascent preferences appear to be strongly context dependent, particularly by perceptions and experiences of climate change, and strongly informed by values.
- Main themes emerging from public acceptance studies are moral hazard, 'messing with nature' and unnaturalness, climate exposure, conspiracy thinking and connections to justice and equity, among others.
- Perceptions held by experts and those involved in decisions to fund research, implement policy, or shape deployment outcomes outline rationales in favour of SRM but also several points of concern.

Actor networks and interest groups

Sovacool et al (2024) conducted 125 expert interviews to elicit which actors were seen as most important or influential when it came to SRM research, deployment, and governance. The respondents (12 of them from the Global South) identified governments, followed by scientists and civil society as most relevant, while assigning a low relevance to industry, and a marginal one to the public or indigenous peoples.

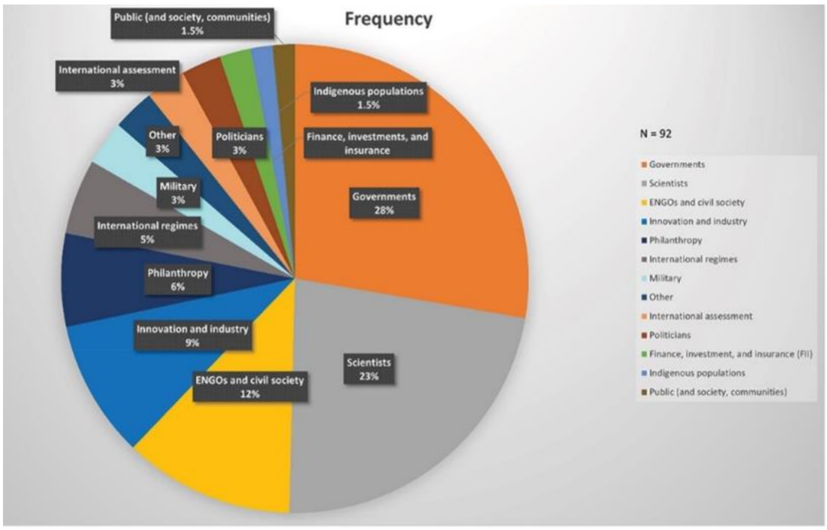


Figure 4: Relevant actor groups for SRM globally from an expert survey. Source: Sovacool et al (2024). Note: 125 experts were asked 'Who are the relevant or most important actors (or stakeholders/networks) for the commercialisation, development, and/or acceptability of solar radiation management technologies?', and 92 answered.

Commercial actors

Despite the potential appeal of SRM to some commercial actors -- when compared to the collective externality of climate change mitigation through emissions cuts and removal of CO2 -- SRM has not yet drawn in serious private investment, i.e. projects remain in the millions to hundreds of millions but not yet the scale ofbillions. Some experimentation labelled by some as 'rogue' has been ongoing by private actors. In April 2022, a US company called 'Make Sunsets' launched a balloon containing sulphur particles on Mexican territory and wanted to sell "cooling credits". After Mexico took steps to prohibit SRM experiments, the company shifted its operations to the US and claims to have launched over 20 balloons to date (Burns & Talati, 2023, p.15). The claimed injection amounts are so tiny, and would have no impact on the climate, as would much larger balloon endeavours since the amounts needed for substantial cooling are on the order of 10-18 megatons of sulphur per year (cooling about 1°C WMO2022), while each balloon can only carry in the range of grams or kilogram. It should be noted that Mexico called in the latest UNEA discussion of a draft SRM resolution (eventually withdrawn) for the international community to condemn such unregulated activities that violate national sovereignty of countries in the strongest possible terms.

Civil society

Non-governmental organisations (NGOs), especially environmental ones (ENGOs) have vocal, but with mixed positions (Reynolds et al, 2016). Some ENGOs cautiously support SRM research while many others are generally against SRM. Several SRM-specific NGOs have been set up recently (Burns & Talati, 2023, p.10-12), yet no other organisation has been around for as long as the DEGREES initiative, which was incorporated as a stand-alone organisation in 2011 from SRMGI, which then had already been operational for a decade run in partnership of the Environmental Defense Fund, the Royal Society and TWAS (under UNESCO). In these two decades the initiative has funded over 150 SRM researchers in the Global South in 26 projects situated in 21 developing countries and its workshops have reached more than 1000 climate experts in developing countries. The 2017-founded Carnegie Climate Governance Initiative, which sought to bring SRM governance challenge to the attention of policymakers has completed its work in 2023. US-based SilverLining advocates for research on SRM, promoting a multi-year research programme with US policymakers. The Alliance for Just Deliberation on Solar Geoengineering seeks to empower civil society in the Global South to participate in SRM-related deliberations. The Climate Overshoot Commission was set up to "propose strategies to mitigate risks should global warming exceed the 1.5°C target" and thus also examined implications of SRM. A moratorium for SRM deployment was suggested until more research has been done.

Many environmental NGOs have taken a public position on SRM. For example, Environmental Defense Fund, Bellona and NRDC) have made statements in support of research activities but not deployment. Meanwhile, other environmental NGOs like Friends of the Earth and the Climate Action Network (CAN) ETC Group, CIEL, and the Heinrich Boell Foundation strongly oppose SRM in general, including research activities. More than 1500 civil society organisations have endorsed the call for an international non-use agreement on solar geoengineering.

Scientific bodies

Some national scientific bodies, largely confined to the US and the UK, have endorsed SRM research. These include the UK Royal Society, the US National Academies, the American Geophysical Union, the American Meteorological Society, and the Institution of Mechanical Engineers (UK). AGU is developing "an ethical framework for climate intervention research", while the World Climate Research Programme has launched a lighthouse activity on SRM.

Academic institutions

A group of over 500 academics from 61 countries have called since 2022 for an International Non-Use Agreement on Solar Geoengineering.[^2] In response, over 100 natural scientists in 2023 signed a letter calling for research.[^3] A third academic public letter and article -- *Call for balance in research and assessment of SRM* -- was issued in 2023 arguing to offer a middle ground (Wieners et al, 2023).[^4]

Government actors

Mexico became the first country in 2023 to ban all outdoor experimentation relating to SRM over its territory. In 2023, the African Ministerial Conference on the Environment (AMCEN) expressed concern over promotion of technologies such as solar radiation management and called for "a global governance mechanism for non-use of solar radiation management". This call for a global non-use mechanism was reiterated strongly in 2024 by the African Group again, supported by other developing countries including Mexico, Vanuatu, Colombia and Fiji, during the recent United Nations Environment Assembly (UNEA6) discussion in Nairobi in February 2024 of a proposed resolution on solar radiation modification, which was withdrawn following lack of agreement among governments.

The European Parliament in November 2023 noted in the lead-up to the Conference of the Parties to the UNFCCC (COP28) that 'there is growing scientific and political interest in solar radiation modification (SRM) as a set of climate engineering approaches proposed to artificially reflect sunlight and cool the planet, such as stratospheric aerosol injection; stresses that SRM does not address the root cause of climate change and is not an alternative to mitigation efforts [...and] calls on the Commission and the member states to initiate a non-use agreement at international level, in accordance with the precautionary principle and in the absence of evidence of its safety and a full global consensus on its acceptability".[^5]

Public and social perceptions

An examination of the literature on public and social perceptions of the acceptability of SRM technologies reveals about 60 studies, pointing to a definite and increasing relevance of the topic at the European level. The two countries examined most often in the literature are the United Kingdom (23 appearances) and United States (21), with Germany the third-most examined (13) (see Table 1 below). These three countries dominate, with no other country having more than five appearances.

However, there is a relatively strong scope of SAI perceptions research in the European Union, with fourteen of the EU-27 countries appearing at least once: the studies found include the thirteen on Germany, three on Sweden, two each on Austria, Netherlands, Portugal, Spain, Finland, and Italy, and one each for Ireland,, France, Poland, Greece, , Denmark, and Estonia. Members of the European Economic Area (Norway, three), the Single Market (Switzerland, five), and accession candidates (Turkey, twice) have also been examined.

Table 1. Consulted literature on social and public perceptions of, and attitudes towards, SRM technologies

Authors	**Year**	**Country focus**	**Technology (only SRM methods listed)**	**Methods**
Shepherd	2009	UK	Geoengineering in general	Four focus groups + opinion poll (1000 respondents) + specialist workshop
Ipsos MORI (NERC)	2010	UK		Workshops in 3 UK cities (85 participants) + final event; discussion groups; online survey (65 respondents); open access events
Bellamy & Hulme	2011	UK	Geoengineering in general	Email questionnaire (287 participants - students) + focus groups (15 participants - students)
Mercer et al	2011	UK, US, Canada	SRM in general	Survey (3105 participants)
Borick & Rabe	2012	US	SRM in general	Survey (887 participants)
Bostrom et al	2012	Austria, Bangladesh, Finland, Germany, Norway, USA	Stratospheric aerosol injection	Survey (664 participants - economics undergraduate students)
Pidgeon et al	2012	UK	Geoengineering in general	Semi-structured interviews (53 participants); Survey (1822 participants)
Hiller & Renn	2012	Germany	Geoengineering in general	International media analysis, 2008-2010
Corner et al	2013	UK	Geoengineering in general (including Stratospheric aerosol injection)	Deliberative workshops in 4 UK cities (11x4 participants)
Pidgeon et al	2013	UK	Stratospheric aerosol injection	Deliberative workshops in 3 UK cities (32 participants, in three groups)
Macnaghten & Szerszynski	2013	UK	SRM in general	Deliberative focus groups in 3 UK cities (around 50 participants, in seven groups)
Corner & Pidgeon	2014	UK	Geoengineering in general	Survey experiment: three treatment groups (610 participants)
Scheer & Renn	2014	Germany	Geoengineering in general	Literature review and Group Delphi workshop for experts
Wright et al	2014	New Zealand, Australia (quantitative)	Stratospheric aerosol injection; Cloud brightening; Mirrors in space	Semi-structured interviews (30 participants) and quantitative brand image analysis (2028 participants)
Amelung & Funke	2015	Germany	Geoengineering in general (interview) and Stratospheric aerosol injection, Marine cloud brightening	Semi-structured interviews and budget-allocation task (98 participants - students)
Corner & Pidgeon	2015	UK	Stratospheric aerosol injection	Survey experiment: two treatment groups (412 participants)
Kahan et al	2015	US, England	Geoengineering in general	Survey experiment: three treatment groups (3000 participants)
Merk et al	2015	Germany	Stratospheric aerosol injection	Online survey (1040 participants)

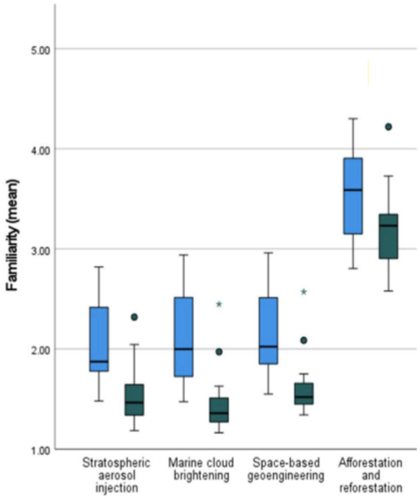
Wibeck et al	2015	Sweden	Geoengineering in general	Focus groups (45 participants, in eight groups)
Bellamy et al	2016	UK	Stratospheric aerosol injection; Cloud albedo enhancement; Space reflectors	Two strands: citizens (13) and specialists (12). Citizen workshop; specialists' interviews; then joint workshop (only 2 specialists participated)
Fairbrother	2016	UK	SRM in general	Survey experiment: four treatment groups (440 participants)
Gregory et al	2016	US	SRM in general (plus Marine cloud brightening, Stratospheric aerosol injection, Mirrors in space, urban albedo modification)	Survey (decision pathway) (800 participants)
McLaren et al	2016	UK	Geoengineering in general (plus Stratospheric aerosol injection, Marine cloud brightening)	Deliberative workshops (44 participants, in four groups)
Merk et al	2016	Germany	Stratospheric aerosol injection	Framed field experiment (survey): three treatment groups (658 participants)
Asayama et al	2017	Japan	Stratospheric aerosol injection	Focus groups (36 participants, in six groups)
Bellamy et al	2017	UK	Stratospheric aerosol injection, Marine cloud brightening	"Experimental" deliberative workshops, three treatment groups (21 participants)
Merk & Pönitzsch	2017	Germany	Stratospheric aerosol injection	Survey (927 participants)
Sütterlin & Siegrist	2017	Switzerland	SRM in general	Survey experiment: three treatment groups (250 participants)
Tingley & Wagner	2017	US	SRM in general	Survey and discourse analysis on social media (1000 participants)
Visschers et al	2017	Canada, China, US, UK, Germany, Switzerland	SRM in general	Survey (2327 participants)
Wibeck et al	2017	Japan, Sweden, US, New Zealand	Geoengineering in general	Focus groups (136 participants, in 23 groups)
Bellamy & Healey	2018	UK	Stratospheric aerosol injection, Marine cloud brightening	Scenario development workshop (16 experts, mostly from UK, but also Brazil, Germany, India)
Braun et al (a)	2018	Germany	Stratospheric aerosol injection	Survey experiment: six treatment groups (3526 participants)
Braun et al (b)	2018	Germany	Stratospheric aerosol injection	Panel survey experiment: three treatment groups (3905 participants, first wave; 1934 participants, second wave)
Buck	2018	Finnish Lapland	SRM in general	Focus groups and stakeholder interviews (22 participants)
Carr & Yung	2018	Kenya, Solomon Islands, Alaska (US)	Geoengineering in general	Semi-structured interviews (100 participants)
Cummings & Rosenthal	2018	Singapore	Geoengineering in general	Survey (1235 participants)
Mahajan et al	2019	US	SRM in general	Survey experiment: three treatment groups (1000 participants)
Mathur & Roy	2019	India	SRM in general, Stratospheric aerosol injection	Semi-structured expert interviews (8 participants)
Merk et al (a)	2019	Germany	Stratospheric aerosol injection	Surveys (891 participants in survey 1, 399 participants in survey 2) and citizens' jury (17 participants)
Merk et al (b)	2019	Germany	Stratospheric aerosol injection	Multi-survey design (1617 lay public participants, 253 expert participants – international, more than half from Germany)

Raimi et al	2019	USA	Stratospheric aerosol injection (though stated as SRM in general)	Survey experiment: four treatment groups (749 participants)
Carlisle et al	2020	New Zealand, US, UK, Australia	Marine cloud brightening; Mirrors in space; Stratospheric aerosol injection	In-depth interviews (15 participants in New Zealand), brand image analysis and survey (2978 participants)
Jobin & Siegrist	2020	Switzerland	Stratospheric aerosol injection; Cloud brightening; Mirrors in space	Survey experiment: 10 treatment groups (1575 participants)
Klaus et al	2020	Germany	Stratospheric aerosol injection	Survey experiment: 4 treatment groups (678 participants)
Raimi et al	2020	US	Geoengineering in general	Multi-survey design (1014 participants, unevenly divided between for surveys)
Sugiyama et al	2020	Australia, Japan South Korea, China, India, Philippines	Stratospheric aerosol injection	Survey (3086 participants)
Cherry et al	2021	US	SRM in general	Survey experiment: two treatment groups (1571 participants)
Klaus et al	2021	Germany	Stratospheric aerosol injection	Survey experiment: ten treatment groups (568 participants)
Bolsen et al	2022	US	SRM in general	Survey experiment: eight treatment groups (1075 participants)
Carlisle et al	2022	UK	Marine cloud brightening; Mirrors in space; Stratospheric aerosol injection	Survey experiment: three treatment groups (1558 participants)
Carvalho & Riquito	2022	Portugal	Geoengineering in general	Focus groups (online) (34 participants, in six groups)
Sie et al	2022	Australia	Cloud brightening (and fogging)	Survey (4410 participants: 3082 nationally, 1328 within 50km of Great Barrier Reef)
Bellamy	2023	UK	SRM in general	Survey (1773 participants)
Bolsen et al	2023	US	Stratospheric aerosol injection	Media content analysis and longitudinal survey experiment: eight treatment groups (3500 participants, first wave; 90% retention rate, second wave)
Fenn et al	2023	UK	Stratospheric aerosol injection	Cognitive-affective mapping (58 participants) and Survey (579 participants)
Müller-Hansen et al	2023	-	SRM in general; Stratospheric aerosol injection, Marine cloud brightening; Surface albedo modification, Cirrus cloud thinning, Space mirrors	Social media (Twitter) analysis (English-language, 1452184 tweets from 314484 users
Rosenthal et al	2023	Singapore, US	Stratospheric aerosol injection	Survey (1008 participants)
Baum et al (a)	2024	Brazil, Chile, India, Indonesia, South Africa, Kenya, Saudi Arabia, Nigeria, Dominican Republic, China, Singapore, United States, United Kingdom, Canada, Australia, Japan, Austria, Germany, France, Sweden, Poland, Switzerland, Greece, Italy, Netherlands, Norway, Spain, Denmark, Turkey, Estonia	Stratospheric aerosol injection, Marine cloud brightening, Space mirrors	Survey experiment: three treatment groups (30284 participants)

Baum et al (b)	2024	US, UK, Mexico	Stratospheric aerosol injection	Survey experiment: nine treatment groups (3013 participants)
Hussain et al	2024	Pakistan, Nigeria, Kenya	Stratospheric aerosol injection	Survey (1035 participants, students, faculty, and policymakers)
Merk & Wagner	2024	US	SRM in general	Social media (Facebook) “revealed preference” experiments: four treatment groups (experiment 1) and five treatment groups (experiments 2 and 3) (340,000 user participants in total)
Contzen et al	2024	Australia, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Switzerland, UK, USA, Argentina, Brazil, China, Iran, Nigeria, Kazakhstan, Mexico, Russia, Taiwan, Turkey	SRM in general	Survey (6828 participants: 4583 students and 2245 from general public)

Limited public awareness

Prior awareness and understanding of SRM remains low (see Figure 5 below). Recent global-level studies established that the vast majority of the public, typically around 75%-80%, knows nothing at all or very little about SRM (Baum et al., 2024a; Contzen et al., 2024). This underscores how little the understanding of the public has evolved since the earliest public-perceptions studies (Mercer et al., 2011; Pidgeon et al, 2012). To a significant degree, SRM remains a hypothetical proposition to the public. As such, substantial caution is advised when attempting to draw inferences on the status quo of public opinion on SRM. Even to the extent that it might be claimed public perceptions, nascently, are being developed, it remains to be seen how they will be shaped by growing media attention and a more active public discourse -- let alone, if this topic were to become more polarised.



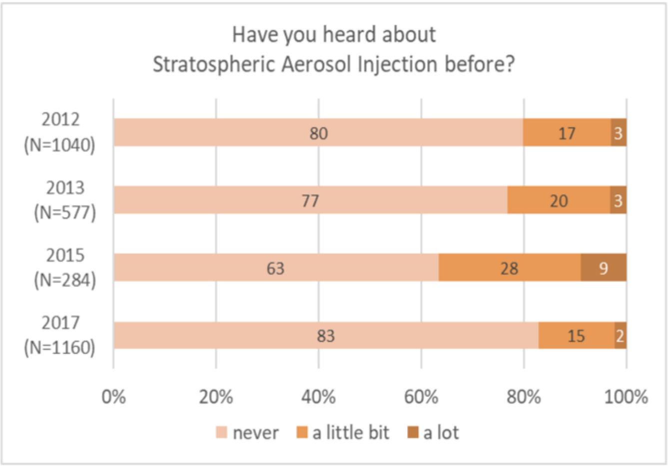


Figure 5. Public familiarity with SRM options. The left panel based on Baum et al (2024), 1=never heard of it, 5=very familiar. The right panel shows awareness about Stratospheric Aerosol Injection in public perceptions surveys in Germany 2012, 2013, 2015, and 2017; all surveys use the same question and response format after study-specific descriptions of SAI. For description of data collection see: 2012: Merk et al (2016); 2013: Braun et al (2018); 2015: unpublished data description of data collection see Merk et al (2016); 2017: unpublished data (Merk, Baatz & Rehdanz, in prep) description of data collection see survey 1 in Merk et al (2019).

A dearth of Global South perspectives

Despite a clear focus on the Anglosphere (e.g. United States, United Kingdom, Canada, Australia, New Zealand) in SAI public-perceptions research -- with 53 appearances, around 36% of total -- public perceptions of those residing in EU/EEA members (and Switzerland) are more than proportionally represented: 45 appearances (30%). By contrast, only twenty countries from across the Global South have been examined by the identified studies, none more than four times (China), for a total of 33 appearances (22%). The weight of the debate on SRM, and geoengineering more generally, bears a considerably Western, developed country focus. However, the group of African countries at the UN Environment Assembly 2024 spoke out against SRM and in favour of a non-use mechanism on SRM, supported by other developing countries, including Mexico and Colombia.

Growing research interest in public and social perceptions of SRM

Overall interest in this topic has grown over time, with a peak, in terms of the number of publications in 2017, though principally having four of five such studies appearing every year (see Table 1). There is also a trend towards greater representation in terms of countries considered, particularly including more representatives of the Global South. Interestingly, more than three-quarters of studies examining the United Kingdom were published before 2016, indicating its early dominance of the literature (e.g. through government support for the SPICE project).

Towards multi-country and multi-technology surveys

Recently, two of the first multi-country surveys on SRM (at times, with other climate-intervention techniques) to include multiple European countries (Baum et al, 2024a; Contzen, et al 2024) -- previously, only two other studies included more than one European country (Bostrom et al., 2012; Visschers et al., 2017), the former with a focus on undergraduate economic students. Similarly, only four of the studies (Baum et al., 2024b; Bostrom et al., 2012; Visschers et al., 2017; Wibeck et al., 2017) have facilitated a direct contrast between European and non-European countries.

Though small and necessarily tentative, this literature indicates that European countries occupy a distinct position when it comes to the acceptability of SRM, having lower degrees of support and greater perceptions of risks versus benefits than both their Anglosphere counterparts as well as Global South countries. There is some divergence across the EU though, with acceptability appearing to be lowest in Austria, Switzerland, and Germany, in the Baltics (Estonia) and across Scandinavia (Baum et al, 2024a; Bostrom et al., 2012; Contzen et al., 2024); in contrast, participants in southern Europe (e.g. Greece, Italy, and Spain) seem much more willing to countenance SRM methods, to levels even similar to those in the Global South (Baum et al, 2024a; Contzen et al., 2024). Another distinguishing aspect of European countries, with some divergence, is the conjunction of significant concern about climate change with relatively lower expectations and/or exposure to climate harm (Baum et al, 2024a; Bostrom et al, 2012; Contzen et al., 2024; Visschers et al., 2017) -- countries in southern Europe offer a contrast here. Concerns over tampering with or manipulating nature also emerge as especially prominent in Europe, most often established in the context of Germany (Braun et al 2018a, Klaus et al., 2020; Merk et al., 2015; Merk & Pönitzsch, 2017; Visschers et al., 2017).

A thematic analysis of the public and social perceptions literature

In terms of the literature reviewed, earlier studies tended to be generalist in nature, mostly dealing with the topic of SRM (and geoengineering) in the context of climate change and mitigation measures. Over time, the focus on stratospheric aerosol injection (SAI) as the proposed method has become more explicit -- of the studies examined, around half look at this method; the other half at SRM in general. By contrast, other potential SRM methods such as marine cloud brightening (ten studies), mirrors in space (eight), and cirrus cloud thinning (one) have received much less attention. The methods most frequently used are deliberative workshops, focus groups, surveys, at times with an experimental design, and less frequently various kinds of interviews (semi-structured, structured). Since 2020, surveys have come to dominate the literature on public perceptions of SRM, being either the only one or one of the mixed methods employed in 21 studies (out of 23 in total) -- two studies used a mixed-methods design combining surveys with a qualitative method such as interviews (Carlisle et al, 2020) or cognitive affective mapping (Fenn et al, 2023). At the same time, the heavy reliance on surveys also presents a possible limitation -- such approaches provide us insights about attitudes on SRM, as well as key factors underlying these perceptions, but do not typically enable more in-depth discussion and deliberation. Also, as noted above, the limited public awareness of SRM poses questions about how malleable the preferences elicited by surveys are likely to prove as media attention and public discussions evolve.

The main themes that emerge from public perception studies (see Table 1) on SRM are as follows:

- **Moral hazard:** the possibility that the development and implementation of technological measures to reduce the impact of climate change may generate a perceived permission structure for citizens, industries, and governments not to have to reduce emissions as much. Evidence of moral hazard is empirically very challenging to generate. Existing analyses are inconclusive as some studies observe some moral hazard effects, whereas others find no results or even an increase in support for emissions mitigation after exposure to the notion of SRM (Amelung & Funke, 2015; Baum et al 2024b; Corner & Pidgeon, 2014; Fenn et al, 2023; McLaren et al 2016; Merk et al 2016, 2019; Raimi et al 2019; Visschers et al, 2017). (See also mitigation deterrence below).
- **'Messing with nature':** the perception that human beings may, by intervening or tampering with climate processes be acting in contravention to the natural order, with accompanying expected consequences from the natural elements and/or religious connotations. While many studies observe 'messing with nature' sentiments, some also find that with closer interaction, SRM can be viewed to remedy humanity's degrading impact on nature (Asayama et al, 2017; Baum et al, 2024a, 2024b; Bolsen et al, 2023; Buck, 2018; Carr & Yung 2018; Carvalho & Riquito, 2022; Corner et al, 2013; Corner & Pidgeon, 2015; Fenn et al, 2023; Jobin & Siegrist, 2020; Klaus et al, 2020; Mercer et al, 2011; Raimi et al, 2020; Visschers et al, 2017; Wibeck et al 2015, 2017).
- **'Unnaturalness' of SRM techniques:** related to the previous point, aversion to those techniques perceived to be more 'unnatural', with this factor an important predictor of the potential acceptability of SRM. While initial reactions tend to view SRM as unnatural, this effect can vary with framing effects (e.g. relating to the Anthropocene or SRM seen as counteracting a reduction in bunker fuel emissions (Baum et al, 2024b; Bellamy et al, 2016; Bolsen et al 2023; Corner et al, 2013; Corner & Pidgeon, 2014, 2015; Mercer et al, 2011; Mahajan et al, 2019; Raimi et al, 2020).
- **Climate change harms and exposure:** the degree to which individuals or groups perceived climate change to have a severe impact on their lives, or were directly harmed by climate change or natural disasters, has a crucial influence on support for SRM techniques and more support for SRM research has been found in Global South countries (Baum et al, 2024a, 2024b; Bolsen et al., 2023; Borick & Rabe, 2012; Bostrom et al., 2012; Braun et al., 2018b; Cherry et al., 2021; Gregory et al., 2016; Hussain et al., 2024; Jobin & Siegrist, 2020; Klaus et al., 2020; Mercer et al., 2011; Merk et al., 2015, 2016; Pidgeon et al., 2013; Raimi et al., 2020; Rosenthal et al., 2023; Sugiyama, Asayama & Kosugi, 2020; Visschers et al., 2017).
- **Less preferable than other climate solutions:** there is consistent evidence of the public assigning SRM approaches, most of all stratospheric aerosol injection, less support and viewing them to have greater risks versus benefits than carbon dioxide removal and, especially, emissions reduction approaches like renewable energy, energy efficiency and energy conservation (Amelung & Funke, 2015; Baum et al, 2024a; Bellamy, 2023; Bellamy et al., 2016; Bostrom et al., 2012; Carlisle et al., 2020, 2022; Jobin & Siegrist, 2020; Merk et al., 2019b; Müller-Hansen et al., 2023; Wright et al., 2014).
- **Need to establish fair regulation, need to distribute benefits and costs fairly:** among those who do not oppose SRM on principle, there emerges a call for the establishment of precise regulation delimiting its use, as well as questions over the extent to which this would be feasible (Asayama et al., 2017; Bellamy et al, 2016, 2017; Buck 2018; Macnaghten & Szerszynski, 2013; Hussain et al, 2024; Sugiyama et al, 2020). Intergenerational fairness has

long been a consideration with calls to ensure future generations are properly equipped to take decisions on the potential use of SRM (Betz, 2012; Goeschl, Heyen & Moreno-Cruz, 2013, Quaas et al., 2017).

- **Need to inform and consult citizens prior to development and deployment:** connected to the previous point, respondents express the need for choices about these technologies to be made with the involvement and consent of citizens, both out of justice considerations and in accordance with democratic principles (Asayama et al., 2017; Baum et al, 2024a, 2024b; Bellamy et al, 2016, 2017; Buck 2018; Macnaghten & Szerszynski, 2013; McLaren et al, 2016; Sugiyama et al, 2020).
- **Conspiracy thinking:** though a smaller strand in the literature, there are established connections between discourse and discussions on SRM in the public sphere and prevailing conspiracies (notably, on chemtrails), with this revealed at the individual level through surveys (Bolsen et al., 2022; Mercer et al, 2011; Tingley & Wagner, 2017) and in a more general manner through social media analysis (Debnath et al, 2023; Müller-Hansen et al, 2023).

The evidence suggests that the perception of the risks of climate change and those of SRM as well as its benefits may play a central role in shaping opinions about its development and deployment: public opinion on SRM is strongly contingent on the how, where, and why of SRM discussions, not to mention the scale of activities envisioned: e.g. laboratory or modelling research, small-scale field trials, immediate deployment, field research (Amelung & Funke, 2015; Baum et al, 2024a; Mercer et al, 2011; Merk et al, 2014, 2019). Moreover, public preferences can be a double-edged sword: they can signify patterns of support which could shape deployment patterns positively, e.g. contributing to the 'slippery slope'. or conversely, lack of support could be evident, leading to a 'sticky slope'. As one expert interviewed in Sovacool et al (2022) explained:

> Many opponents worry about a slippery slope to deployment. I think it will be the opposite: a sticky slope. The more we do some of these options, the harder it is socially and politically, preliminary deployment oddly reduces the probability of actually doing it.

Depending on the SRM technology considered, results can also vary, with more regionally focused methods potentially seen as less problematic (Baum et al 2024a; Bellamy et al, 2016, 2017; Carlisle et al, 2020, 2022; Corner et al, 2013; Jobin & Siegrist, 2020; Müller-Hansen et al, 2023; NERC, 2010; Sie et al, 2022; Wright et al, 2014). Encapsulation refers to whether the method is modular and contained, such as is the case with space reflectors, or whether it involves material released into the wider environment, as is the case with sulphate aerosols or ocean fertilisation (Shepherd, 2009, p.38). Generally, however, the prevailing attitude towards SRM is ambivalent, though typically relatively more negative than towards emissions reduction or certain carbon dioxide removal methods (Amelung & Funke, 2015; Baum et al, 2024a; Bellamy, 2023; Bellamy et al, 2016; Carlisle et al, 2020, 2022; Jobin & Siegrist 2020; Müller-Hansen et al, 2023; Wright et al, 2014). There is growing evidence that public opinion in climate vulnerable countries in the Global South may be more favourable than that in global north countries (Baum et al, 2024a; Contzen et al, 2024; Sugiyama et al, 2020; Visschers et al, 2017).

Expert elicitation and elite perceptions

The landscape of actors engaged in discussing SRM and perceptions held by publics are only two aspects of acceptability, support, or opposition. A final aspect are perceptions held by experts and those involved in decisions to fund research, implement policy, or shape deployment outcomes.

Foundational research

Early studies by Morgan and Keith (1995) asked 16 climate scientists about climate interventions, including SAI and cloud brightening, and found that SAI was seen as the most uncertain option. A follow up study more than a decade later of 24 experts ("leading atmospheric and climate scientists") offered subjective probability distributions to reflect their current expert judgment about the value of releasing anthropogenic aerosols at the top of the atmosphere (Morgan et al, 2006). The range of associated with their estimates, especially those for total aerosol forcing and for surface forcing, was often much larger than that suggested in the published literature, including reports from the IPCC.

More recent research

More recently, Himmelsbach (2018) conducted 15 interviews with scientists advising the European Commission in relation to climate change and sustainability. While presenting deep critiques of SRM in terms of not addressing the root causes of climate change, interfering with natural systems, and SRM posing difficult risks for distributive justice, the experts nonetheless presented support for basic research into SRM -- given the difficulty of tackling climate change.

Conversely, using a Group Delphi workshop approach with 12 German experts, Scheer and Renn (2014) identified a general and wide-ranging belief in the conflict potential of SRM deployment, both between countries and within German society -- this resulted in the conclusion that the public and stakeholders in Germany were "highly unlikely" to ever be supportive, though the experts (similar to Himmelsbach 2018) reiterated the need for dialogues with the public to continue to draw on the growing understanding of SRM as a potential option for dealing with climate change.

In addition, Dai et al (2021) conducted face-to-face interviews using formal expert elicitation methods with 26 climate experts from China and the United States and compared their judgments solar geoengineering research and deployment. In contrast to existing literature that often stresses factors that might differentiate China from western democracies, few significant differences between quantitative judgments of US and Chinese experts were found.

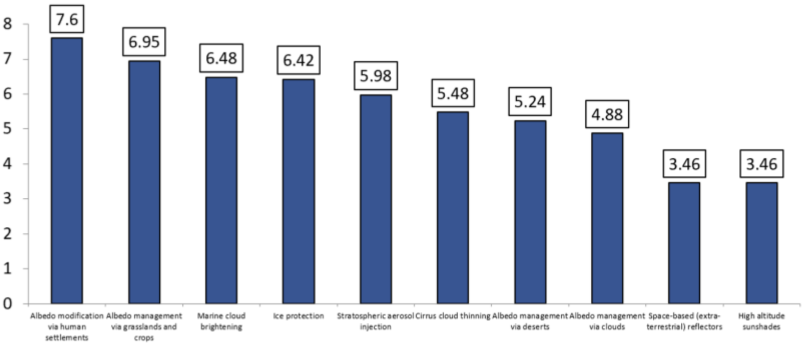
Using 8 semi-structured interviews with experts and policymakers from India, Mathur and Roy (2019) also identified prevailing concerns of SRM representing an unwanted manipulation of nature as well as risking moral hazard by undercutting the need for emissions reductions. Wedded to such concerns, the Indian experts also voiced disquiet about how the unintended consequences of SRM might overly impact those in the Global South and, in this vein, concerns about unilateral action being taken by developed countries, making little distinction here between governments and scientists. Such concerns provoked emphasis on greater transnational participation and representation across all stages of SRM research and deployment along with need for governance approaches at the international level.

The consequences of the lack of effective governance approaches were the principal theme of the scenario development workshops conducted, with 16 international (but mostly UK) experts, by Bellamy and Hulme (2018). Rather than a 'slippery slope', the experts sketched out scenarios whereby stratospheric aerosol injection would confront an "uphill struggle" towards deployment, especially in the absence of international collaboration. While pointing to a rationale for research activities in the short- to mid-term, including with R&D support from governments, the consensus was that SRM would receive only limited interest unless either the impacts of climate change were to become more severe or international climate negotiations veered towards collapse. Even then, the experts foresaw the need to weather down-swings in support, including in the form of an international moratorium on stratospheric aerosol injection. Of note, the workshops by Bellamy and Hulme (2018) also developed scenarios for marine cloud brightening -- despite strong concerns about the uncertainty and feasibility of this approach, there emerged the sense that it could have an easier path to deployment, notably, as a more "local" option that might be deployed by coastal communities seeking to mitigate heat stress. The two examples name-checked were Australia and California, the former of which is currently supporting small-scale field trials as a way to protect the Great Barrier Reef (Condie et al, 2021; Harrison, 2024; Sovacool et al., 2023).

Researchers have also employed survey techniques to elicit the perspectives of experts. Among other insights, this facilitates a comparison with the views of the general public. Drawing on samples of 1617 lay public and 253 expert participants (located internationally, with more than half from Germany), Merk et al (2019b) determined that experts were more likely to perceive stratospheric aerosol injection as risker as well as to characterise the benefits as "very large" or "very small" -- this heterogeneity reflects, in part, the level of expertise with SRM methods. Experts in this survey again concurred that research on SAI should be done in the next 25 years, while offering relatively lower support for field trials at a local or global level (85% of experts disagreed with the latter).

Through parallel strands of deliberative mapping workshops (with 13 citizens and 12 experts), Bellamy et al (2016) similarly identified a greater degree of pessimism on stratospheric aerosol injection among experts (in the United Kingdom). Dannenberg and colleagues (2019) analysed the views of 723 negotiators and scientists engaged in international policy discussions on climate change. They noted more heterogeneity among respondents, and that those who expect severe global climate change damages and who have little confidence in current mitigation efforts are more opposed to geoengineering than respondents who are less pessimistic about global damages and mitigation efforts. Nevertheless, they also find that respondents are more supportive of SRM when they expect severe climate change damages in their home country than when they have more optimistic expectations for the home country.

Finally, Sovacool et al (2022) asked 74 experts who had published on the topic of SRM or patented SRM relevant technologies about desirability, pathways to commercialisation, and risks facing 10 different options, including stratospheric aerosol injection, cirrus cloud thinning, marine cloud brightening, sunshades, ice protection and others. For context, ten CDR options were also presented for consideration. As Figure 6 (below) indicates, albedo modification via human settlements (a mean ranking of 7.6 on a 10-point scale) was the most preferred among the SRM options across the sample, followed by albedo management via grasslands and crops (6.95) and marine cloud brightening (6.48). Conversely, space-based reflectors (3.46), high-altitude sunshades (3.46), and albedo management via clouds (4.88) are the least preferred. When assessed in relation to potential for temperature reduction, SAI was deemed, on average, as the most promising, with the ability to avoid almost 1°C of temperature change by 2050. This is followed in order of efficacy by albedo management via crops (a mean of 0.89°C- change) and space-based reflectors (0.656°C- change). The options deemed the least effective were high altitude sunshades (0.333°C- change), cirrus cloud thinning 0.344-degrees, and albedo management via clouds (each 0.344°C change). Given the general nature in which the question was posed, such estimates should be seen as reflecting optimistic scenarios for the development and deployment of SRM approaches. When lastly asked about risks, SAI was however seen as the most risky, albedo modification via human settlements and ice protection the least risky.


8
7
6
5
4
3
2
1
0
7.6
6.95
6.48
6.42
5.98
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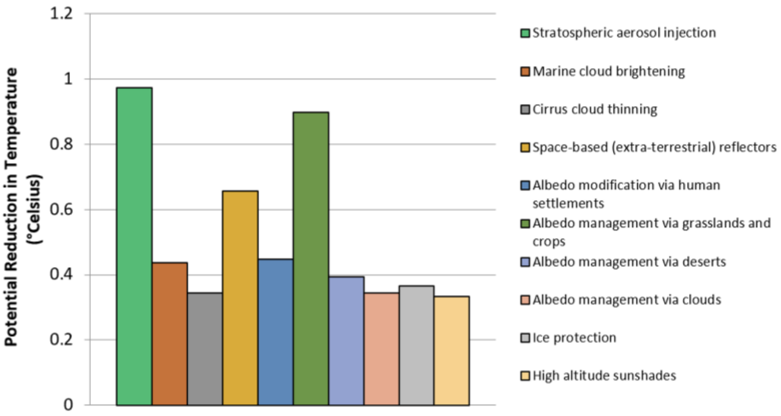
5.24
4.88
3.46
3.46
Albedo modification via human settlements
Albedo management via grasslands and crops
Marine cloud brightening
Ice protection
Stratospheric aerosol injection
Cirrus cloud thinning
Albedo management via deserts
Albedo management via clouds
Space-based (extra-terrestrial) reflectors
High altitude sunshades


Potential Reduction in Temperature (°Celsius)
1.2
1
0.8
0.6
0.4
0.2
0
Stratospheric aerosol injection
Marine cloud brightening
Cirrus cloud thinning
Space-based (extra-terrestrial) reflectors
Albedo modification via human settlements
Albedo management via grasslands and crops
Albedo management via deserts
Albedo management via clouds
Ice protection
High altitude sunshades

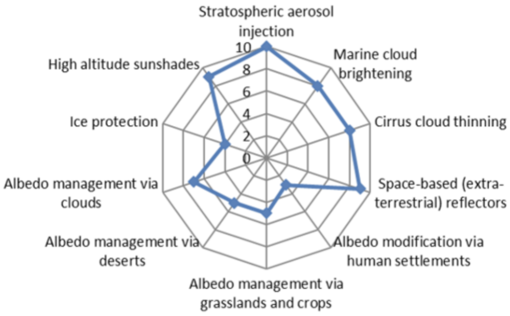
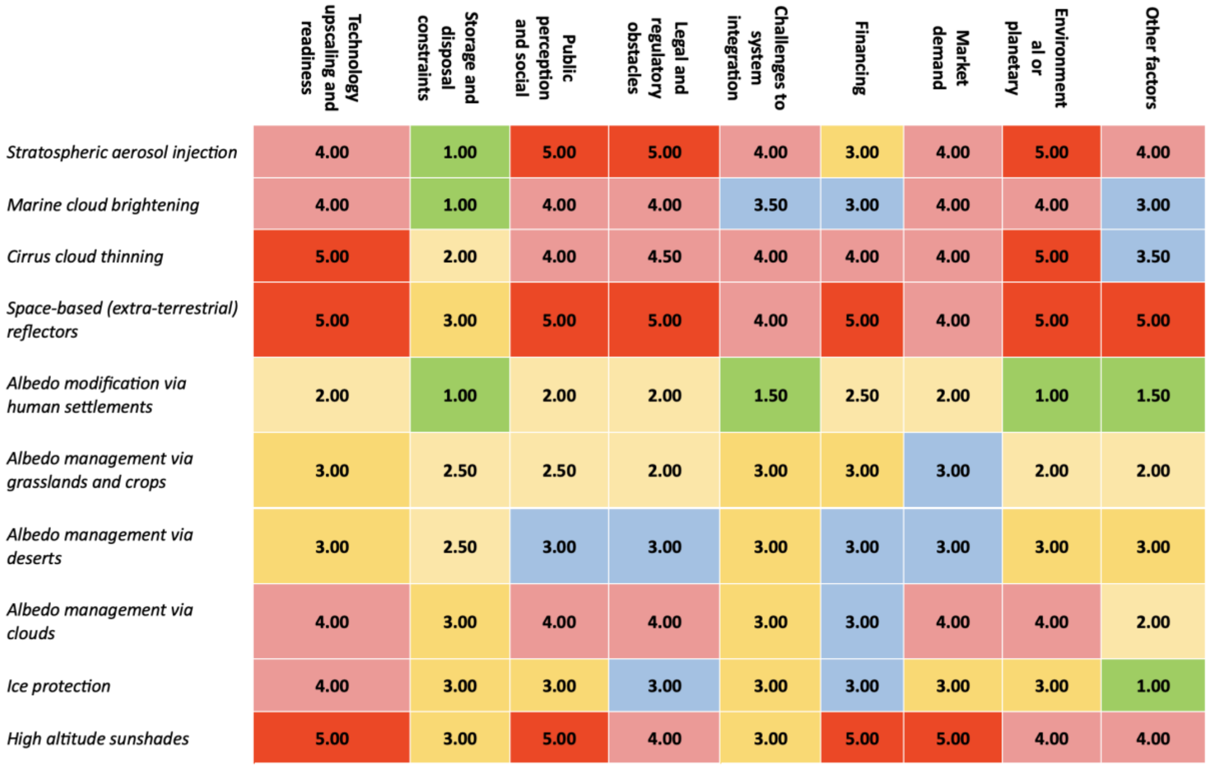

Stratospheric aerosol injection
Marine cloud brightening
Cirrus cloud thinning
Space-based (extra-terrestrial) reflectors
Albedo modification via human settlements
Albedo management via grasslands and crops
Albedo management via deserts
Albedo management via clouds
Ice protection
High altitude sunshades
10
8
6
4
2
0

Figure 6. Expert perceptions on the preferred absolute ranking (top panel), expected temperature reduction (middle panel), and composite risks (bottom panel) for 10 solar geoengineering options. Source: Sovacool et al (2022). (For the top panel, expert respondents were asked 'The literature often discusses the following SRM options. Please rank them against each other in order of your preference.' We left it to each expert to rank these options without any prompts or information treatments. The middle panel shows the results for the question 'In terms of feasibility, by the year 2050, how much global warming or climate change (in degrees Celsius) do you expect each of these options to achieve reducing or addressing?'. The lower panel shows the mean score for the question 'Each of the options below entails different social, economic, environmental, and even political risks. As of our evolving base of knowledge in 2021, how would you rate the risks of each of these options as they might be scaled up or engaged with in the future?'. The higher the number, the riskier the option (medians shown, on a scale from 1 to 10).

Sovacool et al (2022) also asked respondents about the barriers facing all 10 SRM options (see Table 2). Across all interventions, technical-related barriers such as upscaling, storage, and system integration were seen as significant for some options---notably for marine cloud brightening, cirrus cloud thinning, space-based reflectors, albedo management via clouds and high-altitude sunshades. But non-technical barriers arose as significant for options such as SAI (environmental and planetary risk, social acceptance, legal and regulatory barriers), marine cloud brightening (environmental and planetary risk, legal and regulatory barriers), cirrus cloud thinning (environmental and planetary risk, social acceptance, legal and regulatory barriers), space-based reflectors (environmental and planetary risk, social acceptance, legal and regulatory barriers, financing, market demand, other factors) and high-altitude sunshades (social acceptance, legal and regulatory barriers, financing, market viability). This finding validates research and policy focusing well beyond traditional concerns of technology deployment (e.g. beyond basic research and development) to broader themes of acceptability, governance, policy, and markets.



	Technology upscaling and readiness	Storage and disposal constraints	Public perception and social	Legal and regulatory obstacles	Challenges to system integration	Financing	Market demand	Environmental or planetary	Other factors
Stratospheric aerosol injection	4.00	1.00	5.00	5.00	4.00	3.00	4.00	5.00	4.00
Marine cloud brightening	4.00	1.00	4.00	4.00	3.50	3.00	4.00	4.00	3.00
Cirrus cloud thinning	5.00	2.00	4.00	4.50	4.00	4.00	4.00	5.00	3.50
Space-based (extra-terrestrial) reflectors	5.00	3.00	5.00	5.00	4.00	5.00	4.00	5.00	5.00
Albedo modification via human settlements	2.00	1.00	2.00	2.00	1.50	2.50	2.00	1.00	1.50
Albedo management via grasslands and crops	3.00	2.50	2.50	2.00	3.00	3.00	3.00	2.00	2.00
Albedo management via deserts	3.00	2.50	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Albedo management via clouds	4.00	3.00	4.00	4.00	3.00	3.00	4.00	4.00	2.00
Ice protection	4.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.00
High altitude sunshades	5.00	3.00	5.00	4.00	3.00	5.00	5.00	4.00	4.00

Table 2: Expert perceptions about the salience of barriers facing solar geoengineering options. Source: Sovacool et al (2022). Barriers were ranked as equally important. "Other factors" includes any barrier not explicitly listed. (Note: 1 = no/weak barrier, 5 = strong barrier). Median scores ranging from 1.00 to 1.99 are highlighted in pale green; those from 2.00 to 2.99 in pale yellow; from 3.00 to 3.99 in blue; from 4.00 to 4.50 in light red, and 4.51 to 5.00 in dark red.

Table 2: Expert perceptions about the salience of barriers facing solar geoengineering options. Source: Sovacool et al (2022). Barriers were ranked as equally important. "Other factors" includes any barrier not explicitly listed. (Note: 1 = no/weak barrier, 5 = strong barrier). Median scores ranging from 1.00 to 1.99 are highlighted in pale green; those from 2.00 to 2.99 in pale yellow; from 3.00 to 3.99 in blue; from 4.00 to 4.50 in light red, and 4.51 to 5.00 in dark red.

Chapter 6: Ethical and justice considerations, feasibility and required conditions

Key messages

- Ethical and justice considerations are often advanced implicitly or explicitly by natural scientists and climate modellers, especially those advocating for more research into SRM.
- Moral concerns raised about the development and use of SRM technologies can be divided into distributive justice, and procedural justice and legitimacy. Additionally, issues of both recognitional justice and rectificatory justice have been emphasized, albeit it less so. Key issues include moral hazard/mitigation deterrence, side distribution of adverse side-effects, hubris, and genuine public participation in decision-making including those who are or have historically been excluded.
- Economically, SRM deployment entails costs that can include the technology as well as observational and infrastructural systems supporting it, but also benefits from improved economic development and enhanced welfare from prospectively curtailing climate change, especially in most vulnerable countries, although there is opposition to this kind of strategy some of these nations.
- Institutional governance at global level with just outcomes over extended time periods is extremely challenging, given several examples of scenarios for the development of SRM institutions which each assume different functions, objects, and agents involved, as well as possible implications on democracy and overall world order instabilities.
- Geopolitical and security themes in the literature include militarization and weaponisation, perceptions of risk, unilateralism, geopolitical entanglements, blame, termination shock, and wider securitization concerns.

This chapter focuses on the moral (ethics and justice) considerations of SRM, as well as various dimensions of feasibility and required conditions including economic, institutional, political and geopolitical. The scientific literature advances different types of distributive and procedural justice considerations, as relevant for national and international decision-making about SRM. Additionally, issues of recognitional and rectificatory (i.e. compensating for past losses and damages), have also been emphasized, albeit less so than the other forms of justice. This literature mostly features contributions from the humanities and social sciences (e.g. moral and political philosophy, political theory, political sciences). Given the moral contentiousness of SRM (Baatz et al, 2016) and its almost endless moral implications, this technology vigorously challenges dominant beliefs and attitudes (Svoboda, 2017), as it would involve new conceptions of the Earth and of human beings (Hulme, 2012; Hamilton, 2013b).

Feasibility is also a term that admits of different interpretations, especially across academic disciplines and between academia and wider political discourse. A simple way to distinguish between understandings of feasibility claims is to consider whether they concern "hard constraints", such as physical limitations and "soft constraints", such as economic or political circumstances. The IPCC's definition of feasibility is "the degree to which climate goals and response options are considered possible and/or desirable. Feasibility depends on geophysical, ecological, technological, economic, social and institutional conditions for change. Conditions underpinning feasibility are dynamic, spatially variable, and may vary between different groups". While there are some questions about the IPCC's linking of feasibility with desirability, rather than simply with possibility, we use the various conditions listed here to structure the following discussion.

Considerations of ethics and justice

As noted above, academic contributions to questions of justice or ethical issues raised by development and any eventual use of SRM have mainly come from the social sciences and humanities. In the English language academic literature, the majority of work is done by academics in the Global North and employs normative concepts taken from the modern secular Western tradition, although there are some exceptions. For example, Wong (2013; 2015) considers a Confucian perspective, Jain (2019) applies Hindu-Jain ethical concepts, and the contributors to Clingerman and Brian (2016) come from a Christian standpoint. Shorter explorations of Jewish, Islamic and Buddhist perspectives are presented in the report *Playing God? Multi-faith Responses to the Prospect of Climate Engineering* (Clingerman and Gardiner eds. 2018). It is increasingly acknowledged that indigenous peoples' perspectives must be brought into political decision-making about SRM, but in the academic literature persons with indigenous heritage remain a minority (for the most prominent exception, see Whyte 2012, 2019).

In the prevailing literature, the moral concerns raised about the development and use of SRM technologies invoke a variety of concepts which can be used to give a rough categorisation of different broad kinds of moral concerns. To structure this section, we use the following categories to sort out different concerns: distributive justice, recognitional justice, procedural justice and legitimacy, and rectificatory justice, and ethics.

The first distinction is between issues of *justice* and issues of *ethics*. Justice here is regarded as concerning the political realm. A conception of justice (implicit or explicit) sets out reasonable expectations of persons qua citizen, that is, as an individual human being, bracketing any personal relationships or other morally significant ties that individuals might have with each other. A complete conception of justice lays out the moral rights of the citizen as a standard by which that citizen's society may be judged. Issues of ethics, by contrast, refers to the moral questions human beings face when considering their personal relationships and their understanding of their place (and sometimes humanity's place) and role in the world. Ethical worldviews can include but are not limited to religious and spiritual worldviews and are often expressed in terms of the ideals and norms that maintain specific, partial, valuable social and spiritual relations.

What follows is a summary of the moral issues that could potentially be raised by the development and use of SRM mostly, but not exclusively as they are discussed in the academic philosophical literature. Heyward (2013) emphasises that it should not be assumed that all kinds of SRM will face all of the following problems, but that the idiosyncratic features of each particular SRM proposal, plus contextual factors will influence which particular set of moral issues arise in each case. Moreover, it should also be noted that emissions reduction, carbon dioxide removal and adaptation also raise questions of justice or ethics, again, depending on the particular form these measures take and the particular context in which they are discussed or enacted.

Distributive justice

Whether the development and use of any SRM technology results in an injustice depends on the features of the individual technology concerns, the context in which it is developed or used, plus the prevailing conception of justice used as the standard of evaluation. The literature indicates the following ways in which injustices might arise or current injustices be exacerbated by the development and/or use of an SRM. In the following, both the possible global and intergenerational scope of these injustices should be emphasised (Gardiner, 2011). For instance, Gardiner (2011a, 2013a) contends that focus on the distribution of benefits and risks in the present generation masks the neglect of how future generations could be adversely affected by SRM -- he specifically uses the term "intergenerational buck passing". Here, the risks of termination shock play a salient role, whereby future generations would experience a reduced opportunity space for making decisions. Echoing concerns over moral hazard, now intergenerationally conceived, Gardiner (2011a) proposes that committing to the use of SRM, without simultaneously emissions reductions, would increasingly exacerbate the risks of abrupt climate change -- thereby increasing the incentives of each generation to use SRM.

Wong (2014) stresses the ethical importance of consideration of "post-implementation" scenarios involving SRM, beyond more near- to mid-term questions of research and deployment. Both Hartzell-Nichols (2012) and McKinnon (2019) recommend precautionary approaches as a way to ensure more just outcomes for future generations, whether by ensuring that the risks and consequences of potential catastrophes or lock-in effects are taken seriously. McKinnon (2020) specifically locates such intergenerational injustices as resulting from overly optimistic, utopian assumptions regarding the prospects of successful international cooperation in the future (see also Gardiner, 2010, 2011a; Hourdequin, 2019).

Impacts of use

The possible impacts of climate change upon human wellbeing are already well documented and it is their severity which justifies calls for action against climate change, including those calls for research into SRMs. Both climate change -- and accordingly SRMs as a response will disproportionally affect the most vulnerable, developing states and future generations. Accordingly, the projected beneficial or adverse impacts of any use of SRMs (see Part 1) is similarly a matter of concern for reasons of global and intergenerational distributive justice. For example, should the use of SRM cause significant changes in precipitation patterns, the increased or decreased rainfall may threaten homes, food and fresh water supplies in a given area, which, if left unaddressed, would count as unjust on nearly all conceptions of distributive justice (Callies, 2019; Heyward, 2019; Pamplany, 2020; Preston, 2016; Svoboda et al, 2011). Any unmanaged termination shock would likely have very severe impacts on human wellbeing due to the speed as well of the scale of environmental change (Hartzell-Nichols, 2012); and would thus constitute a severe injustice to those impacted (McKinnon, 2019).

However, the use of SRM also has the potential to reduce the global temperature increases associated with a given atmospheric concentration of greenhouse gas and, by the same token, reduce some of the environmental changes associated with said increase in global temperature (other climatic changes, such as ocean acidification are left unchanged). Given the severe consequences of climate change, some commentators have suggested that use of some SRMs might benefit the global poor, i.e. further goals of global distributive justice (Horton & Keith, 2016). By presenting SRM as a response to climate change, it is argued that distributive injustices associated with the development and use of SRM must be considered within this context -- in a so-called "risk-risk" framing (Keith & Irvine, 2016; Reynolds, 2019b).

By reducing the mean global temperature, SRM could partially offset direct (threats to public health) and indirect effects (such as agricultural loss) associated with climate change. Horton and Keith (2016) argue that due to this potential, there is an obligation, based on distributive justice concerns, to at least research SRMs. Svoboda et al (2018) draw similar conclusions. Buck (2012) suggests that SRMs could be a logical extension of humanitarian agencies' preparations for climate adaptation and argues that the possibility that SRM might be able to partially reduce projected temperatures, with "important humanitarian implications" should at least be considered (Buck, 2022; see also Arrighi et al, 2023). In particular, the 'non-ideal' situation is emphasised: as it is assumed unlikely that a completely fair climate policy strategy will be pursued, the use of some SRMs might be preferable, from the perspective of global and intergenerational distributive justice, as an "incompletely fair" measure (Svoboda, 2017).

while those sympathetic to the idea of 'humanitarian SRM' generally emphasise that its use would be a non-ideal measure, the general argument outlined above that SRMs might be useful as a 'lesser evil' is contested. Critics maintain that the argument relies on too simple a picture of the problem of climate change and misses out key morally salient features. One prominent line of criticism rests on the idea of justice as recognition (see below). The other form of criticism concerns the 'lesser evil' argument. It points out that this argumentative strategy can be used to disguise a certain form of moral corruption (Gardiner, 2010, 2011a).

Another common argument that appeals to an implicit ideal of intergenerational distributive justice is the "buying time argument". First proposed by Wigley (2006; also for discussion see Horton, 2015 and Corry, 2017), this argument suggests that certain forms of SRM could be used to lower temperature rises temporarily while necessary mitigation measures are enacted. This would allow the costs of mitigation measures to be spread over a longer period of time and be less burdensome on current generations, without subjecting future generations to the impacts of very high temperature rises. The buying time argument assumes that substantial mitigation will occur at the same time as SRM is used to "peak-shave". Many critics, however, argue that the promise of SRM development and use will actually reduce motivation to enact the kind of mitigation measures that are necessary. This commonly made objection is known (among other names) as 'moral hazard'.

Moral hazard/mitigation deterrence

This most often discussed concern regarding geoengineering technologies is the so-called problem of 'moral hazard', also called the "mitigation deterrence" argument, the "mitigation obstruction argument" (Morrow), the "problem of trade-offs" (Baatz, 2016). Put simply, it is the concern that research and use of SRMs will detract from or replace efforts to reduce GHG emissions and thus result in worsening of the global and intergenerational distributive injustices associated with dangerous climate change.

Some forms of SRM might be more likely to be implicated in moral hazard than others. For example, those which are perceived as being easier or cheaper to implement than emissions reduction might be more attractive in some policy circles. This is particularly key if SRM is to be temporary in any way, since then simultaneous successful emissions reductions (and potentially carbon removal) may have to happen and any trade-offs would have to be reckoned with (Baatz, 2016).

Whether the prospect of SRMs will in fact lessen mitigation efforts is an empirical matter and is uncertain. Some studies have been conducted among members of the public but much depends on how exactly the issue is presented (e.g. Andrews et al., 2021; Austin & Converse, 2021; Cherry et al., 2021; Merk & Wagner, 2024). However, even if the prospect of SRM does not in fact cause a reduction in mitigation measures (e.g. because mitigation happens to be low on the policy agenda in the first place) it might be used as a political justification for continued low effort or delay. These unintended social and political risks of delay of climate mitigation due to research or the prospect of SRM were noted early on during discussions of SRM (e.g. Corner, 2014).

An example of social mechanisms includes when a new or projected technology is modelled in scenarios as cheaper in the future than near term mitigation methods, and on this basis near-term emissions reductions are automatically replaced with, e.g. future carbon removal or SRM (McLaren, 2016). If this were to reduce the 'required' pace of decarbonisation allowing more near-term and total emissions, but then the future use of SRM were to underperform (in price or effectiveness) or fail to materialise entirely due to unforeseen technical or political obstacles, there is a risk of more emissions than if SRM had never been relied upon.

Here, it is possible that some lessons could be learned from experiences with carbon-dioxide removal technologies, which also face the moral hazard objection. Historical studies of negative emissions technologies show over-promising or unrealistic assumptions of zero emissions or leakage are common for CDR technologies (Carton et al., 2020). Automatic or unintended risk is much discussed in relation to integrated economic-physical model scenarios (IAMs) where carbon removal technologies such as large-scale BECCS 'allow' more emissions (expand the carbon budget by projecting future giga-ton scale 'negative emissions') (Geden, 2015, 2016; Carton et al., 2021). This also happens when emissions reduction and carbon removal options are modelled with SRM, the latter significantly reducing projected need for the other two methods (Belaia et al., 2021). If a perceived need for SRM rests on mitigation not being anywhere near optimal, a further lowering of planned mitigation, replaced by promised future technologies, would put such substitutions into the category of 'mitigation deterrence' (McLaren, 2016).

The 'political' risk scenarios, on the other hand, centre on the risk of politicians shying away from -- or seeking justification for not pursuing -- more rapid decarbonisation on the back of promises of future risk management via SRM. SRM provides a possible way for rich countries or other actors like corporations or individuals, to divert attention from their responsibility for their disproportionate emissions, or to justify continued high emissions, while promising a cheaper and easier alternative.

Evidence of mitigation-sceptical political actors endorsing SRM can be found, e.g. among right-wing US think-tanks, and some commentators. Assessing the extent of this risk among decision-makers is hard, however, due to the absence of counterfactual scenarios and the motivation of politicians to hide mitigation. Furthermore, the Paris Accord of 2015 'has shifted policy attention to temperature targets (without associated emissions targets): a change that opens a very large opportunity/loophole for SRM advocacy' (McLaren, 2016).

Critiques of SRM however underscore that the proposition of an alternative to difficult emissions reductions, not least one able to be wielded by a small group of actors, is exactly what makes it problematic for distributive justice (Gardiner, 2013b; Heyward, 2013; Jamieson, 2013; Wolff, 2020). As noted by multiple authors (e.g. Hartzell-Nichols, 2012; Smith, 2018), the aggregation of risks and impacts across groups in a society, let alone at global level, elides fundamental differences between minimal risks to be borne by many people versus catastrophic risks being placed on a small number. Even if the prospect of SRM does not in fact cause a reduction in the use of mitigation measures (e.g. because mitigation happens to be low on the policy agenda in the first place) it might be used as a political justification for continued low effort (Gardiner, 2010; Wolff, 2020).

Due to these political risks of mitigation deterrence, the argument that SRM might engender a problem of 'moral corruption' needs attention. Instead of tackling climate change seriously, beneficiaries of 'business as usual' could find excuses, often embedded in visions of technological omnipotence, to search for technological fixes that make it possible to continue with business-as-usual behaviour, which has so far proved extremely harmful for the climate system (Gardiner, 2011; Preston, 2013). Mitigation deterrence itself, however, includes a wider set of mechanisms than mere moral corruption, through which planned SRM could offset or delay mitigation efforts. It also refers to risks of uncounted social costs associated with prolonged extraction and burning of fossil fuels, such as air pollution, being caused by substitutions of mitigation for 'alternatives', in processes that ignore or externalise such costs from the calculations or political argument.

If it occurs, moral hazard could also contribute to the technology becoming "locked in" due to path dependency as continued inaction on mitigation might make it more tempting to use SRMs to avoid the worse impacts of climate change. Lock-in can happen in other ways, for example, due to a desire to make use of what would otherwise become "sunk costs" of previous investment "economic lock-in"

(Rayner et al 2013) and desire to avoid termination shock "technological lock-in (Rayner et al, 2013). It too raises problems of both distributive and procedural intergenerational injustice.

Profiting from commercialised SRM

A final, less discussed way in which the development of SRM raise issues of distributive justice is the prospect of profiting from the development their development or eventual deployment use of SRM (Buck, 2012). Depending on how research into SRM is funded and what kinds of property rights are assigned to technologies, some individuals or organisations could profit from a decision to take SRM approaches seriously (e.g. the Make Sunsets group). The size of profits allowed may be a concern of distributive justice. This question would take on an extra dimension if the agents who profit from the development of SRM technologies are also those who significantly contributed to climate change in the first place (for example "carbon majors" and oil-producing states). For these and other reasons, the regulation of intellectual property in SRM development is a key concern (Reynolds, 2019).

Some prominent academic proponents of SRM research have come out against the ability to patent SRM technologies (e.g. Keith, 2013). Notably, it was intellectual property issues which caused the cancellation of the outdoor delivery mechanism test in the SPICE project (Stilgoe, 2016; Watson 2012). while the scale of any profit may not raise much concern from the point of view of distributive justice, still, this issue becomes morally loaded if the agents who would benefit from the development of SRM technologies, even if indirectly, are also those who significantly contributed to climate change in the first place. A term has even emerged -- "geoclique" -- to reflect the fact that SRM research tended to be driven by, and reflect the interests of, a small group of mainly US-based male scientists (Keith, 2013; McKinnon, 2020; McLaren 2016b) as suggested also by studies on SRM procedural justice (reported below).

Recognitional justice

As noted above, advocates of recognitional justice emphasise how the unjustness of social and power structures, relationships and contexts (e.g. historical context) can not only result in unfair distribution of material goods but are an important concern in their own right, given the pervasive impact these factors have on people's lives. Fundamentally, issues of voice and engagement take on deeper importance when seen through the lens of recognition -- in a direct sense, as recognition of this type has so often been absent (Heyward & Rayner 2015; Hourdequin, 2019; Whyte, 2012, 2018b). Recognition is also relevant given the cultural and symbolic losses that indigenous and vulnerable groups might suffer, whether from climate change or the use of SRM. Here, many authors have underlined the differences in meaning that can be attached to such changes, notably, for relationships both between humans and between humans and non-human beings and/or physical environments (Buck, 2018; Oksanen, 2023; Whyte 2012). Any use of SRM must necessarily engage with experienced histories of oppression and colonialism -- on the one hand, given that SRM is positioned as a response to climate change, which emerges from and is manifested through histories of, e.g. "settler colonialism" (e.g. Whyte, 2016, 2018a). The fact that the planning and decision-making around SRM has so far been dominated by a select few, and where the use of SRM could be undertaken unilaterally, assumes particular significance when "dominance" takes on historically rich meaning (Hourdequin, 2019; Smith, 2018; Whyte 2018b). Apart from acknowledging the need for taking recognitional justice seriously when assessing the possible development of SRMs (e.g. Preston and Carr (2020) who suggest combining it with ethics of care), there are relatively few in-depth examinations of it as it relates to the development of SRMs.

However, there are clear indications that recognitional justice concerns will play a pivotal role in the development of SRM (Oksanen, 2023; see also Buck,2018; Carr & Yung, 2018). The case of the Sámi people's objections to the planned SCoPEx process-test (Oksanen, 2023) provides one of the clearest recent examples of when recognitional concerns were neglected. Despite not having received prior and informed consent SCoPEx planned to test their equipment, together with a local partner (the Swedish Space Agency) on traditional Sámi lands. The subsequent backlash, led by the Sámi people, led to the postponement and, eventually, the cancellation of the proposed test. By contrast, a marine cloud brightening test on the Great Barrier Reef, part of the Reef Restoration and Adaptation Program, made explicit efforts to engage with and pursue the active participation and express consent of local indigenous groups (Sovacool et al., 2023).

Other scholars (Hourdequin, 2019; Whyte, 2016; 2018a) have highlighted the value of taking justice as recognition seriously. Addressing Horton and Keith's care for "humanitarian SRM", Hourdequin (2019) contends that even if the use of SRMs could alleviate some of the harms of climate change for the world's most vulnerable, "participatory processes that take recognition seriously might raise the question of whether these are the only relevant harms" -- given unresolved challenges and concerns over dominance and potentially exacerbating maldistributions of power". According to Whyte (2012), the recognition of indigenous sovereignty would necessarily entail Indigenous peoples be closely engaged already on questions of SRM research. The African Group's objections to SRM at the UNEA assembly in Nairobi earlier this year gives some support to this view.

As such, the humanitarian argument for SRM has been critiqued as a form of the "lesser evil" argument, one with unfortunate similarities to justifications of policies that have oppressed or silenced indigenous peoples in the past (Whyte, 2016). To avoid such dangers, SRM governance should adopt an open, inclusive, dialogical approach that takes into account all the different viewpoints, especially the perspectives of the subjects most impacted by climate change and of those with the least possibility to have a voice in decisions on it (Oksanen, 2023; see also Buck, 2018; Carr & Yung, 2018). This would have to include different understandings of the very problem of climate change itself. Whyte (2016, 2018b) points out, for a number of indigenous peoples, climate change is bound up with the history of colonialism and "geoengineering, whatever its form" cannot be isolated and discussed simply in terms of its pros and cons to the local community.

Procedural justice and legitimacy

Issues of institutional feasibility (see Economic feasibility and required conditions) also intersect with concerns over procedural justice and legitimacy. One major challenge is to avoid SRM being outsourced or captured by elites, who could manipulate decision-making processes in their own interests -- the "geoclique" noted above, but more generally those who might benefit from avoiding having to undertake costly emissions reductions (Hamilton, 2013; McKinnon, 2020; Morrow, 2020). These elites could consist generally of large companies (e.g. fossil fuel, chemical, hi-tech, aerospace), industry representatives, political authorities, governance institutions, technocrats, bureaucrats, international managerial groups, knowledge networks and the financial system (Möller, 2023; Sovacool et al., 2023; Stephens & Surprise, 2020; Surprise & Sapinski, 2023; Szerszynski et al, 2013; Winsberg, 2021).

One way to minimise this danger is to ensure that procedural justice and legitimacy are part of SRM (Bodle et al., 2014; Frumhoff & Stephens, 2018; Morrow et al., 2013; Rayner et al., 2013; Schäfer et al, 2015; SRMGI, 2011; Zürn & Schäfer, 2013). Drawing on Barry (2002, pp. 97-99), procedural justice on SRM can be grounded in two fundamental criteria: impartiality -- the involvement in SRM of agents, all of whom having participatory parity (Fraser, 2005; Heyward & Rayner, 2015; Hourdequin, 2019; Lawford-Smith, 2020); equality of opportunity -- all agents must have the same opportunity to fully understand the issues at stake (Gasso, 2022), which could entail more informed decision-making (Morrow, 2020) and efforts towards broader engagement (Whyte, 2012; Wong, 2016). The impartiality criterion means that SRM should ensure the involvement of agents on an equal footing: SRM can attain procedural justice when the same rules, procedures, and formalities are applied to all agents. Regarding these two criteria, Lawford-Smith (2020) enumerates three approaches for engaging with publics in a democratic fashion, including representative sampling and surveys or deliberative polling.

By way of generally defensible principles, the rules for agents should be non-arbitrary and non-biased (e.g. Heyward & Rayner, 2015; Oksanen, 2023; Whyte, 2012). It is also necessary for the involved agents to control the functioning of such arrangements. Additionally, all SRM initiatives should maximise the cultural and social diversity of agents involved, ideally to be as representative of affected group as possible (e.g. Lawford-Smith, 2020; Smith, 2018). The equality of opportunity criterion relates in different ways to knowledge and is fundamental to reducing the complexity of SRM (Hourdequin, 2019; Wong, 2016) -- one of its salient traits. Equality of opportunity means that all the involved agents' concerns must be considered, such that potential conflicts are minimised between the institution itself and agents, and amongst agents, and that interactions between agents are seen as fair. Equality of opportunity is achieved when all agents play a proportionately equal role in SRM decision making.

In a broader perspective, given its complexity, procedural justice applies also to the ways in which political decisions about SRM governance and processes are made. When political decisions are carried out on the basis of inclusion and participation, SRM governance and processes can be argued to be more procedurally just than in cases when decisions are made on unilateral or minilateral bases (Callies, 2023). Different notions of consent -- explicit, implied, and hypothetical -- can be used as normative requirements for addressing some of the procedural issues raised by SRM (Rayner et al 2013, Wong, 2016). Explicit consent the easiest to ascertain and is the preferred form in participatory or deliberative models. However, it, and other liberal visions of democratic consent might also be contested from other perspectives (Wong, 2013). Ideas of democracy and democratic consent are themselves contestable and the fact that a decision-making process does not adhere to a given model of consent should not be automatic grounds for labelling it "undemocratic" (Heyward & Rayner, 2015).

Regarding legitimacy, a general reference is to its normative perspective, as it offers a benchmark of the acceptability or justification of governance arrangements (such as socio-technical systems). Normative legitimacy is indispensable for governing systems to gain more than purely strategic or self-interested (Buchanan and Keohane, 2006) or coercion-based backing (Buchanan, 2013; Hurrell, 2005) -- and specifically to foster open, inclusive, and independent decision-making on SRM. Although universal criteria for the legitimacy of governance systems do not exist it is possible to determine suitable ones for SRM by drawing on the relevant literature (Buchanan, 2013; Buchanan & Keohane, 2006; Keohane, 2011; Zürn & Stephen, 2010; and to make specific reference to solar geoengineering legitimacy (Callies 2018, 2019a; Morrow et al., 2013). Given its functional nature, SRM decision-making should abide by two criteria that specifically refer to the relationship of this socio-technical system with stakeholders representative of the general public. The first requires that SRM avoids inflicting serious injustices; the second requires the provision of sound information for dealing with normative disagreement and uncertainty (Buchanan & Keohane, 2006).

Looking more closely at some of the legitimacy issues at stake in SRM, the relevant literature suggests that the value of non-domination, especially in relation to global inequality, is essential to increase the legitimacy of SRM research (Smith, 2020). At the same time Jinnah et al (2020) propose to establish advisory commissions to contribute to the legitimacy of SRM research as sub-state level: according to the authors these institutional arrangements should meaningfully engage the public; include an iterative and reflexive learning mechanisms; and mechanisms for adaptation and diffusion of successful governance mechanisms across jurisdictions and scales. Morrow (2020) instead argues for well-designed mission-driven research programme to increase SRM legitimacy.

The discourse on legitimacy intersects with that on democratic authority in SRM. In this regard, there has been an active debate about the degree to which democratic decision-making is or is not at odds with the socio-technical system of SRM (Heyward & Rayner, 2015; Macnaghten & Szerszynski, 2013). Lawford-Smith (2020) maintains that global democratic authorisation to SRM is in principle possible and could be achieved on the basis of large-scale representative sampling and that the deployment of SRM by a single actor is impermissible. Whyte (2012) suggests instead that to grant democratic coordination to SRM a governance approach bases on the capacity of the various components of civil society to work creatively among themselves and in coordination with institutional agencies and representatives is necessary.

Rectifactory justice

The fact that SRMs might cause or worsen the situation, especially, of more vulnerable people, naturally raises the question of how to remedy these injustices. A means of remedying such injustices must be an essential part of any governance system for SRMs but there is relatively little literature on what such a scheme would look like and which principles for rectification should be chosen (see Heyward (2014), Svoboda (2017) and Callies (2018) for early contributions). In terms of the latter, there might be some useful insights from literature on remedying the injustices of climate change (e.g. Bell, 2009; Caney, 2005, 2012; Shue, 1999). Caution should be exercised and simply "applying" this literature to the case of SRMs but based upon it there are certain normative principles and that seem promising enough to at least be worthy of further investigation. This includes three principles for allocating remedial duties: the "contributor pays", the "beneficiary pays" and the "ability to pay" principles. There is general consensus that the "ability to pay" and "contributor pays" principles are essential to any sound rectificatory theory of climate justice, and some, but not all accounts also bring in the beneficiary pays principle, understood as a prohibition on "unjust enrichment" (Page, Caney, for criticism see, Heyward (2021) and Garcia Portela (2023)). Svoboda and Callies outline these three principles specifically with reference to SAI but neither offer a detailed account of responsibility to compensate. Svoboda, but not Callies, expresses some doubts about the viability of the beneficiary pays principle. Heyward (2014) is more optimistic about its viability, providing certain conditions are met. Another key insight from the climate justice literature that should be considered in future that normative priority of ensuring that rectificatory measures aim at ensuring that people can carry on with their previous way of life and maintain traditional relationships as much as possible. It also points to, the importance of symbolic measures and non-material forms of rectification as well as material compensation (Goodin, 1989), (Heyward & Page, 2016). The latter is especially relevant for any cultural and symbolic losses of indigenous groups that might arise from climate change and the use of SRMs (e.g. Whyte, 2016), and might also be emphasised by those who argue for recognitional" approaches to justice (e.g. Hourdequin, 2019; Preston & Carr, 2019; Whyte 2016).

Ethical issues

Several commentators have addressed specifically ethical questions about the prospect of certain SRM technologies, particularly sulphate aerosol injection. Most (but not all) raise a concern that to develop or use these technologies is hubristic: i.e. it exhibits the vice of excessive pride and arrogance. Concerns about hubris are often voiced in conjunction with ideas of "messing with nature" or description of the technologies as "Promethean" (Hamilton, 2013). There are two slightly different ways in which hubris (and its opposite, humility) can be understood (Heyward, 2018). The first appeals to the idea that it is simply not humanity's place to intervene in "natural" systems; rather humans should "live in accordance with nature", or in a reciprocal relationship with nature (Jamieson, 1996). It should be noted that such ideas are expressed in many religious and spiritual systems, including those held by historically excluded and oppressed groups and thus can be constitutive of individuals' identity (Hourdequin 2019; Whyte 2012).

The second does not claim that there is anything intrinsically morally wrong about large-scale intervention in nature, but warns that as these systems are very complex, the limits to human understanding and capacities must not be underestimated. Supporters of precautionary approaches (see above) might implicitly or explicitly appeal to this kind of hubris, as does Hulme (2012), when he expresses doubt that humans will ever be able to anticipate or control all the effects of deploying SAI. For instance, notions of precaution recur frequently in this literature (Hartzell-Nichols, 2012; McKinnon, 2019; Wolff, 2020). Among other arguments, a precautionary approach is contended to preclude inflicting serious injustices or indeed catastrophic risks (Hartzell-Nichols, 2012), the ability to effectively respond to long-term economic or political challenges (Wolff, 2020; Wong, 2014), having a pre-ready strategy to assess the risk of lock-in effects and to slow down or halt should such risks arise (McKinnon, 2019), and to broadly enable open, inclusive, and wide-ranging participation and informed decision-making on SRM (Heyward & Rayner, 2015; Lawford-Smith 2020; Morrow 2020; Smith 2018; Whyte 2012). Through the latter, stakeholders would be informed about changes in knowledge and consequences of SRM and be afforded the opportunity to respond accordingly.

As use of SRM would be a *deliberate* intervention in the climate system, and it is commonly thought that intentional acts are more morally praiseworthy or blameworthy than unintentional ones, the "doctrine of the double effect" might appear to be relevant. The doctrine of the double effect argues that it can be permissible to foreseeably cause some harms provided those harms are side-effects and are not the aim of an agent. However, this issue has received little discussion, with the exception of Preston (2017), whose tentative conclusion is that an agent who uses SRM might "bear less responsibility for any comparable unintended harms of SAI than the unintended harms of carbon pollution [GHG emissions]", particularly if those emissions are used to provide luxuries, rather than to provide basic subsistence.

Another ethical issue highlighted, but less discussed, is the potential issue of "agent regret", where decision-makers are placed in a situation where they have to decide where harms and injustices fall by having to decide whether to bring SRM into use or not. (Gardiner 2011a, 2011b; Svoboda, 2015). Gardiner (2010, 2011a) argues that having to make such choices can irredeemably tarnish an individual's life, even if the eventual choice was morally permissible, or even the best under the circumstances.

Finally, as noted above, concerns about moral hazard have been given an extra dimension, that of "moral corruption", referring to the temptation that some may have to knowingly put off emissions reduction measures and justifying it by arguing that research into SRM will make up for such a delay. Gardiner further suggests (while noting it is controversial) that any decision to favour the use of SRMs suggests that (a large proportion of) humanity is showing a continuing and deepening failure to meet a part of the human challenge of finding the right kind of relationship with nature (Gardiner, 2011a).

Economic feasibility and required conditions

Economists have evaluated the prospects and consequences of SRM for a long time. William Nordhaus's first paper introducing the DICE integrated assessment model in 1992 already featured geoengineering as a policy experiment (Nordhaus 1992). A few years later Thomas Schelling (Schelling, 1996) discussed the economic diplomacy of climate engineering. These two examples have significantly shaped the literature that has followed: the vast economics literature on SRM has tackled the problem either from the view of a central planner interested in weighing benefits and costs of SRM, or from a decentralised viewpoint in which different actors engage in strategic behaviour.

Methodologically, these two strands of literature have used methods from benefit-cost analysis and game theory respectively.

If SRM relatively achieves a temperature stabilisation cheaply, as suggested in the early literature on SAI (Barrett, 2007) and thus prevents uniformly across the globe the welfare losses associated with climate change (Belaia et al., 2021), and more cheaply than emissions reduction and CDR, it could be said to have high global feasibility. Yet these uniform global win-win outcomes may be hard to realise in practice. Moreover, recent evidence suggests this affordability is now challenged by issues of technical feasibility, making it technically challenging and limited to a few countries with engine production capacity (McClellan, Keith & Apt, 2012; Smith, 2020). Relative cost considerations aside, the literature also addresses possibilities for cooperation breakdown, primarily driven by diverging preferences over global temperature targets (Bas & Mahajan, 2020; Parker et al, 2018). Feasibility would be negatively affected if SRM alters global resource flows, thus raising an international cost-distribution issue. This could include compensation provided for harm from SRM countries/communities demanded as part of a possible international agreement (Craik, 2021; Horton et al, 2015; Reynolds, 2015), although such an agreement would be notoriously complicated to reach, judging by how complex and longstanding the contestations have been around compensation for loss and damage from climate change itself. SRM may therefore cause countries to worry that, as happens in other situations of international collaboration, some partners are economically benefitting more than themselves (Grieco et al., 1993).

We aim to succinctly review these main sub-streams of literature in what follows. We notice that review articles on climate engineering economics already exist, though they are now a few years old (A. Harding & Moreno-Cruz, 2016; Heutel, Moreno-Cruz, & Ricke 2016; Klepper & Rickels, 2012).

Economic costs of deploying solar geoengineering

SRM deployment entails costs that can be broken down between direct technology and indirect supportive or infrastructure costs. The main working assumption is that deploying SRM leads to side-effects and thus to economic indirect costs which need to be factored in. SRM could lead to potential disruptions for atmosphere, hydrological cycle, ecosystems with impacts for health (see Chapter 3). More work is needed to ascertain the indirect costs of SRM, and their spatial and social distribution. Economic costs would also include setting up an observing system that can monitor the effects, though few studies focus on these. Economic costs might also result from mitigation deterrence, whereby some costs of greenhouse gas emissions might be increased in a deployment relative to a non-deployment scenario, notably in terms of ocean acidification or negative impacts on public health from coal power plants.

Economic benefits

The economic case for SRM depends on two factors. The first is to what extent impacts from global warming will affect economic development and more generally welfare. The second is the extent to which SRM can offset such adverse consequences, bearing in mind that mitigation deterrence could lead to increased greenhouse gas emissions in an SRM deployment scenario relative to a non-deployment scenario. Regarding the first point, one of the most important developments in climate economics in the past 10 years is the mounting evidence of the adverse effects of climate change on economically relevant variables, such as economic growth, economic inequality, poverty etc.

Empirical methods using historical weather and climate records and GDP have been used to construct model estimations of non-linear relationships between temperature and economic development (Burke, Hsiang, & Miguel, 2015; Dell, Jones & Olken, 2012; Kalkuhl & Wenz, 2020; Kotz, Levermann & Wenz 2022; Kotz et al, 2021). This line of research agrees that regions which are already hot and poor today, where the largest part of the population will increasingly reside, will be the most impacted by climate change and that climate change impacts worsen inequality between regions (Gazzotti et al., 2021).

Accordingly, some research suggests that the relative economic benefits from SRM interventions would be largest in the Global South. Modelling comparing very high unabated emissions pathways (RCP8.5) and scenarios where SRM is used to cancel out all aggregate warming in such pathways, shows reduced between-country inequality in the latter case. However, this excludes "side-effects of SRM such as changes in ground-level UV" (A. R. Harding et al, 2020) as well as the "substantial secondary benefits" from the expansion of low carbon energy sources associated with mitigation scenarios (Diffenbaugh & Burke, 2019). On the other hand, the economic preferences for cooling will differ significantly across countries, creating economic trade-offs which could have important implication for SRM governance (Weitzman, 2015, and next section).

Summing up, the new evidence of significant economic impacts from climate change especially on the poor provides a *pro tanto* economic rationale for SRM, depending on the background emissions and adaptation capacity. These benefits, for example on temperature-attributable mortality can more than offset the indirect costs described in the previous section (Harding et al, n.d.). However, several caveats are in place. First, though the empirical evidence is growing, uncertainties remain, especially to what concerns the economically ideal temperature (Newell, Prest & Sexton, 2021). Second, SRM works well for global temperature offset but not for regional climate, especially for what regards precipitation (Yu et al 2015). The empirical evidence of the impacts of precipitation on economic growth is less clear than for temperature, but evidence is accumulating (Kotz, Levermann & Wenz, 2022). SRM is generally believed to reduce precipitation, which would harm economic development, though climate change is likely to intensify them. But once more, regional hotspots will be at economic risks, especially if SRM is not deployed at the right latitudes. More work is needed to ascertain these effects.

Benefit-cost analysis

Equipped with estimates -- albeit uncertain -- of benefits and costs of SRM strategies, economists have used a classical tool of policy evaluation, that of benefit-cost analysis. This has typically taken the view of a world, benevolent social planner which aims to maximise global welfare, typically defined as non-linear function of consumption. This kind of 'economically optimal' analysis has been carried out either with analytical or simple numerical climate-economy models. For example, the DICE model developed by Nordhaus in the early 1990s envisaged climate engineering playing a significant role in climate policy, given its lower implementation costs and fast effects (Nordhaus 1992). Subsequent work using similar tools has showed that the economic case for global, internationally coordinated SRM is sensitive to the parametrisation of costs and benefits, which as discussed are hard to quantify (Bakalova & Belaia, 2023; Bickel & Lane, 2009; Goes, Tuana & Keller, 2011; Gramstad & Tjøtta, 2010; Moreno-Cruz & Smulders, 2017). Some papers have looked at potential regional inequities arising from economically optimal SRM deployment, finding that on temperature these are expected to be relatively small (Kravitz et al, 2014; Moreno-Cruz, Ricke & Keith, 2012;), though uncertainties remain, and studies have neglected additional climate metrics and extremes (Heyen, Wiertz & Irvine, 2015).

Most of these analyses are deterministic, but a strand of literature has recognised the uncertainties and imperfections of SRM and put them in stochastic theoretical or numerical modelling. When accounting for uncertainty about the effectiveness and consequences of SRM, the main results of benefit-cost assessments shift towards more precaution and more limited substitutability between SRM and emission reduction (Emmerling & Tavoni, 2017; Heutel, Cruz & Shayegh, 2015; Manoussi, Xepapadeas & Emmerling, 2018; Moreno-Cruz & Keith, 2013).

Governance and cooperation

Economists have used theoretical and numerical models to explore the implications for SRM for international climate agreements from a strategic incentive viewpoint classic of the economic approaches and game theory, starting already in the 1990s with pioneering work of Schelling (Schelling, 1996). The literature is vast and has implications for SRM governance more generally (Victor, 2008). It is motivated by the long-studied problem of free-riding on public goods, which has a long tradition in environmental economics and empirical support through economic experiments. Free-riding is often cited as a primary reason for the lack of international efforts to curb GHG emissions and limited effectiveness of self-enforcing international agreements (Barrett, 1994). Scholars have noticed how climate engineering can transform the climate game from one of cooperation (notoriously hard to solve), to the simpler one of coordination.

Others point out how SRM could lead to cooperation breakdown and conflict, as the cooling preferences of different states may diverge (Bas and Mahajan 2020; Lockyer & Symons 2019; Parker et al, 2018). Self-interested strategies from different countries when these have different preferences for cooling can lead to detrimental economic effects: it has theoretically shown that the country with the preference for the largest cooling through SRM has an incentive to unilaterally implement SRM to the detriment of others -- if deployment costs are low (Weitzman, 2015). This new strategic behaviour has been dubbed 'free-driving' and would result in reduced global economic welfare. Behavioural economics experiments have empirically confirmed these theoretical fears (Abatayo et al., 2020; Ghidoni et al, 2023), and numerical simulations have shown that they can be quantitatively significant (Emmerling & Tavoni, 2018).

More generally, in rational models SRM changes economic incentives to form international coalitions to fight climate change. There are several game theoretic analyses of the interplay between SRM and emission reductions: the literature is vast with many findings but in general indicate that SRM could help sustain international climate coalitions when deployment of SRM is credibly seen as a threat, but that the effectiveness of SRM to fight climate change might not change or be achieved without sufficient emission reductions (Finus & Furini, 2023; Heyen & Lehtomaa, 2021; Heyen, Horton & Moreno-Cruz, 2019; Manoussi & Xepapadeas, 2015; Millard-Ball, 2012; Moreno-Cruz, 2015; Pezzoli, Emmerling & Tavoni, 2023; Ricke, Moreno-Cruz & Caldeira, 2013; Urpelainen, 2012).

These findings contrast with scholarship that highlights the risk of SRM leading to reduced mitigation efforts (e.g. McLaren, 2016b). Furthermore, while sophisticated in their mathematical treatments of strategic economic interactions, all these studies make rather simplistic assumptions about SRM.

Finally, all the literature discussed above focuses on SRM implementation. Few papers in economics have examined whether and how research on SRM should be governed. Generally, they find a positive economic value of undergoing research on SRM if this can reduce the uncertainties around its effectiveness and side-effects (Harding, Belaia & Keith, 2023; Quaas et al., 2017). However, the same research emphasises the potential risks that SRM research could lead to its deployment and to reduced emission reduction efforts.

Institutional feasibility and required conditions

The institutional feasibility dimension of SRM involves dilemmas of governance (expanded upon more in Chapter 7) but also democratic constraints. Some argue that SRM does not need radically new institutions, at least until fully-fledged deployment (Reynolds 2019a), while others suggest that current global governance and law are currently largely lacking in effective and equitable institutions (Biermann et al., 2022; Talberg et al., 2018) and that 'de-facto' governance emerges in unintended and undeclared ways e.g. through authoritative assessments and research norm curation (Gupta and Möller, 2019). A related issue is that governance, because research and deployment are inherently linked through the co-production of knowledge and technologies, norms and institutions, cannot wait until the moment of fully-fledged deployment (McLaren & Corry, 2021). However, whether SRM, as a complex socio-technical system, should rely on current institutions and uncoordinated norm development, depends also on what requirements such institutions should fulfil and what role SRM is envisaged to play in tackling climate change (Gupta et al, 2020)

The dilemma of institutional governance

There are several examples of scenarios for the development of SRM institutions which each assume different functions, objects, and agents involved (e.g. Bodle et al, 2013; Lloyd & Oppenheimer, 2014; Parson & Ernst, 2013), at the international level. Some argue the urgency of the climate crisis means SRM would end up relying on the available institutions (Chhetri et al, 2018), as time constraints would not allow for the establishment of new ones. For others, risks of a potential clash with current institutions leads them to discourage institutional innovation for SRMs (e.g. Bodansky, 2013). However, Talber et al (2018) point to current 'default' governance and find it to be 'characterised by uneven regulation from existing multilateral agreements established for other purposes' resulting in 'unplanned and piecemeal governance' (p. 249) and call instead for multilateral institutional arrangements to emerge through 'anticipatory governance, which also prioritises public participation, deliberation, and adaptive management, but emphasises the need for foresight' (Tabler et al, 2018, p.250) or through single countries or consortia of countries (Virgoe, 2009). This more stop-down strategy begins with one or a few countries cooperating around SRM.

For example, Keith and Irvine propose that 'a coalition of smaller democracies including a mixture of high-income and low-income countries could play an important role' rather than asking the US to lead alone (Keith & Irvine, 2021). However, the latter reinforces a fear that Western states -- or the US on its own as the lone superpower with the capacity and incentive to do so (Surprise, 2020) -- would assume effective or formal control. Another position is that existing institutional arrangements, simply require development, potentially in a polycentric way, to develop the legal mandates and the political capabilities to govern SRM, including most immediately developing a transparency mechanism for research; creating a global forum for public engagement and including consideration of SRM in the global stocktake under the Paris Agreement (Nicholson et al., 2018).

In all cases legitimacy of governance is considered important and is often considered to depend "on the perceived neutrality of decision-making institutions. However, judgments as to what constitutes an unbiased process rest on culturally specific civic epistemologies, or public understandings of the right ways to generate and evaluate policy-relevant knowledge" which vary from country to country (Jasanoff, 2019 pp. 81-84), as well as among experts (Sovacool et al., 2023).

Democratic constraints

SRM development and especially deployment on a potentially a planetary and decadal scale poses considerable challenges to democratic mechanisms of representation, accountability and control. Some scholars argue democracy in global governance is not necessarily incompatible with SAI (Heyward & Rayner, 2015, Heyward, 2017; Horton et al, 2018), while others argue planetary interventions would place severe strains on liberal democracy as well as the notion of meaningful global democratic process (Szerszynski et al., 2013). Democracies are for some, better-suited to providing environment-related goods in the public interest (Bernauer & Böhmelt, 2013) though whether this includes research and deployment of SRM is uncertain. Some claim that democracies, by virtue of their greater institutional capacity, can better contribute to, and participate in, collaborative international environmental action (Ward, 2008), while others argue that threats to public safety could require more authoritarian responses to the climate crisis (Mittiga, 2022), adding weight to the risk that governing transboundary SRM would compromise democratic principles of consent.

Second, public awareness of the threat posed by climate change, of the features and objectives of SRM, as well as public engagement are expected by some to be influential determinants of institutional constraints, given the extent to which decision-makers, though mainly in democratic societies, respond to public pressure (see Public and social perceptions). It is assumed by some that where awareness of SRM technologies (Burns et al., 2016) and public engagement are higher (Carr et al, 2013), SRM would clash less with existing institutions, since decision-makers are more willing to accommodate meaningfully agreed social and political requests. The recent maturing of far-right parties' climate change policy agendas (Malm & the Zetkin Collective[^6]) raises potential questions about the potential role of SRM in climate policy landscapes influenced by anti-migration and anti-global governance ideologies or scenarios where traditional high-carbon lifestyles are defended against pressure to decarbonise rapidly (McLaren & Corry, 2023).

The third factor relates to interest groups -- in particular the carbon intensive industries -- and the role of non-governmental organisations, especially environmental ones, mentioned under Actor networks and interest groups.

Political, security and geopolitical feasibility and required conditions

Much climate modelling that simulates possible risks and benefits of stratospheric aerosol injection excludes "geopolitical strife over attempts to implement geoengineering" (Kravitz et al 2014, 6). This element is thus potentially underestimated in climate model-heavy evidence base used so far to assess risks and benefits of SRM. This is reinforced by common metaphors of SRM that project the idea that a singular global actor or coordinated coalition would be doing the global cooling, for example, as a medical drug that a doctor could choose to administer. Here, not only is the geoengineer singular, but the Earth is by implication an individual body or 'patient' in need of therapy (see Nerlich and Jaspal 2012). For analytical reasons, however, many climate model studies assume a "central planner framing" (e.g. Keith & MacMartin, 2015) or a 'global utility' policy aim ---both of which leave out many implications of the world being divided into multiple uneven societies. The risk of overestimating the feasibility of SRM based on this is noted, and may increase the probability of high-risk options being pursued: "narrowly framed considerations of performance and risk offered by traditional technocratic expert-analytic methods of appraisal" (Bellamy, Chilvers, Vaughan & Lenton, 2012) may contribute to cognitive lock-in and bias decision-making processes towards high-risk courses of action (Cairns, 2016) .

This chapter further explores issues of feasibility that connect with the following political and geopolitical and security themes: militarisation and weaponisation, perceptions of risk, unilateralism, geopolitical entanglements, blame, termination shock, and wider securitisation concerns.

Militarisation and weaponisation

According to Sovacool et al (2023) the risk of proliferation and spread of new capabilities makes for potential 'spill-over into an arms race or new technology in the hands of new actors' who could become military or hostile. Surprise (2020) argues that a 'logic of militarism' is more likely than a 'logic of multilateralism' that is often assumed in modelling and governance literatures. This is based on the idea that US' strategic goal of global pre-eminence currently builds on global operations and dollar primacy that both remain dependent upon fossil fuels (to facilitate global reach of bases and weapons systems, and to undergird the US dollar as reserve currency). Assuming this reliance, no other actor has the capabilities and strategic interests to deploy SRM at global scale. Security dimensions are also envisaged through critical infrastructures that either require military protection or logistics (Nightingale & Cairns, 2014) or involve a blurring of civilian research infrastructures and military or strategic infrastructure such as COPERNICUS earth system modelling partly for environmental, partly military/national security purposes. (Rothe, 2017). Others consider there are risks of military uses in that states "could utilize geoengineering technologies to build their military capacity, similar to the dual-use option of things like nuclear technology" (Sovacool, Baum & Low, 2023).

Historical studies show that interventions in weather systems have been closely linked to military ideas and planning, although very often unsuccessful in terms of gaining purposive control of weather or in terms of security peace and stability (Fleming, 2012b). The entanglements of climate modelling and national security interests, including Cold War research into implications of nuclear weapons explosions (Allan, 2017) and attempts to control weather, for the US during the Vietnam war (Schwarz-Herion 2018), and for civilian purposes, suggest that potential future interlinkages between solar geoengineering and security infrastructures and interests cannot be ruled out (Scheffran, 2019). However, they also show that there is a difference between plans and imaginaries of the potential uses of such intervention techniques and the success and/or severe difficulties in determining effects and attribution (Fleming, 2012a).

Perceptions of risk and disagreement

Briggs (2018) argues:

> "A general view in the US security community holds that geoengineering (and in particular, SRM) projects are not tightly controllable, and therefore are analogous in some ways to biological or chemical agents. Militaries tend to dislike platforms that are not tightly controllable and predictable."

Here the unpredictable outcomes of it present an unwanted factor for military planners and security officials who put a premium on stability and predictability. Another route to potential security concerns is through disagreement.

Another classical framing involves disagreement about preferred climate outcomes leading to conflict, sometimes encapsulated through the metaphor of 'who controls the thermostat'. This envisages that national interests are linked (or can be politically associated with) certain temperature preferences (or other climatic variables deemed desired or unwanted) and that states might compete to provide their ideal or preferred climate via geoengineering, potentially leading to compensatory 'counter-geoengineering' (Bas & Mahajan, 2020). This is a doubtful assumption, that national interests can be read directly off temperatures or given climatic conditions, but one that features often in modelled scenarios with strategic (or rational) actors, in which possible geoengineering strategy and conflict is explored (Heyen, Wiertz & Irvine, 2015; Ricke, Moreno-Cruz & Caldeira, 2013; Rickels et al., 2018). However, not much is known yet about how climatic changes can or will be interpreted differently by different countries and actors, and how 'national security' might be politically linked to (partly chosen) climatic states. Gareth Davies (2010) proposes that SRM is actually conductive to international cooperation.

Unilateral action

The risk of unilateral action figures prominently (e.g. Low et al., 2022; Victor, 2008), while there are opposing perspectives contending that such concerns are overblown (Horton 2011; Smith & Henly, 2021). In general, most literature concludes there are limits to who might be able to plan, launch and sustain global scale geoengineering in the face of likely international resistance. One argues that currently only one state has the interests, capabilities and strategic, financial and military infrastructure to carry out global scale SRM (Surprise, 2020). Rabitz assesses that "Only powerful states have motives and capacities for unilateral use in the short term" but that in the longer term the threshold may be lower. (Rabitz, 2016). Some consider unilateral action by non-state actors a possibility though mainly in relation to economic interests or -- hypothetically -- environmental groups taking matters into own hands. "If a rogue nation develops launch systems, that opens a door to their launching new satellites or defence systems or even missiles, creating tensions", (Sovacool et al., 2023) this could involve militarisation through solar geoengineering.

Entanglement with geopolitics

A growing literature leaves behind the idea of solar geoengineering causing conflict as an isolated factor and attempts to assess the possible interactions with other existing or future geopolitical rivalries and tensions. Lockyer and Simmons assess Australian defence policies and geopolitical issues finding solar geoengineering to be a 'secondary' derived risk factor in Southeast Asian and Pacific context (Lockyer & Symons, 2019). They conclude:

> Since solar geoengineering is unlikely to become a first-order international issue, disputation over solar geoengineering will likely reflect, or act as a proxy for, wider patterns of state interaction. However, scenarios in which China and the United States take different positions, or in which there are divisions among regional powers, such as Indonesia, Malaysia, India and Singapore would pose the greatest threat to Australia's national security.

European considerations in comparable scenarios with great power (between China and the US, for example) or regional rivalry have not been explicitly reported on but a study of expertise on Arctic security matters judged that geoengineering to 'refreeze' the region would not be in the common interests of the multiple significant players in the region, including the largest, Russia. (Versen, Mnatsakanyan & Urpelainen, 2022). The conclusion is that "a variety of short-term economic opportunities" would prevent coordinated geoengineering, although "imminent climate crises elsewhere" may prompt greater attention in the future. Another analysis suggests that Arctic geoengineering experiments and scenarios play into an increasing 'global Arctic' framing that disconnects the region from local actors and empowers global ones, but that conflicts between local Arctic and more remote interests, could become a possibility (Corry, 2016).

Blame

The idea that solar geoengineering, and by extension the 'design approach' especially, might recast existing 'natural disasters' as hostile actors or results of unfriendly foreign actions has been discussed. One common narrative in the debate is that already tense areas of conflict such as the India-Pakistan border might be affected by extreme weather which, during a deployed global or local geoengineering programme, could be interpreted as the result of hostile acts of climate intervention by one party (Corry 2017; Nightingale & Cairns, 2014). A related discussion suggests that conspiracy and disinformation or hybrid forms of warfare involving alleged or real geoengineering could become a major stressor of inter-societal relations (Cairns, 2016; McLaren & Corry, 2023). Cases of Russian alleged misinformation about the malicious causes of wildfires in Russia have been recorded and suggested as an indicator of the potential for such dynamics to become intertwined with geoengineering.

Termination shock

The oft-cited risk that a cessation, voluntary or involuntary, of a solar geoengineering programme, involves potential for a 'security' risk, either in terms of ecological or human security endangered by rapid temperature risk, or in terms of the leverage or threat from actors able to and willing to disrupt the continued provision of SRM. Some analysis judges this scenario to be low risk (Parker & Irvine, 2018) whereas others argue that the assumptions behind such analysis exaggerate the rationality of actors. They may tolerate 'blowback' hitting them, or non-state or 'rogue' states might contemplate using disruptions to an ongoing SRM program as threat or leverage.

Securitisation and wider 'security' concepts

If 'security' is a wider concept than 'national security', or similar logics of existential threats, necessity and emergency measures is traced, a wider set of issues surrounding solar geoengineering come into focus. This includes the notion of 'ecological security' whereby climate becomes viewed as an existential threat to fragile Earth systems or ecosystems and vulnerable populations alike (McDonald, 2022). Conversely the argument is made that solar geoengineering may contribute to preserving existing 'ways of life' and incumbent interests dependent upon or ideologically linked to fossil fuels, by providing a climate strategy that ostensibly protects climate (albeit imperfectly) as well as prized or privileged societal traditions or privileges. In this case vulnerable populations are excluded from richer areas in the guise of 'migrants', while the problem of 'stranded assets' in potential fossil fuel earnings is avoided and financial stability or existing distributions are protected (McLaren & Corry, 2023). Relatedly, certain 'fractions of capital' including but also beyond fossil fuel industries have shown interest in funding solar geoengineering research and one argument links the interests of 'big tech' and other industries and sectors with similar interests in security future ecological or political space or licence to operate (Surprise & Sapinski, 2021).

Chapter 7: Governance dimensions and legal issues

Key messages

- Governance can be both an enabler of SRM, creating favourable conditions for adoption, or an inhibitor of SRM, setting restrictions and prohibitions.
- The challenges of governing SRM research are likely to be different for different SRM technologies, given potential risks and benefits of technology development or eventual deployment.
- Potential future deployment scenarios, whether enabling or restrictive, raise their own, distinct political challenges, including consistency with existing international legal commitments, as well as with existing governance practices in regard to other, comparable types of activities.
- Even though there is no specific international treaty governing SRM activities, several customary law and treaty law obligations pose binding requirements for the governance of SRM research and deployment. It could also be necessary to design and establish entirely new international institutions to achieve intended or desired results, including those explored in modelling.

Governance can be both an enabler of SRM, creating favourable conditions for adoption, or an inhibitor of SRM, setting restrictions and prohibitions. As Figure 7 (below) indicates, a diversity of proposed models of global governance of solar geoengineering exists in the academic literature. In addition to examining research and deployment governance (both enabling and restrictive), the chapter also delves into legal principles and existing duties under international law.

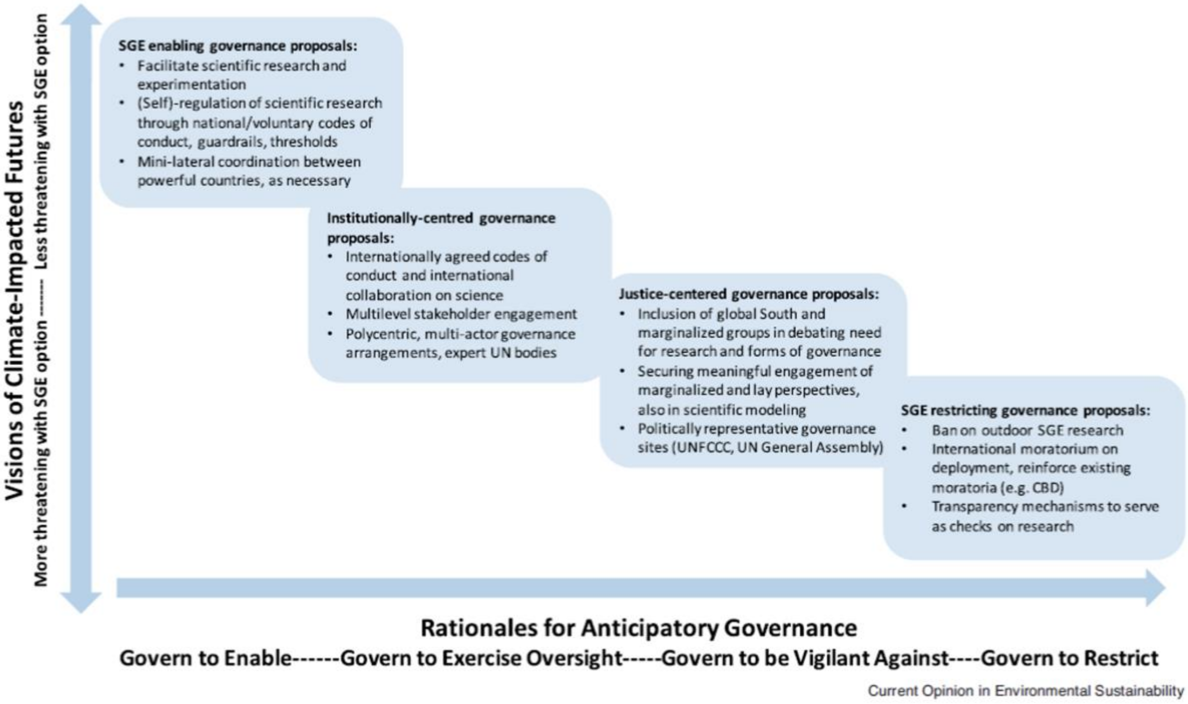


Figure 7: A diversity of governance approaches to SRM: reflecting contrasting visions of its role in climate-impacted futures Source: Gupta et al 2020. Some of these seek to enable SRM, whereas others seek to restrict SRM.

Research governance

The challenges of governing SRM research are likely to be distinct for different SRM technologies, given potential risks and benefits of technology development or eventual deployment. The most far-reaching consequences are envisioned for techniques that would have planetary scale impacts, such as SAI. Debates on SRM research governance have so far largely taken place within expert communities and academia. Many have called for scientists follow codes of conduct, scientific review processes, and university ethics boards in the absence of government oversight (Hubert, 2021, Dilling and Hauser, 2013) while an overwhelming amount of the literature has focused on possible oversight from public authorities (Biermann et al., 2022; Brent et al., 2019; GESAMP, 2018; Parson & Keith, 2013 on 'marine geoengineering', and CBD (2009) on 'geoengineering'), at national and international levels. In general, a distinction between 'indoor' and 'outdoor' SRM research may be useful: regardless of any applicable desirability considerations, 'indoor' (i.e. laboratory- or desk-based) SRM research enjoys significant legal protection at the international and European levels, as well as at the level of EU member states.

There are limited, if any, ways of restricting or even prohibiting indoor research in the absence of far-reaching legal (and possibly constitutional) changes. This does not necessarily limit the placement of restrictions on, or the creation of additional oversight mechanisms for, public funding flows directed towards such indoor research (see Biermann et al., 2022). In the case of outdoor research, different sets of considerations apply due to the potential environmental impacts, as well as the potential for going down a slippery slope from testing towards technology development. These impacts and the link between some outdoor testing and technology development require research governance and regulatory oversight. The environmental impacts and risks would need to be assessed, managed, and where appropriate avoided, in line with existing or potentially new legal and regulatory provisions, at international, European and national levels. With this distinction between indoor and outdoor research in mind, one important consideration or research question is whether both give rise to the 'slippery slope' problem in the same way; or whether those are more likely to be associated with outdoor research (for instance due to sunk cost effects from the comparably higher investments into technology and infrastructure required for outdoor research relative to indoor research).

Current state of SRM research governance

SRM research governance and oversight would need to have both national and multilaterally agreed components. At both national and international levels, some first attempts at providing frameworks for SRM research governance already exist. Although there are only few specific research governance frameworks for (different) SRM techniques, several voluntary guidelines have been put forward by individual scientists or science networks (Biermann et al., 2022; Boettcher et al, 2023; Gardiner & Fragnière, 2018; Hubert, 2021; Oxford Principles; Rayner et al., 2013; Tollgate Principles).

Importantly, research governance is also part of some international treaty systems (see State obligations under international law and legal principles). Likewise, global governance advisory bodies have drafted anticipatory principles that are pertinent to research governance and engagement (e.g. UN Human Rights Council, 2023; UNESCO, 2023). More generally, obligations of general international (environmental) law govern transboundary risks and further guidance could be derived from the principles of 'do no harm' or the precautionary principle, which is a general principle of EU law binding upon EU institutions, some argue that it is not straightforward in its application to SRM (Florin et al., 2021). These international obligations are pertinent not only to potential future use or non-use of SRM techniques, but also to various stages of SRM research (see also State obligations under international law and legal principles).

Given that much of the SRM literature addresses SAI and given its potential for global effect, proposed research governance frameworks focus largely on SAI. These frameworks can be grouped into: (i) possibilities of polycentric research governance (Nicholson et al., 2018; Reynolds, 2019a); (ii) developing frameworks for constructing multi-dimensional scenarios that help reveal geopolitical contestations (Grieger et al, 2020; Gupta et al., 2020; Low et al., 2022; McLaren, 2023) or comparative risk frameworks (Felgenhauer et al., 2023; Sovacool et al., 2022); or (iii) improving global stakeholder engagement (Biermann & Moller, 2019; Whyte, 2019; Winickoff et al., 2015) without instrumentalising new stakeholders towards established positions (Owen, 2014).

National-level institutions largely in the US and the UK, including the UK government, the UK's Royal Society, the UK's Institution of Mechanical Engineers, Australia's Office of the Chief Scientist, and the United States National Academy (NAS, 2021) have called for SRM research and research governance. Some analyses point out the merits of national research efforts in line with freedom of research and corresponding sovereign rights of nations (Bodansky & Wanser, 2021), while others note the dangers of current US dominance in SRM research programmes (Stephens et al., 2023). A recent comparative assessment of potential policy responses in three other countries --- China, Australia and Germany --- to launching of an SRM national research programme in the US, concludes that these countries would be 'likely to seriously consider comparable efforts only in response to a US programme, although their reasons for doing so and specific programme designs would differ', noting therefore that 'the global trajectory of solar geoengineering depends disproportionately on developments in the US' (Horton et al, 2023). On the other hand, there are also prominent examples of countries restricting research and experimentation (for example, Mexico); and key cases of outdoor experimentation that have been cancelled or not permitted in the face of internal controversy about patent applications or civic opposition (SPICE and SCoPEx-- see Oksanen 2023; Stilgoe et al., 2013), with parallels to other prospective forms of climate intervention, see Gannon & Hulme, 2018; Low et al., 2022; Strong et al., 2009).

Governing the demarcation between research, technology development and deployment

A first consideration is the need to demarcate between laboratory research, field research, technology development and deployment, and to avoid a slippery slope from research to deployment. Many are concerned that field research might come with higher risk of advancing toward deployment capability. It it is unclear whether and how such a slippery slope dynamic may play out in the case of field research or whether guardrails can be developed to mitigate this risk (Cairns, 2014; NASEM, 2021; Stilgoe et al., 2023; Tang, 2023).

The types and stages of research may be important variables in a research governance process, though the levels of transparency and public engagement following principles of responsible research and innovation are important across multiple types and stages of research (Low & Buck, 2020; Smith, 2018). Typically, distinctions are made regarding how to exercise oversight for indoor theoretical research, such as modelling or social science analyses; oversight and control over small-scale outdoor experiments; and oversight and control over large-scale outdoor experiments, though proposals on distinguishing based on scale (Parson & Keith, 2013) have not found broader agreement.

A related issue is whether additional oversight over experiments that focus on fundamental climate-system investigations (e.g. cloud dynamics) is warranted without impeding research that would be needed to answer pressing knowledge needs. There is also ongoing debate how to introduce oversight of research endeavours that would critically test technological viability, yet in doing so might also develop technological capability (i.e. injection methods). Outdoor experiments typically might overlap in scope and findings between basic research, research to identify limitations in technological capabilities, and technology capability development, making a careful and detailed governance approach to guiding such research, including full prior informed consent from all relevant stakeholders crucial, if it is to be contemplated. Larger scale experiments may more straightforwardly be governed based on their potential for adverse environmental impacts and the corresponding obligations in (international) environmental law, environmental impact assessment, via ethics boards' approval processes and similar.

The larger the scale of an experiment, the higher the need for political control and consent. Political discussions under the London Convention/London Protocol, where an international regime for marine climate engineering has emerged (currently limited to some forms of carbon dioxide removal, but with an ongoing exploratory process toward a potential inclusion of marine cloud brightening, as well as reflective bubbles and particles in a marine context) , also highlight the importance of defining criteria for delineating "legitimate" forms of (outdoor) scientific research from non-legitimate forms that are either capricious in nature or pretexts for commercial deployment.

Related challenges here include how to define safe 'thresholds' of activity and impacts, including whether and where to draw the line between small and large-scale experiments (see e.g. Parson & Keith, 2013). A core consideration for a planet-altering technology like SAI, and even for regional but transboundary approaches, is the need for an inclusive, multilaterally agreed political decision-making process. Some precedents to determine what constitutes legitimate (and hence permitted) scientific research exist within research governance frameworks in international (environmental) regimes (e.g. CBD, LC/LP; mining in Antarctica); in other restrictive legal international regimes in areas of acknowledged harm (e.g. chemical and biological weapons); and in emerging national or transnational governance of potential future risks posed by novel technologies (e.g. human cloning). In many of these issue areas, some distinction between permitted and non-permitted research and oversight of legitimate research is provided for, even as technology development may be restricted (Gupta et al., 2024).

Governing (and assessing) a narrow versus broad set of research-related impacts

Another central policy choice is whether research governance should address only the narrow and immediate environmental impacts of specific experiments or their broader political impacts and implications flowing from the symbolic nature of appearing to "test" a controversial technology -- which is particularly salient for outdoor small-scale experiments (Low et al., 2022). However, it is also a concern regarding indoor theoretical research where a dominance of modelling 'designed' around optimised climates can create a false impression of long-term controllability. For some, this is inherently problematic (McLaren 2018). It may also be problematic on the grounds that such knowledge might itself provide the conditions for greater inequality and domination (Smith 2018). For others, this points to a need to co-create a wider array of scenarios for analysis also of imperfect and (geopolitically) messy SRM applications (Low & Honegger, 2021). This issue arises also in relation to the international 'no harm' principle that should guide research oversight. An important question here is whether harm should be narrowly or broadly understood; whether to consider immediate environmental impacts or also broader political and symbolic consequences of research and experimentation. While both perspectives are evident in the academic literature (e.g. Parson & Keith, 2013 and Parker, 2014 vs McLaren 2023; McLaren & Corry, 2020; Stilgoe, 2015), it is worth noting that real-world examples reflect broad conceptions of harm, with rationales underpinning social opposition to outdoors experiments going beyond narrow forms of physical harm to expansive, multidimensional, and global perceptions of risk (Low et al., 2022; Oksanen, 2023; Stilgoe et al., 2013; Strong et al., 2009).

Research governance to facilitate more informed global decision-making

A fourth core issue for research governance is that the risks posed by SRM require information about the long-term effects of deployment at planetary scale over a sustained period, which may unfold in a non-linear manner and with unequally distributed effects (Reynolds & Parson, 2020). As such, a fundamental question facing SRM research governance is what each respective research effort (short of full-scale deployment) can usefully reveal about planetary scale, sustained non-linear effects of SRM. It is important to acknowledge potential limits to "knowability" through research, given non-linear effects from global deployment that cannot be extrapolated from small-scale or even large-scale field experiments. It remains unclear whether and how a concerted interdisciplinary effort can help to identify what those limits of knowability might be.

This also raises the concurrent broader question of whether the findings would provide relevant evidence to decision-makers. Some have argued that there is a risk that research may provide a false sense of security that decision-making in the future might be facilitated via the research underway, even as this may well not be the case (Biermann et al., 2022; Corry, 2014; Low & Honegger, 2020; McLaren, 2023). This is a crucial point when contemplating the purposes of SRM research and its governance: if outdoor experiments cannot realistically deliver (some) of the information that decision-makers think that these experiments will deliver, this may introduce a pro-SRM research bias into decision-making, with consequences for technology development and eventual future deployment, even if not intended. A possible remediation of this is to require a concerted effort to sharply identify the potential knowledge contribution as well as its limitations of each research endeavour. This may require a critical-constructive interdisciplinary research design including both at project and programme level.

A related consideration is whether public funding should go to controversial SRM techniques with uncertain risks, such as SAI, with some arguing that this should not be the case (Biermann et al., 2022). Here, a relevant question is whether there are precedents or analogues for restricting public funding for research that may lead to technology development in the case of other novel technologies (e.g. the US bans federal funding for research on human cloning).[^7] Some are concerned that while such an approach can work to limit research within a jurisdiction, it would not prevent research conducted elsewhere, resulting in a situation in which the more restrictive government would be hindered by an absence of domestic (governance and research) expertise in shaping the global (research) governance of the technology. Restricting research in other jurisdictions would accordingly require international rules and norms, as is the case for other types of high-risk research (e.g. Tucker, 2006).

Research governance of both public and private activities

Additional considerations include how to exercise public oversight over private research, nationally and internationally. While much formal international law focuses on state actors, research oversight mechanisms at national and international levels also put the onus on states to regulate and exercise oversight over private SRM research activity within their jurisdictions (see State obligations under international law and legal principles), including through information disclosure obligations, obligations to solicit research permits, undertake impact assessments and/or to solicit informed consent of impacted parties (Gupta et al., 2024). This research oversight would apply to both public and private parties seeking to conduct SRM research, particularly outdoor research. Some note that its effectiveness would depend on the oversight mechanism at hand, as international instruments tend to be limited to transboundary risks and publicly funded work.

Commercial implications remain highly underassessed. Although the literature posits that most forms of SRM would ultimately come under state (and security planning) control, there are possibilities for upstream outsourcing of infrastructure innovation and intellectual control through patenting (Reynolds, Contreras & Sarnoff 2018; Reynolds 2019a). A recent episode involving a small-scale, firm-led experimental deployment in Mexico (all such activities have since been banned by the Mexican government) that encouraged online purchasing of unverified 'cooling credits' has reopened a debate about profiteering motives in SRM development.

Transparency as a core research governance mechanism

Principles and practices of anticipatory governance (Guston, 2014) or responsible research and innovation (RRI) (Stilgoe et al., 2013) have been proposed as a set of guiding principles to govern research into novel and speculative future technological interventions, such as climate engineering (see also Gupta & Moller, 2019). The EU-funded Co-CREATE project starting in 2024, which explores conditions and potential guidelines and principles for SRM research, pursues this endeavour also with a view to practice RRI principles.

Amongst various principles, many agree that transparency about who is doing what kind of research, funded by whom, is crucial to secure accountability and effective oversight and governance. Here, a global registry of research has been proposed in the literature as an important aspect of research governance (Craik & Moore, 2014). This could be relevant not only at national levels but also at the internationally scale, though beyond European-funded research it would likely remain a voluntary effort. Examples from other areas of global governance of novel technologies include proposals for a global observatory system for (human) gene editing (Jasanoff & Hurlbut, 2018; Nelson et al, 2021) and analysis of how global clearing houses of information for biosafety or safe use of biotechnology are set up and functioning (Gupta, 2010a; 2010b). In the case of SRM research governance, such registries could enhance transparency about, for example, (potential dual use) research, patent applications, or technology developments.

Governing SRM research to avoid mitigation deterrence

A final consideration in developing and adopting frameworks of research governance is to ensure that SRM-related research will not inadvertently or intentionally delay mitigation programmes (Baatz, 2016; McKinnon, 2019; McLaren, 2016b). The prospects for such a crowding-out effect are hard to empirically research or document, notably, whether (hypothetical) availability of SRM options may encourage reduced investment in or commitment to mitigation activities.

While robust evidence is not yet available in relation to SRM, insights might be gleaned here from the broader psychological and behavioural scientific literature, for instance, on how technological developments in the climate or health space might (inaccurately) affect subjective estimates of risk and thereby promote biased decision-making or insufficient behavioural change (e.g. Otto et al., 2014; Hornsey & Fielding, 2020; Osman et al., 2020).

In the context of SRM, there is some experimental evidence on the relationship between learning of SRM and individual support (among members of the public) for mitigation-related activities (Andrews et al., 2021; Austin & Converse, 2021; Cherry et al., 2021; Merk & Wagner 2024). Using a game-theoretic framework where players sought to prevent a simulated climate disaster (and where one participant assumed the role of "policymaker), Andrews et al (2021) however found use of SRM had no effect on mitigation contributions -- interestingly, this was despite research participants believing this would occur, leading them not to opt for SRM. Using a survey experiment with 1571 US participants, Cherry et al (2021) also found that providing individuals with information about SRM increasing their likelihood of supporting a proposed national carbon tax. Lastly, employing social-media analysis (on Facebook), Merk and Wagner (2024) established that messages about SRM (or CDR) had limited effect, both failing to encourage support for the mission of a US environmental nonprofit or, conversely, undermine the effectiveness of climate messaging.

While finding few crowding out effects, it should be noted that these studies are conducted with members of the public instead of policymakers and are broadly hypothetical in nature, with results also shaped by who is being asked what kinds of questions, how the options for SRM versus mitigation are presented, and what theoretical risks and potential promises are attributed to each. Extrapolating from such hypothetical studies that mitigation deterrence will not occur is therefore risky, particularly given that this phenomenon is notoriously hard to empirically document.

In any case, in the real world, the evolution of the EU's Green Deal and other existing climate policy commitments should serve as a key guide, notably, as awareness of SRM increases. It remains a challenging question, nonetheless, as to where the responsibility rests to avoid mitigation deterrence and moral hazard, including at the research stage, and how this can be ensured. There are few models or proposals in the literature currently to guide policy on this, at least none that are likely to pass the tests of being perceived globally as legitimate, effective and politically feasible (Reynolds, 2022). If we extend out to include ethical and moral discussions (see Considerations of ethics and justice), particularly those employing a precautionary lens, some proposals are available (Hale, 2012; Hartzell-Nichols, 2012; Jamieson, 2013; Wolff, 2020).

To summarise, how to exercise public oversight over different SRM research stages and different SRM techniques, and how to ascertain and govern to mitigate both narrow environmental but also broader political risks and impacts are core issues for SRM research governance. While the need for inclusive decision-making and multistakeholder consultative processes is widely acknowledged, how to design these to assess not only the narrow environmental but also the broader political risks from specific experiments is a crucial challenge. Going beyond this, for planet-altering interventions or those with transboundary consequences, there is a need to exercise multilateral political oversight over SRM research in a globally inclusive manner (even if the research is underway in national jurisdictions), especially if such research may lead to technology development with the potential for eventual deployment.

Deployment governance

Potential future deployment scenarios raise their own, distinct governance challenges. Fundamentally, the question is how to govern potential SRM deployment in a manner that is consistent with existing international legal commitments, as well as with existing practices in regard to other, comparable types of activities. Anticipation of future decisions on potential SRM use or its deterrence ought to consider the EU's existing climate policy goals, as well as existing international obligations as well as the possibility of new international developments regarding the risks of climate change and SRM. In addition, governance options for potential SRM deployment need to take into account wider considerations in EU environmental diplomacy, particularly its climate policy goals centred around emission reductions and adaptation and its foundational commitments to effective multilateralism and the precautionary principle. Below, we evaluate two different governance options: one for the prohibition of deployment and one that would enable deployment in a regulated manner subject to international oversight.

The analysis below assesses core institutional design features associated with, respectively, international regimes for deployment prohibition and deployment regulation. However, it should be noted that there is only limited scientific literature dealing with the specific technicalities of such regimes for the case of SRM in greater detail. Where the literature does address SRM governance options, those typically remain fairly general and unspecific. Accordingly, a robust evidence review must draw on experiences and lessons learned from international regimes for comparable issue areas, in particular for hazardous activities and various types of transboundary technological and environmental risks. Broadening the scope of the analysis in this manner leads to a more comprehensive evidence base, as there a numerous analogies that can be drawn between SRM and other activities that governments have previously decided to regulate or prohibit at the international level. A core assumption informing the following paragraphs is, in other words, that SRM is not an issue area *sui* generis but shares certain characteristics with other issue areas that makes the experiences and lessons learned with the latter transferable.

Deployment decision considerations

Earlier contributions tended to survey which international institutions could play a role in decisions on SRM *(*Bodle & Oberthür, 2014; Lloyd & Oppenheimer, 2014, Lin, 2015; Victor 2008, Virgoe, 2009). This includes outcome-agnostic analyses of polycentric governance for research (Nicholson et al., 2018). There are also (very few) assessments of mini-lateral arrangements including among 'great powers' (Reynolds, 2019a), but these would suffer from serious legitimacy hurdles (Ricke et al., 2013).

The "Non-Use Agreement" academic initiative mentioned earlier calls for governments and various United Nations bodies to agree to an international non-use agreement on SRM, particularly SAI, on grounds that any future deployment of SRM will not be placed (by those in a position to develop these planet altering technologies) under the control of inclusive international political processes with requisite enforcement authority.

As detailed under Institutional feasibility and required conditions and State obligations under international law and legal principles, the emphasis of existing international law is on international cooperation, information sharing, and norms regarding the use of global commons for the good of humanity. Some view current provisions in international law as restrictive, notably the "quasi-moratorium" under the CBD. A 2013 amendment to the London Protocol (which has as of yet not entered into force), defines marine geoengineering as activities with potentially deleterious environmental effects and prohibits parties from engaging in activities specifically listed in the Protocol's new Annex 4, unless they have obtained a permit. Parties to the LP are currently exploring whether to broaden the scope of these restrictions, presently limited to ocean fertilisation, to other forms of marine climate engineering, including CB though the primary scope of the Protocol -- pertaining to the ocean and not the atmosphere above -- would seem to preclude a straightforward expansion. Some international agreements also encourage cooperative approaches and do not predetermine eventual decisions in favour of using -- or further restricting -- SRM.

Core long-standing principles of international law are also of key relevance in devising an EU policy approach to future global decisions on potential SRM use or its restriction (such as the no harm principle, and the precautionary principle, amongst others, as discussed below). For some, their application to SRM is far from straightforward (Florin et al, 2020). The possibilities of risk-superior moves attenuating multiple risks at once are increasingly considered, opportunities for no-regret efforts in the governance of SRM conceived as a complex risk governance challenge (Grieger et al., 2019; Harrison, Pasztor & Schmidt, 2021).

A challenge for designing a governance regime is how to prevent unilateral deployment (Rabitz, 2016) while operationalising the norm that far-reaching decisions on SRM including its potential use should be taken at the global level and with adequate global participation and representation as is the case for other coordination problems through appropriate decision-making procedures. Other considerations include how to assess and mitigate geopolitical risks of developing the capacity for deployment, in addition to actual potential future deployment of SRM, and particularly planetary scale interventions such as SAI, especially over sustained periods of time. Here, social science and security studies literatures point to key geopolitical risks and considerations (McLaren & Corry, 2021; Sovacool et al., 2022; Young, 2023). These are explored more under Institutional feasibility and required conditions. Lessons can also be learned from other areas of restrictive global governance, for options to design legitimate and effective options for restrictive SRM governance (Gupta et al., 2024).

Regulation of deployment

An international regime for the controlled, regulated global deployment of SRM would aim to pursue two objectives. The first objective is to manage the free-driver problem, whereby a single actor (state or non-state), or a small group thereof, would initiate deployment without multilateral authorisation and outside of effective international oversight (e.g. Weitzman, 2015). The institutional solutions which this requires are identical as for the case of an international moratorium. The focus below is, accordingly, on the second objective: to enable high-quality multilateral decision-making processes on the modalities of global deployment, in the presence of effective mechanisms for compliance, risk management as well as compensation for harm and redress. These are the central building blocks of an international deployment regime to be discussed below. Moreover, while some authors have proposed limited membership to facilitate cooperation (Parson and Ernst, 2013; Lloyd and Oppenheimer, 2014), most scholars stress the need for inclusiveness and multilateralism as preconditions of political legitimacy (e.g. Biermann & Möller, 2019; Bodansky, 2013; Virgoe, 2009; Zürn & Schäfe, 2013). Also bearing in mind that a commitment to effective multilateralism is the bedrock of EU foreign policy (Drieskens & Van Schaik, 2014), the review and analysis below proceeds on the assumption that any international regime for controlled and regulated global SRM deployment would be multilateral in nature.

Decision-making procedures

An international deployment regime requires procedures for deciding on the modalities of deployment. These modalities would involve different parameters, including the choice of specific techniques, geographic and seasonal considerations, aggregate intensity, specific temperature targets and so forth (MacMartin et al., 2017; Reynolds, 2019a, pp. 63-64). One aspect of decision-making procedures is voting architectures: who gets to vote, to what extent are votes weighted, and what specific voting system (e.g. consensus versus majoritarian) is being used? The literature frequently points out the challenges of conventional multilateralism, where decisions are being taken consensually and on the basis of sovereign equality (Bodansky et al., 2013, p.549; Reynolds, 2019a, pp. 62-63). Arguing against an architecture where every state casts a single vote, Abelkop and Carlson (2012, pp. 802-804) propose that voting be weighted by a given country's greenhouse gas emissions and simultaneously correspond to the relative financial contributions that this country would be required to make to the international governing body. Conversely, Bodansky et al (2013) suggest that participatory approaches might be needed to ensure the legitimacy of potential SRM deployment. Some authors have also advised about the risk that emergency framings of climate change might be used as a pretext for bypassing democratic decision-making on deployment (Gupta et al, 2020).

A related matter is the informational basis on which decision-making should take place. As the hypothetical efficacy of many, or most, SRM schemes is not a matter of serious debate, this aspect primarily relates to unintended side-effects or, in other words, the assessment of risks and environmental impacts. What information would need to be available for enabling informed, high-quality decision-making on potential deployment? How would this information be produced? Limited to no attempts have been made so far to frame SRM in terms of established categories of (technological) risk assessment, for instance through characterisation of hazards and exposure. On environmental impact assessment, authors acknowledge the diversity of potential approaches towards different SRM techniques and deployment scenarios (Irvine et al., 2017). More generally, some authors stress the centrality of scientific expert advice as a basis for decision-making on SRM deployment (MacMartin et al., 2019), with ample discussion on whether or not this would imply technocratic governance incompatible with democratic norms (see Horton et al, 2018; Szerszynski et al., 2013).

More specifically, while there would be a strong need to interface decision-making on the modalities of SRM deployment with scientific expert advice on risk assessment, there have virtually been no attempts so far to extend conventional assessment methodologies to different SRM techniques and deployment scenarios (Diamond et al, 2022). This means that it is unclear, as of present, what a necessary informational basis would need to look like, and how it might be produced, for evidence-based, high-quality decision-making on SRM deployment scenarios and modalities.

Risk management

Risk management means reducing the likelihood with which hazardous events occur and/or ensuring that their impacts are less harmful than they would be otherwise. In case of regional SRM, this may involve bilateral or multilateral compensation mechanisms (Quaas et al., 2016). Termination shock is a prominent risk associated with global SRM deployment whereby global temperatures would rapidly rebound to equilibrium levels upon abrupt discontinuation, without resumption, of significant SAI deployment.

The greater the intensity of temperature-masking, the greater the global environmental impacts of such sudden discontinuation would likely be, with one study arguing that species extinction and ecosystem collapse would result in a modelled scenario where a global SRM scheme is abruptly terminated after four decades (Ross & Matthews, 2009). For prolonged and intense SRM deployment, this firmly places termination shock in the category of existential global risks. The same risk is also the reason why some consider such abrupt discontinuation of a large SAI deployment as exceedingly unlikely, given the many opportunities for redundancy and the many motivated actors around the globe (Parker & Irvine, 2018; Reynolds et al., 2016). Causes of discontinuation might include the breakdown of international cooperation in SRM governance; the occurrence of unanticipated and catastrophic side-effects from SRM that make (some) governments prefer immediate discontinuation; or military or terrorist attacks against physical infrastructure that is essential for maintaining continuing operation of an SRM scheme. Notably, this implies that some forms of SRM will have greater propensity towards the risk of termination shock than others. Both CB and SAI entail critical infrastructure components that might be targeted by military or terrorist actors. This is not the case for more decentralised forms of SRM, such as CB or surface albedo modification. Similarly, safe and regulated global deployment of CB and SAI would likely require greater degrees of international cooperation than is the case for surface albedo modification. Risk management for termination shock would thus require arrangements facilitating the gradual and safe phase-out of an SRM scheme, should this turn out to be a necessity (Rabitz, 2019).

Compliance and enforcement

The compliance of states with their international legal obligations is typically driven by two factors: the normative pull of rules that are widely accepted as legitimate, authoritative and reasonable; and the calculation that the expected gains from non-compliance would be below the gains associated with continuous compliance (Chayes & Chayes, 1993). In contexts where the first factor dominates, instances of non-compliance typically occur because states are unable, rather than unwilling, to follow their legal obligations. These cases are usually addressed through international mechanisms for domestic implementation support, through technical, financial or other means. The literature on SRM governance does not generally address this issue of compliance management, rather focusing on the second factor and the associated challenge of compliance enforcement. Here, enforcement means a credible threat that non-compliance of a state actor with its international legal obligations will be detected and sanctioned in a way that is costly to the perpetrator.

Thus, enforcement both serves as a deterrent and an incentive for states found to be in non-compliance to resume acting in line with their legal obligations. As enforcement operates by imposing sanctions that change the cost-benefit calculus of rational state actors, the magnitude of sanctions and the comprehensiveness of associated monitoring components must be proportionate to the benefits that non-compliance might potentially confer on states. For a global SRM deployment regime, relevant instances of non-compliance would primarily occur in situations where states exceed their respective contributions to a global SRM scheme beyond what is consistent with a collectively agreed-upon temperature target; or where states interfere with the contributions that other states make to such a global scheme.

Situations where states undersupply their contributions to a global SRM scheme are unlikely to constitute political challenges due to the existence of reserve capacities held by other states being an indispensable feature of any deployment scenario (Reynolds et al, 2016, p.565). States would exceed their contributions in order to achieve greater degrees of global cooling. States might also interfere with SRM deployment by other states to reduce aggregate cooling levels. For instance, some scholars have noted how states might engage in "counter-geoengineering", possibly through large-scale methane venting, in order to offset the cooling effect induced by SAI (Heyen et al., 2019; Parker et al., 2018). Either action would likely be taken due to concerns regarding negative impacts of global warming or global cooling on vital national interests and compliance enforcement would accordingly require the threat or the imposition of considerable costs for non-compliant state (see Rabitz, 2016, p.105). In other words, enforcing compliance with the deployment parameters of a global SRM regime would require threatening or imposing sanctions commensurate with what are likely to be formidable drivers of non-compliance.

An extensive literature on compliance and institutional design (e.g. Bernauer et al., 2013; Tørstad, 2020) suggests that the inclusion of an appropriately robust enforcement mechanism in an international SRM deployment regime would severely constrain membership. In other words, states tend not to participate in international arrangements that include robust compliance components when they consider themselves likely to end up being in non-compliance themselves. Designing an international deployment regime that would combine a stringent compliance mechanism with multilateral participation would accordingly require additional enticements and incentives, a softening of cooperative depth or differentiation of legal obligations (Farias et al., 2023; Tørstad, 2020). The requirement for a compliance mechanism, in other words, has considerable knock-on effects for other aspects of institutional design.

Compensation for harm and redress

SRM has the potential to create harm for some states, including (depending on the applicable decision-making procedures) states that may not have consented to the deployment of SRM in the first place. In international law, states can in principle be held liable for harm that results from their lawful activities. Questions of liability have permeated numerous international negotiation contexts dealing with technological risks, from nuclear energy over industrial accidents to genetically modified organisms, typically in a specific North-South context (Brunnée, 2004). Liability has also been a major political factor in international negotiations on hazards such as oil spills or transboundary movements of toxic waste (Abelkop & Carlson, 2012, pp. 799-801).

Some authors have questioned the practicality and conceptual usefulness of considering liability as an element of SRM governance, instead suggesting other mechanisms for compensation for harm (Reynolds, 2019b, p.20). Others have argued for the need for a strict liability regime, where deploying states could be held liable for harm even in the absence of fault, including lack of due diligence (Packard, 2018). Some have made the case that a liability component would be required to grant an international SRM regime legitimacy in the face of concerns regarding potential harm (Abelkop & Carlson, 2012, pp. 799-800). Horton et al (2014) discuss the notion of parametric insurance as a specific, and unconventional, type of compensation regime for SRM.

Under such a scheme, states could obtain payments if relevant climate indicators deviate from an agreed range. A prerequisite is the agreement between parties to accept the outcome of climate modelling tools for counterfactual simulations without SRM for the reference state with regard which damage or benefit is measured (Pfrommer et al., 2019; Quaas et al., 2016). This could entice hesitant states to agree to a global deployment scenario, knowing that they would be compensated if specific pre-defined trigger points are reached. There are thus several authors who consider a liability component crucial for ensuring the political feasibility of a global SRM deployment regime. At the same time, liability is typically politically controversial due to the financial commitments which it entails (Abelkop & Carlson, 2012). Past international negotiations on liability for nuclear accidents or for harm from genetically-modified organisms, as well as ongoing discussions on loss and damage under the UNFCCC, suggest that liability would be a major sticking point when designing an international regime for the controlled and regulated global deployment of SRM. Irrespective of such negotiations, States that cause transboundary harm through SRM could be held liable for compensation also under customary international law (see State obligations under international law and legal principles).

The above analysis and literature review highlights the institutional design components that would have to be in play for an international regime to effectively regulate global SRM deployment in accordance with parallel policy objectives, legal obligations as well as considerations of fairness and equity. The requirements for such a regime may not be insurmountable but they are certainly considerable. Decision-making procedures would have to reconcile practical feasibility with the demands of political legitimacy while, at the same time, ensuring an appropriately tight interface with scientific advice regarding risk assessment. Risk management, from reductions of climate change to termination shock to changes in global precipitation patterns, would require international solutions. Robust mechanisms would have to be in place for monitoring instances of non-compliance and for corrective enforcement. The compensation issue, finally, raises the question of how much money proponent states are willing to put on the table in order to ensure the consent of hesitating or opposed states.

This raises two questions. First, is it plausible to assume that states are capable of negotiating such a regime, considering the political challenges they consistently face when dealing with subject matters that have considerably lower impacts on vital national interests? For instance, if states hesitate to consider robust compliance mechanisms in areas such as transboundary movements of hazardous waste, what does this say about their willingness to consider similar mechanisms in an area where key national interests are at stake? Or consider that states, typically from the Global North, hesitate to take on board financial obligations regarding (comparatively) limited risks associated with nuclear energy or genetically-modified organisms. Would they be more willing to accept potentially unlimited liability when it comes to technology that interferes with the global climate system in an unprecedented manner and in the presence of numerous deep uncertainties? In other words, the historical experience with issues that are politically considerably less complex suggests the need to manage expectations regarding the political feasibility of an international SRM deployment regime.

Second, is it plausible to assume that such a regime could be maintained for decades in the presence of fundamental and unpredictable political shifts with potentially transformative impacts on patterns of international cooperation? The Russian-Ukrainian war, for instance, has led to negative spillover effects across a variety of international environmental forums, from the UNFCCC to the Cartagena Protocol on Biosafety. The temporary withdrawal of the US from the 2015 Paris Climate Agreement highlights the sensitivity of international cooperation to sudden and unpredictable changes in domestic politics. Maintaining the integrity of an international regime for global SRM deployment over a time scale of several decades is not a trivial ask in a geopolitical context that is characterized by frequent upheavals that raise fundamental questions of international order. Even if the parameters of a deployment regime could be negotiated, bearing in mind all the considerable challenges states have previously faced when dealing with matters less complex and contentious than SRM, the question would be whether such a regime could be maintained well into the second half of the 21st century. In other words, fair and effective global governance of SRM deployment might be possible but, judging from experience, it is simultaneously improbable.

Below, we evaluate two different governance options: one for the prohibition of deployment and one that would enable deployment in a regulated manner subject to international oversight.

Prohibition of deployment

Governance options for a prohibitory international regime for SRM have received less attention in the scholarly literature than options for a regime permitting controlled, regulated use (e.g. Biermann e al, 2022; Gupta et al, 2024; Reynolds 2019a, pp. 14-15). Compared to a regime for regulated use, a prohibitory regime would be more generic in character, with less need for custom-tailoring institutional design to the technical and political specificities of SRM. The consideration of governance options for an international prohibitory regime should thus draw on the evidence base for the international governance of (other) ultra-hazardous activities and global risks. Yet myriad international moratoria exist on ultra-hazardous activities with high degrees of state compliance at decadal timescales, from biological weapons up to nuclear proliferation. The same applies to human cloning as a technological area of particular ethical concern. There is no reason to assume that a prohibitory regime for SRM would be significantly less effective than regimes in these and similar issue areas. The following section focuses on four design elements of a prohibitory regime: scope, reporting, monitoring, and enforcement.

Jurisdictional and temporal scope

Decision-makers would need to define both the jurisdictional and the temporal scope of an international prohibitory regime for SRM deployment. The first question is thus which types of SRM deployment should be covered and which, if any, differentiations should exist. Existing governance arrangements show considerable variation in scope: whereas the quasi-moratorium pursuant to Decision X/33 of the CBD's COP arguably covers all types of large-scale, outdoor SRM activities (to the extent that they may have direct or indirect biodiversity impacts), the regime that has emerged in the context of the LC/LP would only cover those types of SRM amounting to marine climate engineering, notably including CB. Experiences in adjacent or analogous issue areas show that international regimes governing ultra-hazardous activities or global risks tend to be relatively broad in their jurisdictional scope, presumably to minimise the risk of leaving open governance gaps that contribute to significantly adverse impacts further down the road. The major international agreements prohibiting production, use, stockpiling and other activities related to nuclear, chemical or biological weapons all have comprehensive coverage within their respective domains and do not make use of exemptions or differentiated obligations. However, the nuclear non-proliferation treaty recognises some nuclear states, and three nuclear-power states are not parties, although incomplete membership has not prevented the emergence of a robust norm against nuclear first use (Tannenwald, 2007).

Exceptions to this broad jurisdictional scope typically exist where international agreements might otherwise interfere with other international agreements. The 1992 Convention on the Transboundary Effects of Industrial Accidents, for instance, exempts from its scope nuclear accidents, oil spills, as well as accidents involving genetically modified organisms, all of which were (and continue to be) the subject of other international agreements and international political processes. The jurisdictional scope of an international prohibitory regime for SRM deployment should accordingly be defined in such a way that it covers all proposed SRM techniques with high degrees of practical feasibility, yet without creating inconsistencies with other international agreements.

The temporal scope of an international regime requires further consideration. An international prohibition of SRM deployment does not necessarily need to be permanent. Some authors stress that time-limited moratoria might provide states with the opportunity, in the meantime, to build institutional capacities for effective governance, or to pursue further research for reducing associated uncertainties (Bodansky 2013, p.546; Lloyd & Oppenheimer 2014; Zürn & Schäfer 2013, p.274). Some existing moratoria, albeit not for hazardous activities or other global risks, use such time-limited moratoria. The 1991 Protocol on Environmental Protection to the Antarctic Treaty, which places a moratorium on any mineral resource activities in Antarctica (other than those for scientific purposes) provides its parties with the opportunity to initiate a review of the protocol 50 years after its entry into force. Limitations in temporal scope may ease the political difficulties associated with the negotiation of an international prohibitory SRM regime, as parties that might wish to consider potential deployment in the (relatively distant) future will not be categorically precluded from doing so.

Reporting

International obligations regarding the structure, content and periodicity of national reporting are used in different issue areas to ascertain state compliance with a prohibitionary norm. Reporting obligations are typically intended to create transparency and to build trust among the parties to an international agreement. They are less useful in situations where states might deliberately choose not to comply with a prohibitionary norm, as they would have leeway to omit or misrepresent pertinent information in their national reporting. At the same time, states typically choose international reporting obligations over more intrusive forms of international monitoring (see below) in areas where vital economic or national security interests are concerned (Ward, 2004).

Considerable experience with national reporting systems has been accumulated under the 1972 Biological Weapons Convention (BWC), which prohibits the development, production, stockpiling and all other forms of acquiring or retaining biological weapons, toxins and relevant delivery systems. Since 1986, parties to the BWC have used so-called Confidence Building Measures (CBMs) to communicate and share information on, *inter alia*, national activities and capacities in biological defence research and other areas where dual use considerations apply. The legal basis of the CBMs are non-binding decisions of the BWCs Review Conferences. The CBMs have a spotty track record, as national reporting is typically incomplete and limited evidence suggests that they have "increased confidence in countries' treaty compliance" (Chevrier & Hunger, 2000, p.40; Shearer et al., 2022).

The primary reason for the limited utility of the CBMs is that they do not allow for the effective detection of non-compliance by state parties engaged in the clandestine development of offensive biological weapons programs. National reporting requirements are also being used under various international agreements on nuclear safety. The 1986 Convention on Early Notification of a Nuclear Accident requires state parties to notify and inform other parties about potential or actual nuclear accidents with transboundary dimensions. The 1994 Convention on Nuclear Safety requires its parties to report regularly on the measures which they have taken towards the implementation of their nuclear safety obligations. Likewise, the 1997 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management requires national reporting on domestic implementation.

In the context of the Fukushima nuclear accident, some scholars have questioned whether verification through national reporting, rather than international compliance mechanisms, has contributed to instances of potential non-compliance with international nuclear safety obligations (Čavoški, 2013; Montjoie, 2015). The World Health Organization's (WHO) 2005 International Health Regulations (IHRs) include reporting requirements for "events which may constitute a public health emergency of international concern" (Article 6.1) within the territories of the respective state parties, and within 24 hours of initial assessment. This provision has come under particular scrutiny in the context of international pandemic preparedness and response. There is robust evidence that these reporting requirements were only insufficiently fulfilled in the early stages of the COVID-19 pandemic (e.g. Aavitsland et al., 2021; Gostin et al., 2020).

The insufficient compliance with the IHR reporting requirements was likely driven by "fear of overreactions" by other states in the initial stages of the pandemic (Burci & Eccleston-Turner, 2020, p 3). These examples from biosecurity, nuclear safety and pandemic preparedness and response show that the performance of international reporting requirements tends to be mixed in situations where states have incentives to obscure their non-compliance with international obligations, including due to concerns over reputational impacts. Reporting requirements would thus appear to be better suited for contexts in which non-compliance instead arises unintentionally and because of domestic capacity deficits (see Chayes & Chayes, 1993).

A hypothetical SRM deployment scenario in violation of a hypothetical international prohibitory norm would not appear to fall into this latter category. Instead, the literature on SRM governance consistently emphasises how any such deployment decision would likely be driven by concerns over adverse climate impacts on key national interests (Rabitz, 2016). States would accordingly have incentives to obscure the development of relevant technical capacities or their deployment. Together with the experience from similar issue areas, this would suggest that more robust institutional mechanisms are required for ensuring that states would comply with a hypothetical prohibitionary norm, than mechanisms reliant on self-reporting by states.

Monitoring

Two international regimes governing hazardous activities possess international mechanisms for verifying state compliance with international norms. Whereas reporting requirements function bottom-up and largely depend on states volunteering certain types of information in line with international requirements and guidelines, monitoring mechanisms are top-down in character and give other states, independent experts or even civil society organisations the capacity to actively assess state compliance. States sometimes perceive such monitoring mechanisms as intrusive, particularly where they involve on-the-ground inspections (e.g. Chevrier, 2001; Dupont, 2014). The political costs of negotiating international monitoring mechanisms accordingly for on-the-ground stations may be high.

However, as detailed in Chapter 4, monitoring SRM would have to rely mostly on satellite remote sensing and thus would not require negotiated monitoring mechanisms. A careful detection-attribution mechanism also involving climate modelling could largely rely on established mechanisms of numerical weather prediction. The 1992 Chemical Weapons Convention (CWC) created the Organization for the Prohibition of Chemical Weapons (OPCW) in order to, *inter alia*, implement verification activities to ascertain that state parties comply with international prohibitions on the development, production, stockpiling, retainment, transfer, etc., of chemical weapons. Its far-reaching competences and its ability to carry out on-site inspections make the OPCW unique in the field of international arms control (Dunworth, 2008). While state compliance with CWC obligations tends to be high, including as a result of OPCW verification activities, the costs associated with on-site inspections and the monitored destruction of chemical weapons, and their production facilities, are extraordinarily high (Kelle, 2004).

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) is the cornerstone of the international nuclear non-proliferation regime. Under the NPT, non-nuclear weapons states have concluded Comprehensive Safeguard Agreements with the International Atomic Energy Agency (IAEA), a verification regime that is largely build on national reporting. The IAEA's 1997 Model Additional Protocol deepens this verification regime by expanding the scope for the IAEA to carry out on-site inspections and to access state-level information (Asada, 2011). Several reviews conclude that implementation of the Model Additional Protocol has contributed to non-proliferation efforts, including at the level of export and import controls, by enhancing relevant regulatory frameworks, and as a credible signal of state commitment (Gibbons & Robinson, 2021; Rockwood, 2018).

Evidence from adjacent issue areas thus strongly suggests that international monitoring mechanisms would contribute towards state compliance with a hypothetical international prohibitory norm on SRM deployment. The inclusion of monitoring mechanisms as part of a wider international negotiation agenda can also entail political risks, as state perceptions on the need for, and utility of, such mechanisms frequently diverge. This also means that the inclusion of monitoring mechanisms in an international governance arrangement for the prohibition of SRM deployment could deter participation, particularly from those states that may consider themselves as potential users of SRM technology for mitigating their domestic climate risks. The positive contributions which a monitoring mechanism could make to state compliance would thus need to be carefully balanced with the potential participation-limiting effects which they might cause (Bernauer et al., 2013; Tørstad, 2020).

Enforcement

A broad distinction can be drawn between enforcement via sanctions (where non-compliance with international rules leads to the imposition of various types of material costs) and social enforcement that relies on peer pressure and reputational costs. Enforcement provisions of the former type are exceedingly rare in international law, including in the governance of ultra-hazardous activities and global risks. Provisions for social enforcement, also referred to as "outcasting" (Hathaway & Shapiro, 2011) or "naming-and-shaming" (Dannenberg et al, 2023), are somewhat more common but still limited by the fact that states typically avoid concluding or joining international agreements that might expose them to public scrutiny or peer pressure, or otherwise harm their international reputation. One exception is the compliance committee of the Cartagena Protocol on Biosafety to the Convention on Biological Diversity. Based on the committee's recommendations, the Meeting of the Parties to the Cartagena Protocol on Biosafety may take various types of social enforcement actions, including issuing a warning to non-complying parties or by publishing instances of non-compliance (Sagemueller, 2005).

The Convention on Nuclear Safety utilises an international review process of the reports that each contracting party is required to submit regarding the domestic implementation of its treaty obligations. The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management uses a similar system of international reviewing of national reports. Except for the review component itself, neither convention, however, explicitly provides for additional social enforcement measures geared towards restoring compliance or deterring non-compliance. Enforcement mechanisms in analogous issue areas are thus rare and, where they do exist, weak. This raises not just the question of whether provisions for the soft or hard enforcement of compliance with an SRM prohibitionary norm would be politically feasible: Multiple analogous treaty regimes appear to be performing reasonably well in the absence of more than the most basic enforcement components. While some authors do note a specific need for strong enforcement in the context of SRM governance (Biermann et al, 2022), this option is not common with other types of ultra-hazardous activities and global risks.

Citizen-led and participatory SRM governance

One final aspect of deployment governance relates to governance mechanisms that are beyond nation-states or academic institutions and driven by citizens themselves. In recent years, climate citizens assemblies -- randomly selected representative citizens gathered to make policy recommendations on greenhouse gas emissions targets -- have gained in popularity as a potential innovative solution to the failure of governments to design and adopt ambitious climate change laws and policies (Duvic-Paoli, 2022). Some citizens assemblies have already had a wider scope leading to a strong sufficiency-orientation and not (primarily) to high-tech upscaling or geoengineering (Lage et al, 2023). Fritz et al (2024) conducted 44 focus groups in 22 countries to ask a representative sample of the public their preference for community governance involving SRM options such as SAI, MCB and space shields, and noted preferences across an entire ecology of participation including self-governance, have petitions, and supporting citizens assemblies and plebiscites.

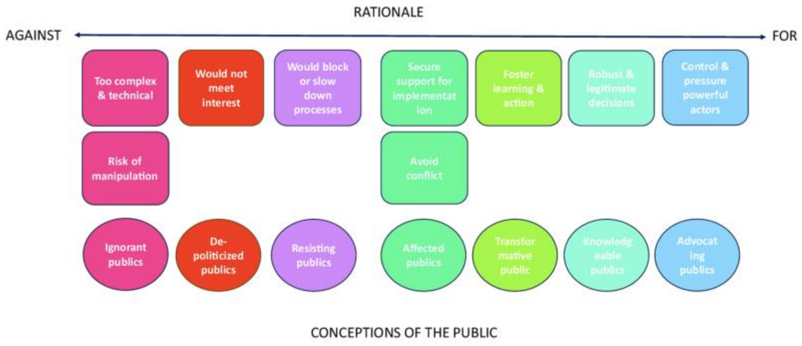


Figure 8: Forms and differing rationales of public engagement with climate-intervention technologies across an ecology of participation mentioned in focus group discussions in 22 countries. Source: Fritz et al, 2024.

State obligations under international law and legal principles

Even though there is no specific international treaty governing SRM activities, geoengineering activities do not take place "in a legal black hole" (Scott, 2013), as several customary law and treaty law obligations pose binding requirements for the governance of SRM research and deployment. The EU's position on SRM should be informed, and aligned with, the legal commitments undertaken by the Union under public international law and EU law. Mirroring the widespread possible impact of SRM, relevant legal limits of SRM research, and deployment can be found in a number of specialised fields, including the law of the sea, protection of the atmosphere, environmental law, and human rights law. Relevant legal obligations include:

- the no-harm principle under customary international law
- obligation to cooperate
- impact assessment obligations
- international treaties
- human rights safeguards, such as the right to science
- the rights of the child
- the principle of intergenerational equity and human rights obligations owed to future generations
- the precautionary principle
- relevant international soft law documents
- relevant rules of EU law

Besides primary legal sources and peer-reviewed publications, the overview of legal obligations also cites grey literature, such as legal opinions drafted by well-known international law scholars. This methodology is justified by the fact that in international law, the teachings of the most highly qualified publicists constitute a subsidiary means of establishing the content of primary obligations (Art. 38 (1)d) of the Statute of the International Court of Justice as annexed to the UN Charter).

No-harm rule (principle of prevention) under customary international law

Applicable to deployment or large-scale experimentation in SRM, the no-harm rule may hold relevance for restrictive norms. It appears to be well founded in the grey as well as the scholarly literature that the no-harm rule applies in the context of large-scale outdoor SRM activities under international law, even in the absence of a specific treaty governing such activities (Bodansky, Brunnée & Rajamani, 2017). The no-harm rule (which is also often deemed part of the principle of prevention) is a long-recognised, well-established, binding obligation of States under customary international law, which provides that States ought to discharge due diligence in order to prevent the use of their territories in a way as to cause significant transboundary environmental harm to other States and to territories beyond national jurisdiction. International fora have already applied this rule in the context of transboundary air pollution (Trail Smelter Arbitration, 1941, Nuclear Tests Case (New Zealand v France, 1973, ICJ).

The breach of the prevention obligation engages the responsibility of the State causing significant transboundary harm, or the foreseeable risk of such harm. Relevant harm includes detrimental effects on matters such as human health, property, or environment in other States, and potentially also extends to "causing harm to the climate system".[^8]

The literature has specifically examined the possibility of establishing state responsibility for the harmful effects of SAI activities (Reichwein et al., 2015). Scholars note the existence of several legal hurdles in attempting to establish such a responsibility, it is nevertheless deemed possible to engage a State's liability for causing harm through SAI deployment (Reichwein et al., 2015).

To invoke the international responsibility of a state, one must establish a breach of an international obligation binding upon the wrongdoer state, and the breach must be attributable to that state. (See ILC Articles on the Responsibility of States for Internationally Wrongful Acts). In the context of SAI, the relevant obligations include the no-harm rule, which is breached if a State fails to apply due diligence in preventing significant transboundary harm through SAI deployment, or foreseeable risk of such harm (Riechwein et al., 2015).

To prove a breach of the prevention obligation, one must be able to show (i) the lack of due diligence on part of the State engaging in SAI activities, unless SAI is deemed to be a hazardous activity (in which case the mere emergence of harm is sufficient), (ii) that the resulting harm was in fact caused by the SAI project in question, and (iii) that the respective project was attributable to the State in question.

Required standard of care

There is a divergence of possible interpretations in the literature regarding the required standard of care. Several scholars suggest that in the context of SAI activities, States have a due diligence obligation, that is a duty of conduct and not that of result, to prevent transboundary harm to occur. This is only breached if the State fails to take appropriate measures to prevent the harm to occur or to minimise the risk thereof (Brent, McGee & Maguire, 2015). According to the ILC, the required degree of care to prevent it "is proportional to the degree of hazard involved."[^9]

However, it is also suggested that SAI projects may qualify as ultra-hazardous activities due to the pervasive risks they carry (Brent, 2018). The ILC defined ultra-hazardous activities as those "with a danger that is rarely expected to materialize but might assume, on that rare occasion, grave (more than significant, serious or substantial) proportions".[^10] Engaging in ultra-hazardous activities entails a higher duty of care and due diligence -- proportional to the degree of risk of transboundary harm. The ILC, though noting the risks posed by SAI, took no position on this question in addressing the responsibilities surrounding causing harm to the atmosphere.[^11]

Another open question concerns whether the level of required care is different for SRM research and SRM deployment. The CBD Secretariat's Regulatory study finds that "The obligation not to cause transboundary environmental harm and the rules on State responsibility do not explicitly distinguish between research and deployment with regard to technologies. It could be considered whether the required level of diligence was different. International coordination could provide guidance in this regard."[^12] Given that some research is not or minimally perturbative even in a transboundary sense it appears likely that a distinction could be appropriate. In any event, any research activities should comply with the principles and limitations provided by the no-harm rule and human rights law.

Types of harm

Scholars suggest that SAI deployment could entail three types of harm (Brent, McGee & Maguire, 2015):

- direct transboundary harm
- indirect transboundary harm
- harm to the global atmospheric commons

However, it may also be conceivable that a State that benefits from a warmer climate may claim harm from the cooling effects of SRM methods (Proelss & Steenkamp, 2022).

The ILC stated that "the degree of harm itself should be foreseeable and the State must know or should have known that the given activity has the risk of significant harm. The higher the degree of inadmissible harm, the greater would be the duty of care required to prevent it".[^13] Given the IPCC's high confidence statements on the foreseeable harm caused by the termination effect, scholars argue that these risks of SAI are foreseeable and trigger an obligation of the host State to prevent such risk by either not deploying SAI or, if they do, by taking reasonable measures to prevent sudden and sustained termination.[^14]

Causation

Experts warn that establishing causation between harm and State conduct appears to be the most problematic aspect of establishing responsibility for SRM (for large-scale deployment, Pfrommer et al., 2019, but even for regional deployment, Quaas et al., 2016). The establishment requires detection-attribution approaches relying on pertinent observations and modelling (Chapter 4). Scientific uncertainties surround distinguishing impacts of SRM deployment or large-scale testing from those of natural causes, the complexities of the climate system, and there is also a need for long observation periods to detect relevant impacts (Packard, 2018). However, some also note that such difficulties are not necessarily fatal to finding causality in each and every case involving SAI (Reichwein et al., 2015). Finally, as to the attribution requirement, linking SAI deployment or large-scale testing activities to a

State of origin is likely to be easier due to the potentially limited number of the actors involved (Reichwein et al., 2015).

Circumstances precluding wrongfulness

Experts also highlight the possibility to claim circumstances precluding wrongfulness. A State causing transboundary environmental harm by geoengineering may claim necessity or distress, arguing that it is severely impacted by climate change and thus attempts to exonerate its wrongfulness. At the same time, under Articles 24 and 25 of ARSIWA, a state of necessity and distress cannot be invoked by those who contributed to the situation of necessity and distress, in this case, climate change[^15].

Standing

Under customary international law, as a general rule, it is the injured State, which suffers damage due to SAI deployment, who is entitled to invoke the responsibility of the State of origin. Furthermore, given that SAI deployment may harm the atmosphere, which is deemed as a global commons, and may counter efforts to effectively mitigate climate change, which is a common concern of humanity, in principle, it may be possible to deem the prevention obligation as having an *erga omnes* character (Reichwein et al., 2015). In such cases, non-injured States would be able to demand standing to invoke the responsibility of the State of origin before international courts[^16]. Others, however, question the *erga omnes* status of rules governing common concerns of humanity, such as climate change. International courts thus far have not suggested the *erga omnes* character of the prevention obligation. Nevertheless, the International Law Commission recognized that "some obligations relating to the global commons" would have *erga omnes* character (ILC's Study on the Fragmentation of International Law, 2006), and scholars recognize that certain environmental norms have *erga omnes* character (P.-M. Dupuy -- J. E. Vinulaes: International Environmental Law, CUP , 2018 p.53.) and the International Court of Justice did confirm that respect for the environment has "great significance ... not only for States, but the whole of mankind." (Gabcikovo-Nagymaros Project case, 1997, ICJ, para. 53).

Remedy

In any event, should the responsibility of a host State for harmful impacts of SRM deployment be established by an international court, possible remedies include ordering the cessation of the SRM activity, providing guarantees of non-repetition, and the compensation and/or satisfaction) (Bodansky, Brunnée & Rajamani, 2017).

The obligation to cooperate

States have a fundamental duty under customary international law to cooperate with each other in good faith regarding matters affecting transboundary impacts on the environment. Moreover, climate change constitutes a 'common concern of humankind' under the UNFCCC, and this status may add a further requirement for States to cooperate with each other in matters affecting the climate. The cooperation obligation supports collaboration toward better understanding the potential and limitations of SRM toward alleviating environmental degradation from climate change. The obligation can also be seen as favouring collaboration efforts toward shared data, SRM detection and attribution capabilities (including collaborations of technical organisations such as EESA and its peers) as well as scientific cooperation (such as under the WMO and its World Climate Research Program). The cooperation obligation may also support efforts to regulate SRM governance through dedicated decisions in global environmental governance (including the UNFCCC, UNEP, UNCBD, the Montreal Protocol, and others) and the establishment of a specialised international treaty (Brunnée, 2008). The duty to cooperate was also proposed to endow non-binding decisions of treaty organs, as discussed below, with "special normative importance."[^17] The decision adopted by states under the aegis of international conventions should be taken into account by any other party and body, including those of the UNFCCC and the Paris Agreement, when addressing geoengineering[^18]. Some argue that observing the quasi-moratorium flowing from UN CBD COP decisions appears to be the sole expression of State's cooperation obligations (Sands & Cook) though the latest UN CBD decisions calling for research and various other agreements (including ENMOD, UNCLOS, CLRTAP) calling for cooperation in scientific research in relevant areas suggests a more nuanced interpretation regarding cooperation obligations on SRM research.

The duty to conduct an impact assessment of any planned SRM activity

Any possible SRM deployment could only be implemented after conducting an a priori environmental impact assessment duly investigating any likely transboundary impacts in line with States' obligations under customary international law (ICJ Judgment in Pulp Mills case) and treaty law, including those under UNCLOS (PCA, South China Sea Dispute, Award).

The duty to conduct an environmental impact assessment in the specific context of SRM activities has also been confirmed by the International Law Commission, in its non-binding Draft guidelines on the protection of the atmosphere. This highly authoritative document drawn up by leading international lawyers stress that "[a]ctivities aimed at intentional large-scale modification of the atmosphere should only be conducted with prudence and caution, and subject to any applicable rules of international law, including those relating to environmental impact assessment." (Guideline 7 on Intentional large-scale modification of the atmosphere). Impact assessment obligations arise also for the parties of the Espoo Convention (see below).

Furthermore, experts and treaty bodies argue that States have human rights impact assessment obligations under human rights treaty regimes, even though the respective covenants do not contain express provisions on such an impact assessment. UNESCO experts stressed that States have an obligation to conduct human rights impact assessments "as an integral part of scientific research" given the possibility of adverse effects[^19]. The CESRC also stated that unacceptable harm of scientific research includes harm to people or to the environment, which is "imposed without adequate consideration of the human rights of those affected."[^20] Furthermore, human rights impact assessments "might be necessary to protect persons against risky application of scientific research" (para.22). The needs of especially vulnerable rights-holders should also be respected. For instance, any environment-related project or policy requires children's rights impact assessments according to the UN Committee of the Rights of the Child's General Comment No. 26, which provides an authoritative interpretation of the UN Convention on the Rights of the Child. The European Council stressed that the standards of that Convention must guide EU policies and actions, which have an impact on the rights of the child, even though the Union as such is not a party to the Convention. According to General Comment No. 26, such assessments should include investigating the possible direct and indirect impacts on the environment and climate, including both short- and long-term, combined, reversible impacts, and interactive and cumulative impacts that may affect the rights of the child (paras. 75-76).

International treaty law

In the absence of any specific SRM-related international treaty, several international conventions contain provisions relevant for SRM. The EU is a party to almost every one of these treaties.

- **Convention on Biological Diversity (CBD):** The EU is a party to the Convention. CBD is based on a precautionary approach. The Conference of the Parties can adopt non-binding decisions. CBD X/33 COP decision (2010) on geoengineering asks CBD parties to consider banning geoengineering activities that impact biodiversity in the absence of "science based, global, transparent and effective control and regulatory mechanisms for geo-engineering, and in accordance with the precautionary approach" until the science is clearer (CBD Decision X/33). The same decision views SRM research to be lawful under the CBD only with certain limitations, only if experiments are small-scale, and done in a strictly controlled environment and if they are justified by the need to gather specific scientific data and are subject to a thorough prior assessment of the potential impacts on the environment. CBD COP decision

XIII/14 calls for more transdisciplinary research and sharing of knowledge in order to better understand climate-related geoengineering.

- **Convention on Long-Range Transboundary Air Pollution:** The Convention's protocols aim to prevent air pollution defined as "the introduction by man, directly or indirectly, of substance into the air resulting in deleterious effects of such a nature as to endanger human health, harm living resources and ecosystems and material property and impair or interfere with amenities and other legitimate uses of the environment" (Article 1), which would apply to such effects generated by SAI projects. The 1985 Helsinki and the 1994 Oslo Protocol set certain limit values for sulphur-dioxide emissions and hence may be relevant for SAI activities, but it is a regional treaty for Europe and North-America (Bodansky, 2019, ref 37). The EU is a party to the Convention and also to the Oslo Protocol.
- **Vienna Convention for the Protection of the Ozone Layer and the Montreal Protocol:** Article 2 of Vienna Convention stipulates an obligation for States to cooperate to "protect human health and the environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer." This may be engaged by the possible ozone depleting effects of SAI projects. Moreover, the 2012 CBD Regulatory study found that the use of ozone depleting substances for SAI projects could be restricted under the Montreal Protocol, which could be expanded in scope leveraged for toward a moratorium and permitting process on some forms of SAI deployment and large-scale testing, though the nature of the Protocol (regulating the production of substances rather than their release) might not be a good fit. The EU and the EU countries are parties to the Vienna Convention and its Montreal Protocol.[^21]
- **1977 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques** (ENMOD): The ENMOD Convention is deemed to be the only international treaty, which directly regulates deliberate manipulation of natural processes, which have "widespread, long-lasting or severe effects" of a transboundary nature (Article 1), and thus is considered by the ILC Special Rapporteur to "offer one possible route towards the prohibition of large-scale geo-engineering practices."[^22] SRM falls within the definition of environmental modification techniques under the ENMOD Convention. This non-binding preamble of the Convention suggests, by reflecting the techno-optimism of the 1970s, "that the use of environmental modification techniques for peaceful purposes could improve the interrelationship of man and nature and contribute to the preservation and improvement of the environment for the benefit of present and future generations" (Recital 5). It requires that environmental modification techniques not be used for military or hostile use (Article II). It explicitly states that it "shall not hinder the use of environmental modification techniques for peaceful purposes and shall be without prejudice to the generally recognised principles and applicable rules of international law" (Article III.1). Hence even such peaceful uses should observe applicable customary law obligations, addressed above. Additionally, the Convention asks that parties to facilitate the exchange of information regarding such peaceful uses, and those parties "in a position to do so shall contribute ... to international economic and scientific co-operation in the preservation, improvement and peaceful utilization of the environment" (Article III.2).
- A key implication of the ENMOD Convention thus regards information sharing as experts noted that "knowledge and technologies gained by conducting field tests must be shared with other contracting parties, especially concerning knowledge gained about negative consequences" (Winter, 2011). The EU itself is not party to the Convention, but 21 of its

member states have signed and ratified it, and 2 further member states have signed it but not yet ratified.

- **UNECE Espoo Convention:** The Convention, to the EU member states are parties to, governs the obligation to carry out environmental impact assessment of likely adverse transboundary projects of certain activities. Climate engineering and SRM are not included in Annex I where such assessment is always mandatory. However, projects that are not included in Appendix I could be treated as if they are listed, if they are likely to cause a significant adverse impact based on the criteria laid out in Appendix III (e.g. the size and location of the project), and if the parties 'so agree'. Experts argue that large-scale outdoor SRM activities would undoubtedly meet these criteria (Winter, 2011). The European Union itself is a regional integration organisation member in the Convention.
- **UNFCCC, Paris Agreement**: Climate treaties are silent on SRM though it could be seen as contributing to the overall objective of holding global warming to well below 2°C and pursuing efforts to limit the temperature increase to 1.5°C. SRM research and development however must not undermine the binding goals and international mitigation efforts set by those conventions. (Sands & Cook). The EU is a party to both instruments.
- **London Protocol to the London Convention:** Though not applying to SRM, the London Convention may serve as inspiration for SRM-related moratorium-and-permitting, which for SAI could be situated under the London Protocol (Bhasin et al., 2022). In 2013, Parties adopted Resolution London Protocol 4 (8) to amend the London Protocol to regulate marine geoengineering, which by way of analogy, could be relevant for SRM activities, too. The Resolution, which is not yet in force, adopts a precautionary approach and envisages a permitting system for ocean fertilisation projects[^23]. Read together with a series of later decisions [^24], experts argue that in effect it implements a moratorium on ocean fertilisation within the system of the London Convention (Sands & Cook).
- **UNECE Aarhus Convention and Escazú Agreement:** These regional international agreements set forth guarantees on public participation in environmental decision-making processes and ensure the right to information. These obligations foster a transparent decision-making concerning outdoor SRM activities that would affect the environment and should be observed by states in engaging in such SRM activities (Adelman, 2017). The EU is party to the Aarhus Convention and implemented its obligations in Regulation (EC) No 1367/2006.

International human rights law: general human rights safeguards

When engaging in SRM activities States must comply with their human rights obligations. The rights, which may be protected or infringed by SRM deployment are suggested to typically include the right to life, right to health, right to private life, right to a healthy environment, right to be free from torture and degrading treatment, and the right to science. For instance, Article 7 of the of the International Covenant on Civil and Political Rights (ICCPR) provides that "No one shall be subjected to torture or cruel, inhuman, or degrading treatment or punishment. In particular, no one shall be subjected without his free consent to (...) scientific experimentation." Some argue that adverse human rights impact supports a restrictive approach to SRM deployment and potentially a moratorium (Sands &

Cook). Others suggest the inverse might also be true as SRM may protect key human rights threatened by climate impacts and that therefore an overly restrictive moratorium would be harmful (Svoboda, Buck & Suarez, 2018).

Derogation from human rights in time of climate crisis

Some view geoengineering as an exceptional, last resort measure, which could become necessary to tackle the climate emergency if global mitigation efforts fail. Should harmful climate impacts wreak havoc in a warming world, States may declare a state of emergency to tackle the abrupt and grave effects of climate change. Under Article 4 (1) of ICCPR, a state of emergency occurs in time of public emergency, which threatens the life of the nation and the existence of which is officially proclaimed. In such a case, however, States may only take measures derogating from their obligations under the ICCPR to the extent strictly required by the exigencies of the situation, provided that such measures are not inconsistent with their other obligations under international law and do not involve discrimination. At any event, some rights, such as the right to life, and the prohibition of torture, are non-derogable under Article 4 of ICCPR, and hence, are expected to impose hard limits on SRM research and deployment (Sands & Cook).

Business entities as duty bearers

Even though the primary addressees of international human rights obligations are States, human rights may be violated by corporate SRM activities. Some suggest that States and businesses should adhere to the non-binding UN Guiding Principles on Business and Human Rights in their SRM activities (Sands & Cook), especially those under Principle 1, under which States should "protect against human rights abuse within their territory and/or jurisdiction by third parties, including business enterprises. This requires taking appropriate steps to prevent, investigate, punish and redress such abuse through effective policies, legislation, regulations and adjudication." **Limits flowing from the right to science:** SRM research activities should observe obligations flowing from the right to science, guaranteed under Article 15 (1) (b) of the 1966 International Covenant on Economic, Social and Cultural Rights (ICESCR), which expresses "the right of everyone to enjoy the benefits of scientific progress and its applications, the commitment for its parties "to respect the freedom indispensable for scientific research and creative activity", and the desire to "recognise the benefits to be derived from the encouragement and development of international contacts and co-operation in the scientific and cultural fields.".

The Committee on Economic, Social and Cultural Rights (CESCR) issued General Comment No. 25 (2020) on science and economic, social and cultural rights, which recognises that limitations on the applications of science and technology may be necessary to protect other human rights (para 22). Any limitation must be in line with Article 4 of ICESCR, and thus should be determined by law, be compatible with the nature of these rights, and solely for the purpose of promoting the general welfare in a democratic society.

It is particularly debated in the literature whether the right to science can be limited by banning SRM research and deployment. Several scholars promote a ban on experiments for SRM technology deployment and call for an international non-use agreement (Biermann et al, 2022). Some are of the view that Article 15(1)(b) ICESCR does not as such support an outright ban on all SRM-related research in the absence of clear and significant risks (Sands & Cook). The precautionary principle, which is a fundamental principle, integral to the right to science, may inform this debate.

General Comment No 25. (GC 25) stresses that the precautionary principle demands that, "in the absence of full scientific certainty, when an action or policy may lead to unacceptable harm to the public or the environment, actions will be taken to avoid or diminish that harm. Unacceptable harm includes harm to humans or to the environment that is: (a) threatening to human life or health; (b) serious and effectively irreversible; (c) inequitable to present or future generations; or (d) imposed without adequate consideration of the human rights of those affected." (para. 56)

The precautionary principle is also an inherent limitation of the right to science. The precautionary principle should not prevent scientific progress but should be able to address risks for human health and the environment that arise from the application of scientific research. (GC 25, para. 57.) States should also prevent and mitigate any health-related risks through careful application of the precautionary principle (GC 25, para. 71).

GC 25 stipulates that States should promote multilateral agreements to prevent risks from materialising from the development and use of risky technologies, (para. 81) which some interpret to support calls for drawing up an international treaty regarding SRM. Further State obligations flowing from the right to science are suggested to include conducting human rights impact assessments to protect against risky research applications (GC 25., para. 57), to offer protection from the harmful effects of scientific advancements by exercising due diligence (Venice Statement on the Right to Enjoy the Benefits of Scientific Progress and its Applications)[^25] and to ensure participation and transparency to allow society to decide about the levels of acceptable risks, through informed, transparent and participatory public deliberation (GC, para 57.). States should also ensure that the development and use of risky technologies comply with transparency, non-discrimination, accountability and respect for human dignity (GC, para, 75).

The rights of the child

Children are particularly vulnerable to harmful environmental impacts. Children's rights in the EU must be interpreted with a view to the UN Convention on the Rights of the Child (New York Convention), which is ratified by all EU member states. As reaffirmed by the EU Council itself, the principles and standards of that Convention "must [...] guide EU policies and actions, which have an impact on the rights of the child"[^26]. Due to the potential adverse impacts of climate change and SRM activities on children's rights, SRM policies of the EU should observe the obligations flowing from the New York Convention.

Most importantly, as the General Comment No. 26 (GC 26) of the UN Commission on the Rights of the Child stresses, States have a "heightened duty of care" in the context of climate change as well as environmental destruction. States should protect children from disproportionate and long-term effects by setting and enforcing legal standards to protect them from environmental destruction. (para. 73) Some may interpret this to call for setting clear legal safeguards in EU law against possible long-term adverse effects of SRM activities, while others may understand this to call for protecting children from the harm of climate change by, among other things, researching and developing SRM.

The precautionary principle

The principle is also widely recognised by international courts as a part of general international law[^27]. The principle guides the implementation of the UNFCCC (Article 3.3) and is applicable under human rights law, as addressed above. It is also applicable under the rights of the child, in which context it calls States "to take appropriate preventive measures to protect children against reasonably foreseeable environmental harm and violations of their rights, paying due regard to the precautionary principle. This includes assessing the environmental impacts of policies and projects, identifying and preventing foreseeable harm, mitigating such harm if it is not preventable and providing for timely and effective remedies to redress both foreseeable and actual harm." (CRC GC 26, para 69.) It is also a primary source of EU law, as discussed above.

The normative content of the principle is, however, subject to competing interpretations. Some scholars note that the precautionary principle could be translated into various actions, ranging from a complete ban on SRM through impact assessment obligations, to justify proactive research to clarify SRM's capability of countering growing climate threats (Florin et al, 2020). Some suggest that the principle should be read as requiring choosing the less uncertain or less risky alternative action, such as imposing a moratorium on fossil fuel extraction, rather than pursuing geoengineering options

(Sands & Cook). while others interpret it as a call for acting on the factors that contribute to risk emergence including e.g. through additional and more responsible research that could help better controlling the technology (Grieger et al., 2019; Morgan & Ricke, 2010).

There is a particularly intensive debate on whether the precautionary principle should be interpreted as justifying a ban on SRM research and/or deployment. Some scholars read the precautionary principle as pointing to a need for conducting research and small-scale experimental projects (Reynolds & Fleurke, 2013). Some scholars deem the precautionary principle to legitimise a ban on SRM deployment (Long & Winickoff, 2010). Generally speaking, there is no legal precedent from other issue areas where the precautionary principle would have been interpreted as mandating either research or potential deployment of high-risk technologies, regardless of the specific risks which those technologies would purportedly address.

The principle of inter-generational equity

Another legal principle relevant to geoengineering is intergenerational equity (Bodansky, 1996). This principle of international environmental law dates back to Principe 2 of the 1972 Stockholm Declaration and envisages using and preserving the Earth resources for the benefit of future generations. The EU Commission has also accepted this principle as the basis which is guiding its climate commitments.[^28]

A prominent argument for researching SRM is the potential for such efforts to result in an empowerment of future generations to utilise or at least know better the merits and shortfalls of SRM to counter increasingly severe climate impacts referred to sometimes as "arming the future" (Betz, 2012; Gardiner, 2010; Jamieson, 2020; Quaas et al., 2017; Winsberg, 2021). With regards to deployment, however, in some scenarios of continued very high emissions and high SAI use, the risk of termination shock of SRM would put future generations on a path dependency and would deprive them of their choice to discontinue such measures in cases where slow phaseout would not be an option (see termination shock addressed above). This would run counter to the conservation of options obligation flowing from the principle of inter-generational equity (E.B. Weiss, 1989).

As the expert-drawn up Maastricht Principles on the Human Rights of Future Generations also point out, States violate the rights of future generations if they fail "to effectively regulate, and where appropriate prohibit, scientific research and activities that pose a reasonably foreseeable and substantial risk to the human rights of future generations, including ... geo-engineering" (Section 19, subsection f). This would also point to a more restrictive approach to SRM deployment.

Obligations flowing from EU law

The founding treaties and secondary EU legislation are still silent on SRM. However, the precautionary principle is a primary source of EU law as a general principle of EU law, which, according to the EU Commission, should be factored into several policies even outside the scope of traditional environmental policy. In the context of EU law, the principle applies where there is uncertainty as to the existence or extent of risks to human health, the institutions may take protective measures without having to wait until the reality and seriousness of those risks become fully apparent. Given the extensive risks of SRM which are not yet fully understood, the precautionary principle is relevant for the EU's policy towards SRM, too.

The EU must also comply with the international obligations flowing from international treaties it is a party to. Such agreements were described above.

Soft law documents

Given the dynamically evolving nature of public international law, soft law rules may become hard law obligations over time, especially at emerging fields such as SRM governance. Soft law documents may capture emerging regulatory consensus among States and could catalyse treaty-making processes or the emergence of new customary rules. Several binding customary obligations in environmental law emerged first in soft law instruments. This necessitates giving a brief overview of such instruments.

The UN GA resolution on the Declaration on the Use of Scientific and Technological Progress in the Interests of Peace and for the Benefit of Mankind (resolution 3384 (XXX) of 10 November 1975) firmly stipulates an obligation for States "to take appropriate measures to prevent the use of scientific and technological developments, particularly by the State organs, to limit or interfere with the enjoyment of the human rights guarantees" under major international covenants.

The WMO Secretariat also stressed that "Before undertaking an experiment on large-scale weather modification, the possible and desirable consequences must be carefully evaluated, and satisfactory international arrangements must be reached."[^29].

Chapter 8: Suggestions for policy options and conclusion

Key messages

- Policy implications involve four dimensions of SRM: those about research, those about governing or restricting deployment, those about monitoring and capacity building, and risk considerations for policy deliberation.
- To exercise oversight over SRM research and ascertain its open-endedness as well as transparency to policy makers and the public, the EU could establish transparency and governance standards
- The EU could facilitate international dialogues on SRM including in context of the overlapping mandates of UNFCCC, UNEP, WMO, UNCBD, Montreal Protocol and others, or sponsor citizens assemblies
- Other options involve monitoring, capacity building and the refinement or development of research tools.

We complete our report by putting forward a range of options that may serve policymakers in choosing restrictive or enabling pathways relating to solar radiation modification. We split these into four dimensions: those about research, those about deployment, those about monitoring and capacity building, and risk considerations for policy deliberation.

Policy options on SRM research

The EU could establish transparency and governance standards for outdoor experiments (e.g. prior informed consent, open access to data, pre-registration of experiments, disclosure of funding, stage-gates and advisory boards, etc.) that may become a global best practice approach that other public and private funders may follow. The EU could also periodically call for proposals of European research groups to conduct scientific review comparing risks of an SRM deployment with climate change risks without SRM deployment, with participation of relevant stakeholders with diverse backgrounds, etc. -- SRM is a fast-evolving field so every 4-5 years, the EU could endorse a review every half a decade. The EU could likewise support such scientific reviews by the appropriate international institutions.

As a stricter form of research governance, EU-based SRM research could be committed not to undertake outdoor activities beyond a certain scale (could be measured by radiative forcing, expected temperature change, etc.). Such a commitment could be reevaluated at regular intervals (e.g. every three years). Outdoor SRM activities at lesser magnitudes could meet specific requirements regarding scientific merit, environmental impact assessments, prior informed consent, demonstration of no significant harm, and public engagement. The EU could endorse or establish an international public repository or registry for research proposals ongoing research, research funding, and research findings, potentially to be established under the World Climate Research Programme (WCRP) or UNEP so as to provide for multilateral coordination, oversight and transparency. The WCRP currently coordinates SRM research through a dedicated lighthouse initiative. The EU could consider prohibiting patenting and intellectual property protection for any potential technology development relating to SRM (see Research governance) with a view to prevent undue accumulation of intellectual property in private hands. In simpler terms, this amounts to the EU not doing or patenting SRM research, but not going the full route of proselytising to others that they cannot do it.

At the strictest level, the EU could consider negotiating an international moratorium on SRM research. The moratorium could be limited to SAI, or it could cover all SRM techniques. It could potentially include a permitting process that specifies the decision-making process that would permit research of high scientific and policy relevance and low environmental and political risk. This option would need to consider that research on SRM is often difficult to delineate from general climate research. Also, a ban on process-oriented field experiments would hamper fundamental understanding of aerosol and cloud processes (Laboratory and field campaigns).

A wide range of design options exist for a permanent or temporary moratorium on SRM deployment. While no institutional design exists that could categorically preclude the possibility of unauthorised global deployment, problems of imperfect compliance are common to prohibitive governance in other issue areas as well as in international law more broadly. The experience with existing moratoria, whether on biological weapons, nuclear non-proliferation, but also in areas that are strongly dissimilar to SRM, including Antarctic mining or whaling, shows that compliance with prohibitionary international norms can remain high over relatively long periods of time (Gupta et al 2024). Further, compliance is not necessarily the only benchmark to consider for evaluating the effectiveness of moratoria. International norms can also shape state behaviour by defining widely shared standards of proper conduct, regardless of whether those standards are being met by each and every state in each and every instance.

An international prohibitionary regime would thus provide a strong normative signal that the international community, at least temporarily, defines SRM deployment as inconsistent with conventional expectations on state behaviour. Examples from other issues areas, for example, the ban on anti-personnel land mines (the landmines ban convention), suggest that even where powerful states, such as the US, choose to remain outside a treaty regime, a strong regime-induced normative shift towards restrictive governance can exercise pressure on non-participating state behaviour as well. For restrictive governance of SRM, widespread embrace of a non-use norm could be crucial in this regard, given the many challenges inherent in compelling powerful actors with an interest in remaining outside a restrictive regime to adhere to its restrictions.

Policy options on SRM deployment

To grapple and engage with the ethical and justice considerations mentioned under Considerations of ethics and justice, especially concerns about 'moral hazard', or the risks and challenges mentioned in Table 3, the EU could facilitate international dialogues on SRM including in context of the overlapping mandates of UNFCCC, UNEP, WMO, UNCBD, Montreal Protocol and others. The EU could commit to subject potential SRM deployment decisions within the sovereign rights of its member states to informed, multilateral and participatory decision-making processes and encourage other governments to do likewise. The EU could prohibit any forms of SRM deployment within the territory of its member states, and work with international partners towards a multilateral prohibition, notably within the context of the Convention on Biological Diversity. It could review the needs for this prohibition in 4-5-year intervals. It could link such a commitment to the multilateral decision processes referred to above and coordinate with international partners on this. The EU could institute citizen assemblies including representatives from different societal sectors, to initiate debate on SRM (without binding value). The geographical scale on which assemblies would be organised could be regional, national, or continental. Or there could be assemblies on several scales at the same time.

Table 3: Risks and challenges facing SRM deployment. Source: Authors.

Method	**Cooling potential (model studies)**	**Uncertainty of effects**	**Observational 'analogue'**	**Lifetime**	**Regional option**	**Technological readiness**	**Remark**
SAI	Global	Moderate	Volcanic eruptions	\> 2 years	Possibly polar	Low	Additional side effects (3.2)
CB	Up to global	Moderate to high	Diverse tracks	Weeks	Yes	Low	
CCT	Unclear	Very high	Little	Weeks	Yes	Very low	Terrestrial spectrum (better compensation)
MCT	Unclear	Extremely high	Little	Weeks	Yes	Extremely low	
Surface brightening	At best local	Low	Land cover diversity	Decades	Only local	High	No option for global cooling
Space mirrors	Global	Low	None	Decades to centuries	No	Virtually zero	

Moreover, the EU could advocate to refrain from including 'cooling credits' into climate agreements or international standards frameworks in ways that would create the impression of fungibility between cooling agents and greenhouse gas emissions.

If the EU chooses to prepare a possible deployment of SRM, solutions will need to be found for this to be consistent with the precautionary principle, which is binding on the EU as a general principle of EU law, and an integral part of various other international obligations. There further would be a need for numerous treaty amendments and institutional adjustments across a wide range of international agreements to prevent an SRM deployment regime from generating legal inconsistencies.

Policy options on SRM monitoring, capacity building and tool development

A final set of options involve monitoring, capacity building and the refinement or development of research tools in addition to acknowledging future research gaps.

For instance, the EU could put in place information procedures to ensure decisionmakers involved in international and domestic decisions are adequately informed upon detection of SRM activities (including large field campaigns). This could make use of operational satellites handled by the EU or its states or organisations (e.g. ESA, EUMETSAT) and might extend to collaborations with similar agencies in its ally countries. An option beyond current capabilities would be a polar-orbiting Earth radiation budget instrument to identify relevant radiative forcings and/or an instrument capable of identifying and monitoring stratospheric aerosol (e.g. a lidar) in addition to existing capability in such regards if required to detect smaller volumes of substances deployed in the stratosphere (Satellite observations and monitoring).

The EU could develop or adapt and operationalise detection-attribution modelling tools for the different time horizons of deployment scenarios considered. This would allow to identify the effects and impacts of SRM from field campaigns, regional/intermittent or global deployment using known or identified SRM action and a counterfactual situation without SRM. The EU could also support collaboration on such tools at the international level including at the World Climate Research Programme (Modelling tools).

The EU could build on its efforts to develop digital twins of climate to develop scenarios for SRM including by involving interdisciplinary groups of experts ranging disciplines and expertise such as atmospheric science, geopolitics, national and European security, political science, engineering, policy, and others. This could include both optimal and non-optimal scenarios including regional deployments targeting specific climate mitigation aims and potential geopolitical dominance conflicts. It could also aim to identify some unintended side-effects e.g. via teleconnections and transboundary effects. The EU could also seek to empower collaboration on scenario development at the international level including at the World Climate Research Programme (Modelling tools).

In order to achieve legitimacy but also maximize its benefits, SRM deployment is also in need of research and capacity building efforts that extend beyond Europe. Capacity building efforts would need to yield benefits to all involved -- researchers, research funders, and policymakers -- by aiding in the coordination of research toward policy-relevant insights, the identification of research gaps and in advancing the research capabilities especially in the Global South.

Lastly, research gaps exist in the evidence base for SRM that the EU and others could fill with targeted funding or programs. The body of research summarised in Part 1 has mostly focused on selected biophysical changes, while the real impacts for human systems and the ecosystem remain largely unknown. Highest priority for research is thus to examine risks or benefits from SRM when it comes to impacts on human systems and ecosystems. Moreover, many scenarios presume "optimal global deployment", but this may be improbable. A focus on non-optimal deployment and its potential consequences is warranted. As discussed in State obligations under international law and legal principles, SRM interventions bear similarities with other global military risks, produce winners and losers, and may thus by themselves become the source of geopolitical conflict or even war. Clearly, the implications of this are insufficiently understood. The risk-risk framework of looking at SRM deployment compared to high-end global warming is simplistic and misses out on the interdependent nature of SRM and mitigation, and potential compounding risks, which also need to be better explored in future research.

Risk considerations for policy deliberation

The range of options put forward in the above sections should be considered in the light of the following general considerations.

- **Moral hazard:** given international commitments to mitigation and the wider context of climate politics, considerable attention should be paid to the problem of 'moral hazard' that can be raised by SRM research. The framing of SRM as a solution to dangerous climate change may be used by certain actors to advocate for reduced or deferred efforts to implement mitigation of emissions that are already agreed in international targets, or hamper acceleration of mitigation activities.

- **Slippery slope:** the danger that increasing efforts in terms of research and development may lead to premature lock-in or path-dependency of certain forms of SRM, fix assessment criteria, prejudice the forms of governance of SRM, and may unduly increase the likelihood and/or magnitude of deployment of SRM. There could also be 'sticky slope' dynamics heading in the opposite direction.
- **Regional inequalities:** preferences regarding climate, technological risk and different solutions vary substantially across and within countries and regions. Impacts of both climate change and SRM differ between regions. Given that even regional climate engineering would imply impacts in other regions via teleconnections, it is very challenging to identify which level of SRM deployment would be globally accepted.
- **Prediction uncertainty:** weather and climate modelling tools are imperfect and do not allow anticipation with full certainty of all physical and environmental consequences of SRM deployment (Modelling tools). Climate models indicate that under idealised conditions as well as more realistic and policy relevant scenarios, global cooling can be achieved via SAI and/or CB, and, with that, reductions in climate impacts that would be expected for high-emission scenarios are broadly possible (Modelling, Model-based evidence). However, the uncertainties are large in predicting the exact cooling potential, regional climate impacts and many technical and political conditions in models do not obtain in reality. This is a relevant caveat for optimal deployment choices, as well as for governance issues such as possible compensation mechanisms for regional inequalities in a loss-and-damage framework.
- **EU commitments:** policy and regulatory action on SRM at European and international level must consider pre-existing legal commitments, including the legally non-binding decision X/33 of the Conference of the Parties to the Convention on Biological Diversity, as well as relevant principles of international law or those stemming from and adhering to the precautionary principle.

Whatever policymakers decide, the deliberation and implementation of policy options should consider carefully the governance dimensions and legal issues of SRM mentioned in Chapter 7.

References

Aavitsland, P., Aguilera, X., Al-Abri, S. S., Amani, V., Aramburu, C. C., Attia, T. A.,...Wieler, L. H. (2021). Functioning of the International Health Regulations during the COVID-19 pandemic. *Lancet, 398(10308*), 1283-1287. https://doi.org/10.1016/s0140-6736(21)01911-5

Abatayo, A. L., Bosetti, V., Casari, M., Ghidoni, R., & Tavoni, M. (2020). Solar geoengineering may lead to excessive cooling and high strategic uncertainty. *Proceedings of the National Academy of Sciences -- PNAS*, *117 (24),* 13393-13398. https://doi.org/10.1073/pnas.1916637117

Abelkop, A. D., & Carlson, J. C. (2012). Reining in Phaethon's chariot: principles for the governance of geoengineering. *Transnational Law & Contemporary. Problems, 21,* 763.

Abiodun, B. J., Odoulami, R. C., Sawadogo, W., Oloniyo, O. A., Abatan, A. A., New, M.,...MacMartin, D. G. (2021). Potential impacts of stratospheric aerosol injection on drought risk managements over major river basins in Africa. *Climatic change, 169*, 1-19.

Ackerman, A. S., Kirkpatrick, M. P., Stevens, D. E., & Toon, O. B. (2004). The impact of humidity above stratiform clouds on indirect aerosol climate forcing. *Nature, 432(7020*), 1014-1017. https://doi.org/10.1038/nature03174

Ackerman, A. S., Toon, O. B., Taylor, J. P., Johnson, D. W., Hobbs, P. V., & Ferek, R. J. (2000). Effects of aerosols on cloud albedo: Evaluation of Twomey's parameterization of cloud susceptibility using measurements of ship tracks. *Journal of the Atmospheric Sciences, 57(16*), 2684-2695. https://doi.org/10.1175/1520-0469(2000)057<2684:EOAOCA>2.0.CO;2

Adelman, S. (2017). Geoengineering: rights, risks and ethics. *Journal of Human Rights and the Environment, 8(1),* 119-138. https://doi.org/10.4337/jhre.2017.01.06

Ahlm, L., Jones, A., Stjern, C. W., Muri, H., Kravitz, B., & Kristjánsson, J. E. (2017). Marine cloud brightening -- as effective without clouds. *Atmospheric Chemistry & Physics, 17(21),* 13071-13087. https://doi.org/10.5194/acp-17-13071-2017

Ainsworth, E. A., & Long, S. P. (2005). What have we learned from 15 Years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2. *The New Phytologist, 165(2),* 351-371. https://doi.org/10.1111/j.1469-8137.2004.01224.x

Alamou, A. E., Obada, E., Biao, E. I., Zandagba, E. B. J., Da-Allada, C. Y., Bonou, F. K.,...Irvine, P. J. (2022). Impact of stratospheric aerosol geoengineering on meteorological droughts in West Africa. *Atmosphere, 13(2),* 234.

Albrecht, B. A. (1989). Aerosols, cloud microphysics, and fractional cloudiness. *Science (American Association for the Advancement of Science), 245(4923*), 1227-1230. https://doi.org/10.1126/science.245.4923.1227

Allan, B. B. (2017). Second only to nuclear war: Science and the making of existential threat in global climate governance. *International Studies Quarterly, 61(4)*, 809-820.

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., & Meinshausen, N. (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature, 458(7242)*, 1163-1166. https://doi.org/10.1038/nature08019

References

Allen, M. R., Friedlingstein, P., Girardin, C. A. J., Jenkins, S., Malhi, Y., Mitchell-Larson, E.,...Rajamani, L. (2022). Net Zero: Science, origins, and implications. *Annual Review of Environment and Resources, 47(1)*, 849-887. https://doi.org/10.1146/annurev-environ-112320-105050

Allen, R., & Evans, W. (1972). Laser radar (LIDAR) for mapping aerosol structure. *Review of Scientific Instruments, 43(10*), 1422-1432.

Alterskjær, K., Kristjánsson, J. E., Boucher, O., Muri, H., Niemeier, U., Schmidt, H.,...Timmreck, C. (2013). Sea-salt injections into the low-latitude marine boundary layer: The transient response in three Earth system models. *Journal of Geophysical Research: Atmospheres, 118(21),* 12,195-112,206. https://doi.org/10.1002/2013JD020432

Amelung, D., & Funke, J. (2015). Laypeople's risky decisions in the climate change context: climate engineering as a risk-defusing strategy? *Human and Ecological Risk Assessment: An International Journal, 21(2)*, 533-559.

Andrews, T. M., Delton, A. W., & Kline, R. (2022). Anticipating moral hazard undermines climate mitigation in an experimental geoengineering game. *Ecological Economics*, *196*, 107421. https://doi.org/10.1016/j.ecolecon.2022.107421

Asada, M. (2011). The Treaty on the Non-Proliferation of Nuclear Weapons and the universalization of the additional protocol. *Journal of Conflict & Security Law, 16(1),* 3-34. http://www.jstor.org/stable/26294713 doi:10.1093/j csl/krr00

Asayama, S., Sugiyama, M., & Ishii, A. (2017). Ambivalent climate of opinions: Tensions and dilemmas in understanding geoengineering experimentation. *Geoforum, 80*, 82-92. https://doi.org/10.1016/j.geoforum.2017.01.012

Aswathy, V. N., Boucher, O., Quaas, M., Niemeier, U., Muri, H., Mülmenstädt, J., & Quaas, J. (2015). Climate extremes in multi-model simulations of stratospheric aerosol and marine cloud brightening climate engineering. *Atmospheric Chemistry & Physics, 15(16),* 9593-9610. https://doi.org/10.5194/acp-15-9593-2015

Austin, M. M. K., & Converse, B. A. (2021). In search of weakened resolve: Does climate-engineering awareness decrease individuals' commitment to mitigation? *Journal of Environmental Psychology*, *78*, 101690. https://doi.org/10.1016/j.jenvp.2021.101690

Baatz, C. (2016). Can we have it both ways? On potential trade-offs between mitigation and solar radiation management. *Environmental Values, 25(1),* 29-49. 10.3197/096327115X14497392134847

Baatz, C., Heyward, C., & Stelzer, H. (2016). The ethics of engineering the climate. *Environmental Values*, 25(1), 1-5. https://doi.org/10.3197/096327115X14497392134766

Bakalova, I., & Belaia, M. (2023). Stability of efficient international agreements on solar geoengineering. *Environmental and Resource Economics*, *86(3),* 673-712. doi.org/10.1007/s10640-023-00807-0

Bala, G., Duffy, P., & Taylor, K. (2008). Impact of geoengineering schemes on the global hydrological cycle. *Proceedings of the National Academy of Sciences, 105(22)*, 7664-7669. https://doi.org/10.1073/pnas.0711648105

Banerjee, A., Butler, A. H., Polvani, L. M., Robock, A., Simpson, I. R., & Sun, L. (2021). Robust winter warming over Eurasia under stratospheric sulfate geoengineering--the role of stratospheric dynamics. *Atmospheric Chemistry and Physics, 21(9),* 6985-6997. https://doi.org/10.5194/acp-21-6985-2021

Barnes, E. A., Hurrell, J. W., & Sun, L. (2022). Detecting changes in global extremes under the GLENS-SAI climate intervention strategy. *Geophysical Research Letters, 49(20)*, e2022GL100198. https://doi.org/10.1029/2022GL100198

References

Barrett, S. (1994). Self-enforcing international environmental agreements. *Oxford Economic Papers*, *46(Supplement-1*), 878-894. https://doi.org/10.1093/oep/46.

Baum, C.M., Fritz, L., Low, S., & Sovacool, B.K. (2024a). Public perceptions of climate intervention technologies across the Global North and South. *Nature Communications, 15*, 2060. https://doi.org/10.1038/s41467-024-46341-5

Baum, C. M., Fritz, L., Low, S., & Sovacool, B. K. (2024b). Like diamonds in the sky? Public perceptions, governance, and information framing of solar geoengineering activities in Mexico, the United Kingdom, and the United States. *Environmental Politics*, 33(5), 868--895. https://doi.org/10.1080/09644016.2023.2301262

Baum, C. M., Low, S., & Sovacool, B. K. (2022). Between the sun and us: Expert perceptions on the innovation, policy, and deep uncertainties of space-based solar geoengineering. *Renewable and Sustainable Energy Reviews*, *158*, 112179. https://doi.org/10.1016/j.rser.2022.112179

Baur, S., Nauels, A., Nicholls, Z., Sanderson, B. M., & Schleussner, C. F. (2023). The deployment length of solar radiation modification: an interplay of mitigation, net-negative emissions and climate uncertainty. *Earth System Dynamics, 14(2),* 367-381. https://doi.org/10.5194/esd-14-367-2023

Baur, S., Sanderson, B. M., Séférian, R., & Terray, L. (2024). Solar radiation modification challenges decarbonization with renewable solar energy. *Earth System Dynamics, 15(2*), 307-322. https://doi.org/10.5194/esd-15-307-2024

Bauer, P., Stevens, B., & Hazeleger, W. (2021). A digital twin of Earth for the green transition. *Nature Climate Change, 11(2),* 80-83. https://doi.org/10.1038/s41558-021-00986-y

Bednarz, E. M., Butler, A. H., Visioni, D., Zhang, Y., Kravitz, B., & MacMartin, D. G. (2023a). Injection strategy -- a driver of atmospheric circulation and ozone response to stratospheric aerosol geoengineering. *Atmospheric Chemistry and Physics*, *23(21*), 13665-13684. https://doi.org/10.5194/acp-23-13665-2023

Bednarz, E. M., Visioni, D., Butler, A. H., Kravitz, B., MacMartin, D. G., & Tilmes, S. (2023c). Potential non-linearities in the high latitude circulation and ozone response to Stratospheric Aerosol Injection. *Geophysical Research Letters*, *50(22*), e2023GL104726. https://doi.org/10.1029/2023GL104726

Bednarz, E. M., Visioni, D., Kravitz, B., Jones, A., Haywood, J. M., Richter, J.,...Braesicke, P. (2023b). Climate response to off-equatorial stratospheric sulfur injections in three Earth system models--Part 2: Stratospheric and free-tropospheric response. *Atmospheric Chemistry and Physics, 23(1)*, 687-709. https://doi.org/10.5194/acp-23-687-2023

Belaia, M., Moreno-Cruz, J. B., & Keith, D. W. (2021). Optimal climate policy in 3D: Mitigation, carbon removal, and solar geoengineering. *Climate Change Economics*, *12(03*), 2150008. https://doi.org/10.1142/S2010007821500081

Bell, D. (2010). Justice and the politics of climate change. In S. Brechin & S. Lee (Eds.) *Routledge handbook of climate change and society* (pp. 423-441). London: Routledge. https://doi.org/10.4324/9780203876213

Bellamy, R. (2023). Public perceptions of climate tipping points. *Public Understanding of Science, 32(8)*, 1033-1047. https://doi.org/10.1177/09636625231177820

Bellamy, R., Chilvers, J., & Vaughan, N. E. (2016). Deliberative mapping of options for tackling climate change: citizens and specialists 'open up' appraisal of geoengineering. *Public Understanding of Science, 25(3)*, 269-286. https://doi.org/10.1177/0963662514548628

References

Bellamy, R., & Healey, P. (2018). 'Slippery slope 'or 'uphill struggle'? Broadening out expert scenarios of climate engineering research and development. *Environmental Science & Policy*, *83*, 1-10. https://doi.org/10.1016/j.envsci.2018.01.021

Bellamy, R., & Hulme, M. (2011). Beyond the tipping point: understanding perceptions of abrupt climate change and their implications. *Weather, Climate, and Society, 3(1)*, 48-60. 10.1175/2011WCAS1081.1

Bellamy, R., Lezaun, J., & Palmer, J. (2017). Public perceptions of geoengineering research governance: An experimental deliberative approach. *Global Environmental Change, 45*, 194-202. https://doi.org/10.1016/j.gloenvcha.2017.06.004

Benas, N., Finkensieper, S., Stengel, M., van Zadelhoff, G. J., Hanschmann, T., Hollmann, R., & Meirink, J. F. (2017). The MSG-SEVIRI-based cloud property data record CLAAS-2. *Earth System Science Data, 9(2)*, 415-434. https://doi.org/10.5194/essd-9-415-2017

Bernauer, T., & Böhmelt, T. (2013). National climate policies in international comparison: the climate change cooperation index. *Environmental Science & Policy*, *25*, 196-206. https://doi.org/10.1016/j.envsci.2012.09.007

Bernauer, T., Kalbhenn, A., Koubi, V., & Spilker, G. (2013). Is there a "Depth versus Participation" dilemma in international cooperation? *Review of International Organizations, 8(4),* 477-497. https://doi.org/10.1007/s11558-013-9165-1

Benduhn, F., Schallock, J., & Lawrence, M. G. (2016). Early growth dynamical implications for the steerability of stratospheric solar radiation management via sulfur aerosol particles. *Geophysical Research Letters, 43(18*), 9956-9963. https://doi.org/10.1002/2016GL070701

Betz, G. (2012). The case for climate engineering research: an analysis of the "arm the future" argument. *Climatic change, 111(2*), 473-485. https://doi.org/10.1007/s10584-011-0207-5

Bewick, R., Lücking, C., Colombo, C., Sanchez, J.-P., & McInnes, C. R. (2013). Heliotropic dust rings for Earth climate engineering. *Advances in Space Research, 51(7)*, 1132-1144. https://doi.org/10.1016/j.asr.2012.10.024

Bewick, R., Sanchez, J., & McInnes, C. (2012). Gravitationally bound geoengineering dust shade at the inner Lagrange point. *Advances in Space Research, 50(10*), 1405-1410. https://doi.org/10.1016/j.asr.2012.07.008

Bewick, R., Sanchez, J.-P., & McInnes, C. R. (2013). Usage of asteroid resources for space-based geoengineering. *Asteroids: Prospective Energy and Material Resources*, 581-603. DOI: 10.1007/978-3-642-39244-3

Bewick, R., Sanchez, J. P., & McInnes, C. R. (2012). Gravitationally bound geoengineering dust shade at the inner Lagrange point. *Advances in Space Research, 50(10*), 1405-1410. https://doi.org/10.1016/j.asr.2012.07.008

Bhasin, S., Ravindran, B., & Moro, E. (2022). Solar geoengineering and the Montreal Protocol: A case for global governance. New Delhi: Council on Energy, Environment and Water

Bhowmick, M., Mishra, S. K., Kravitz, B., Sahany, S., & Salunke, P. (2021). Response of the Indian summer monsoon to global warming, solar geoengineering and its termination. *Scientific Reports, 11(1),* 9791-9791. https://doi.org/10.1038/s41598-021-89249-6

Bickel, J. E., & Lane, L. (2009). *An analysis of climate engineering as a response to climate change*. Copenhagen Consensus Center.

Biermann, F., & Möller, I. (2019). Rich man's solution? Climate engineering discourses and the marginalization of the Global South. *International Environment Agreements*, *19 (2),* 151--167 (2019). https://doi.org/10.1007/s10784-019-09431-0

References

Biermann, F., Oomen, J., Gupta, A., Ali, S., Conca, K., Hajer, M.,...Vandeveer, S. (2022). Solar geoengineering: The case for an international non-use agreement. *WIREs Climate Change, 13 (3)*. https://doi.org/10.1002/wcc.754

Bingaman, D. C., Rice, C. V., Smith, W., & Vogel, P. (2020). *A stratospheric aerosol injection Lofter aircraft concept: Brimstone Angel*. AIAA Scitech 2020 Forum 10.2514/6.2020-0618

Bodansky, D. (1996). May we engineer the climate? *Climatic Change, 33(3),* 309-321. https://doi.org/10.1007/BF00142579

Bodansky, D. (2013). The who, what, and wherefore of geoengineering governance. *Climatic Change, 121(3),* 539-551. https://doi.org/10.1007/s10584-013-0759-7

Bodansky, D., Brunnée, J., & Rajamani, L. (2017*). International climate change law*. Oxford University Press. https://doi.org/10.1017/ajil.2017.54

Bodansky, D., & Parker, A. (2021). Research on solar climate intervention is the best defense against moral hazard. *Issues in Science and Technology*, *37*(4), 19--21. https://www.jstor.org/stable/27092081

Bodle, R., Oberthur, S., Donat, L., Homann, G., Sina, S., & Tedsen, E. (2014). *Options and proposals for the international governance of geoengineering*. Berlin: Ecologic Institute.

Boettcher, M., Chai, F., Conathan, M., Cooley, S., Keller, D., Klinsky, S., Lezaun, J., & Webb, R. M. (2023). *A code of conduct for marine carbon dioxide removal research*. The Aspen Institute Energy and Environment Program (EEP). 10.13140/RG.2.2.22528.40968

Bolsen, T., Palm, R., & Kingsland, J. T. (2022). How negative frames can undermine public support for studying solar geoengineering in the US. *Frontiers in Environmental Science, 10*, 850514. https://doi.org/10.3389/fenvs.2022.850514

Bolsen, T., Palm, R., & Luke, R. E. (2023). Public response to solar geoengineering: how media frames about stratospheric aerosol injection affect opinions. *Climatic Change, 176(8)*, 112. https://doi.org/10.1007/s10584-023-03575-4

Borick, C., & Rabe, B. (2012). Americans cool on geoengineering approaches to addressing climate change. *Issues in Governance Studies*, 46(4), 7.

Bostrom, A., O'Connor, R. E., Böhm, G., Hanss, D., Bodi, O., Ekström, F., Halder, P.,...& Sælensminde, I. (2012). Causal thinking and support for climate change policies: International survey findings. *Global Environmental Change, 22(1)*, 210-222. https://doi.org/10.1016/j.gloenvcha.2011.09.012

Bourassa, A., Rieger, L., Lloyd, N., & Degenstein, D. (2012). Odin-OSIRIS stratospheric aerosol data product and SAGE III intercomparison. *Atmospheric Chemistry and Physics*, 12(1), 605-614. https://doi.org/10.5194/acp-12-605-2012

Braun, C., Merk, C., Pönitzsch, G., Rehdanz, K., & Schmidt, U. (2018a). Public perception of climate engineering and carbon capture and storage in Germany: survey evidence. *Climate Policy, 18(4*), 471-484. 10.1080/14693062.2017.1304888

Braun, C., Rehdanz, K., & Schmidt, U. (2018b). Exploring public perception of environmental technology over time. *Journal of Environmental Planning and Management, 61(1),* 143-160. https://doi.org/10.1080/09640568.2017.1291414

Brent K. (2018). Solar radiation management geoengineering and strict liability for ultrahazardous activities. In N. Craik, C.S.G. Jefferies, S.L. Seck & T. Stephens (Eds.), *Global environmental change and innovation in international law* (pp. 161-179). Cambridge University Press. https://doi.org/10.1017/9781108526081.010

References

Brent, K., Burns, W., & McGee, J. (2019). *Governance of marine geoengineering*. Waterloo, ON, Canada: Centre for International Governance Innovation.

Brent, K., McGee, J., & Maguire, A. (2015). Does the 'no-harm' rule have a role in preventing transboundary harm and harm to the global atmospheric commons from geoengineering? *Climate Law, 5(1)*, 35-63. https://doi.org/10.1163/18786561-00501007

Bretherton, C. S., Blossey, P. N., & Uchida, J. (2007). Cloud droplet sedimentation, entrainment efficiency, and subtropical stratocumulus albedo. *Geophysical Research Letters, 34(3).* https://doi.org/10.1029/2006GL027648

Briggs, C. (2018). Is solar geoengineering a national security risk?. In J.J. Blackstock & S. Low (Eds.), *Geoengineering our climate?* (pp. 178-182). Routledge 10.4324/9780203485262-33

Bromley, B. C., Khan, S. H., & Kenyon, S. J. (2023). Dust as a solar shield. *PLOS Climate, 2(2),* e0000133. https://doi.org/10.1371/journal.pclm.0000133

Bruintjes, R. T. (1999). A review of cloud seeding experiments to enhance precipitation and some new prospects. *Bulletin of the American Meteorological Society, 80(5*), 805-820. https://doi.org/10.1175/1520-0477(1999)080%3C0805:AROCSE%3E2.0.CO;2

Brunnee, J. (2004). Of sense and sensibility: Reflections on international liability regimes as tools for environmental protection. *The International and Comparative Law Quarterly, 53(2)*, 351-368. https://doi.org/10.1093/iclq/53.2.351

Brunnée, J. (2008). Common areas, common heritage and common concern. In D. Bodansky, J. Brunnée & E. Hey (Eds), *The Oxford Handbook of International Environmental Law.* https://doi.org/10.1093/oxfordhb/9780199552153.013.0023

Buchanan, A. (2013). *The heart of human rights.* Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199325382.001.0001

Buchanan, A., & Keohane, R. O. (2006). The legitimacy of global governance institutions. *Ethics & International Affairs*, 20(4), 405-437. doi:10.1111/j.1747-7093.2006.00043.x

Buck, H. J. (2018). Perspectives on solar geoengineering from Finnish Lapland: Local insights on the global imaginary of Arctic geoengineering. *Geoforum, 91*, 78-86. https://doi.org/10.1016/j.geoforum.2018.02.020

Budyko, M. I. (1977). On present-day climatic changes. *Tellus*, *29(3),* 193-204. https://doi.org/10.1111/j.2153-3490.1977.tb00725.x

Burci, G. L., & Eccleston-Turner, M. (2020). Preparing for the next pandemic: The International Health Regulations and World Health Organization during COVID-19. *Yearbook of International Disaster Law Online, 2,* 259-282. https://doi.org/10.1163/26662531_00201_011

Buriez, J. C., Vanbauce, C., Parol, F., Goloub, P., Herman, M., Bonnel, B., ... Seze, G. (1997). Cloud detection and derivation of cloud properties from POLDER. *International Journal of Remote Sensing*, *18(13)*, 2785--2813. https://doi.org/10.1080/014311697217332

Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature (London), 527 (7577)*, 235-239. https://doi.org/10.1038/nature15725

Burns, E. T., Flegal, J. A., Keith, D. W., 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(11)*, 536-542. https://doi.org/10.1002/2016EF000461

References

Burns, W., & Talati, S. (2023). The solar geoengineering ecosystem: Key actors across the landscape of the field. The Alliance for Just Deliberation on Solar Geoengineering.

Boucher, O., Lowe, J. A., & Jones, C. D. (2009). Implications of delayed actions in addressing carbon dioxide emission reduction in the context of geo-engineering. *Climatic Change, 92(3)*, 261-273. 10.1007/s10584-008-9489-7

Butchart, N. (2014). The Brewer-Dobson circulation. *Reviews of Geophysics, 52(2)*, 157-184. https://doi.org/10.1002/2013RG000448

Cairns, R. C. (2014). Climate geoengineering: issues of path-dependence and socio-technical lock-in. Wiley interdisciplinary reviews. *Climate Change, 5(5),* 649-661. https://doi.org/10.1002/wcc.296

Cairns, R. (2016). Climates of suspicion: 'chemtrail' conspiracy narratives and the international politics of geoengineering. *The Geographical Journal, 182(1)*, 70-84. https://doi.org/10.1111/geoj.12116

Caldeira, K., & Wood, L. (2008). Global and Arctic climate engineering: numerical model studies. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 366(1882)*, 4039-4056. https://doi.org/doi:10.1098/rsta.2008.0132

Callies, D. E. (2018). Institutional Legitimacy and Geoengineering Governance. *Ethics, Policy & Environment, 21(3)*, 324-340. https://doi.org/10.1080/21550085.2018.1562523

Callies, D. E. (2019). The slippery slope argument against geoengineering research. *Journal of Applied Philosophy*, *36(4*), 675-687. https://doi.org/10.1111/japp.12345

Callies, D. E. (2019). *Climate engineering: A normative perspective*. Rowman & Littlefield.

Callies, D.E. (2023). The ethics of geoengineering. In Pellegrino, G. & Di Paola, M. (Eds), *Handbook of the philosophy of climate change* (pp. 919-937). Springer, Cham. https://doi.org/10.1007/978-3-031-07002-0_78

Caney, S. (2005). Cosmopolitan justice, responsibility, and global climate change. *Leiden journal of International Law*, *18*(4), 747-775. 10.1017/S0922156505002992

Caney, S. (2012). Global justice, climate change, and human rights. In D.A. Hicks & T. Williamson (Eds), *Leadership and global justice* (pp. 91-111). New York: Palgrave Macmillan US. https://doi.org/10.1057/9781137014696_7

Cao, L., L. Duan, G. Bala, and K. Caldeira (2016), Simulated long-term climate response to idealized solar geoengineering, *Geophysical Research Letters., 43,* 2209--2217. https://doi.org/10.1002/2016GL068079

Cao, L., & Jiang, J. (2017). Simulated effect of carbon cycle feedback on climate response to solar geoengineering. *Geophysical Research Letters*, *44(24),* 12-484. 10.1002/2017GL076546

Cao, L. (2018). The effects of solar radiation management on the carbon cycle. *Current Climate Change Reports*, *4*, 41-50. doi.org/10.1007/s40641-018-0088-z

Carlisle, D. P., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. (2020). The public remain uninformed and wary of climate engineering. *Climatic Change, 160(2),* 303-322. https://doi.org/10.1007/s10584-020-02706-5

Carlisle, D. P., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. (2022). Public engagement with emerging technologies: Does reflective thinking affect survey responses? *Public Understanding of Science, 31(5)*, 660-670. https://doi.org/10.1177/09636625211029438

Carr, W., Preston, C., Yung, L., Szerszynski, B., Keith, D., & Mercer, A. (2013). Public engagement on solar radiation management and why it needs to happen now. *Climatic Change*, 121(3), 567-577. 10.1007/s10584-013-0763-y

Carr, W. A., & Yung, L. (2018). Perceptions of climate engineering in the South Pacific, Sub-Saharan Africa, and North American Arctic. *Climatic Change, 147(1),* 119-132. https://doi.org/10.1007/s10584-018-2138-x

Carton, W., Hougaard, I. M., Markusson, N., & Lund, J. F. (2023). Is carbon removal delaying emission reductions? Wiley Interdisciplinary Reviews. *Climate Change*, *14(4),* e826. https://doi.org/10.1002/wcc.826

Carvalho, A., & Riquito, M. (2022). 'It's just a Band-Aid!': Public engagement with geoengineering and the politics of the climate crisis. *Public Understanding of Science, 31(7),* 903-920. https://doi.org/10.1177/09636625221095353

Čavoški, A. (2013). Revisiting the Convention on Nuclear Safety: Lessons learned from the Fukushima accident. *Asian Journal of International Law, 3(2*), 365-391. https://doi.org/10.1017/S2044251312000331

Chayes, A., & Chayes, A. H. (1993). On compliance. *International Organization, 47(2),* 175-205. https://doi.org/10.1017/S0020818300027910

Chen, D., Rojas, M., Samset, B. H., Cobb, K., Diongue Niang, A., Edwards, P.,...Tréguier, A. M. (2021). Framing, context and methods. In *Climate change 2021: The physical science basis: Working group contribution to the sixth assessment report of the Intergovernmental Panel on Climate Change* (pp. 147-286). Cambridge University Press. https://doi:10.1017/9781009157896.003

Chen, Y., Liu, A., & Moore, J. C. (2020). Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering. *Nature Communications, 11(1),* 2430-2430. https://doi.org/10.1038/s41467-020-16357-8

Chen, Y. C., Christensen, M. W., Xue, L., Sorooshian, A., Stephens, G. L., Rasmussen, R. M., & Seinfeld, J. H. (2012). Occurrence of lower cloud albedo in ship tracks. *Atmospheric Chemistry & Physics, 12(17),* 8223-8235. https://doi.org/10.5194/acp-12-8223-2012

Chen, Z., Bhartia, P. K., Loughman, R., Colarco, P., & DeLand, M. (2018). Improvement of stratospheric aerosol extinction retrieval from OMPS/LP using a new aerosol model. *Atmospheric Measurement Techniques, 11(12)*, 6495-6509. https://doi.org/10.5194/amt-11-6495-2018

Chen, I. C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid range shifts of species associated with high levels of climate warming. *Science, 333(6045),* 1024-1026. 10.1126/science.1206432

Chen, Z., Bhartia, P. K., Torres, O., Jaross, G., Loughman, R., DeLand, M., Colarco, P.,...& Taha, G. (2020). Evaluation of the OMPS/LP stratospheric aerosol extinction product using SAGE III/ISS observations. *Atmospheric Measurement Techniques, 13(6),* 3471-3485. https://doi.org/10.5194/amt-13-3471-2020

Cheng, W., MacMartin, D. G., Dagon, K., Kravitz, B., Tilmes, S., Richter, J. H., Mills, M. J., & Simpson, I. R. (2019). Soil moisture and other hydrological changes in a stratospheric aerosol geoengineering large ensemble. *Journal of Geophysical Research: Atmospheres, 124(23)*, 12773-12793. https://doi.org/10.1029/2018JD030237

Cherry, T. L., Kallbekken, S., Kroll, S., & McEvoy, D. M. (2021). Does solar geoengineering crowd out climate change mitigation efforts? Evidence from a stated preference referendum on a carbon tax. *Climatic Change, 165(1),* 6. https://doi.org/10.1007/s10584-021-03009-z

Chevrier, M. (2001). The Biological Weapons Convention: The protocol that almost was. *Verification Yearbook*, 79-97.

References

Chevrier, M. I., & Hunger, I. (2000). Confidence-building measures for the BTWC: Performance and potential. *The Nonproliferation Review, 7(3),* 24-42. 10.1080/10736700008436823

Chhetri, N., Chong, D., Conca, K., Falk, R., Gillespie, A., Gupta, A.,...Light, A. (2018). *Governing solar radiation management*. https://doi.org/10.13140/RG.2.2.17911.14246

Cirino, G. G., Souza, R. A. F., Adams, D. K., & Artaxo, P. (2014). The effect of atmospheric aerosol particles and clouds on net ecosystem exchange in the Amazon. *Atmospheric Chemistry and Physics, 14(13)*, 6523-6543. https://doi.org/10.5194/acp-14-6523-2014

Cisewski, M.S., Zawodny, J.M., Gasbarre, J.F., Eckman, R.S., Topiwala, N., Rodriguez-Alvarez, O., Cheek, D., & Hall, S. (2014). *The Stratospheric Aerosol and Gas Experiment (SAGE III) on the International Space Station (ISS) Mission*. SPIE Remote Sensing. 10.1117/12.2073131

Clark, B., Xia, L., Robock, A., Tilmes, S., Richter, J.H., Visioni, D. & Rabin, S. (2023). Optimal climate intervention scenarios for crop production vary by nation**.** *Nature Food, 4,* 902-911. https://doi.org/10.1038/s43016-023-00853-3

Clifton, O. E., Fiore, A. M., Massman, W. J., Baublitz, C. B., Coyle, M., Emberson, L., Fares, S.,...& Tai, A. P. K. (2020). Dry deposition of ozone over land: Processes, measurement, and modeling. *Reviews of Geophysics (1985), 58(1)*. https://doi.org/10.1029/2019RG000670

Condie, S. A., Anthony, K. R. N., Babcock, R. C., Baird, M. E., Beeden, R., Fletcher, C. S.,...Westcott, D. A. (2021). Large-scale interventions may delay decline of the Great Barrier Reef. *Royal Society Open Science, 8(4*), 201296. https://doi.org/doi:10.1098/rsos.201296

Corbett, J. G., & Loeb, N. G. (2015). On the relative stability of CERES reflected shortwave and MISR and MODIS visible radiance measurements during the Terra satellite mission. *Journal of Geophysical Research: Atmospheres, 120(22),* 11,608-611,616. https://doi.org/10.1002/2015JD023484

Corner, A., Parkhill, K., Pidgeon, N., & Vaughan, N. E. (2013). Messing with nature? Exploring public perceptions of geoengineering in the UK. *Global Environmental Change*, 23(5), 938-947. https://doi.org/10.1016/j.gloenvcha.2013.06.002

Corner, A., & Pidgeon, N. (2014). Geoengineering, climate change scepticism and the 'moral hazard' argument: an experimental study of UK public perceptions. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372(2031*), 20140063. https://doi.org/10.1098/rsta.2014.0063

Corner, A., & Pidgeon, N. (2015). Like artificial trees? The effect of framing by natural analogy on public perceptions of geoengineering. *Climatic Change, 130(3)*, 425--438. https://doi.org/10.1007/s10584-014-1148-6

Corlett, R. T., & Westcott, D. A. (2013). Will plant movements keep up with climate change? *Trends in Ecology & Evolution, 28(8*), 482-488. https://doi.org/10.1016/j.tree.2013.04.003

Corry, O. (2017). The international politics of geoengineering: The feasibility of Plan B for tackling climate change. *Security Dialogue, 48(4),* 297-315. https://doi.org/10.1177/0967010617704142

Coughlan de Perez, E., Fuentes, I., Jack, C., Kruczkiewicz, A., Pinto, I., & Stephens, E. (2022). Different types of drought under climate change or geoengineering: Systematic review of societal implications. *Frontiers in Climate, 4*, 959519. https://doi.org/10.3389/fclim.2022.959519

Craik, A. N., & Moore, N. (2014). Disclosure-based governance for climate engineering research. Centre for International Governance Innovation, *CIGI Papers (50).*

Crook, J. A., Jackson, L. S., Osprey, S. M., & Forster, P. M. (2015). A comparison of temperature and precipitation responses to different Earth radiation management geoengineering schemes. *Journal of Geophysical Research. Atmospheres*, *120(18*), 9352-9373. https://doi.org/10.1002/2015JD023269

Crutzen, P. J. (2006). Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? *Climatic Change, 77(3), 211-220.* https://doi.org/10.1007/s10584-006-9101-y

Curry, C. L., Sillmann, J., Bronaugh, D., Alterskjaer, K., Cole, J. N., Ji, D.,...& Muri, H. (2014). A multimodel examination of climate extremes in an idealized geoengineering experiment. *Journal of Geophysical Research: Atmospheres,* 119(7), 3900-3923. https://doi.org/10.1002/2013JD020648

Cziczo, D. J., Froyd, K. D., Hoose, C., Jensen, E. J., Diao, M., Zondlo, M. A.,...Murphy, D. M. (2013). Clarifying the dominant sources and mechanisms of cirrus cloud formation. *Science, 340(6138)*, 1320-1324. https://doi.org/doi:10.1126/science.1234145

D'Amico-Damião, V., & Carvalho, R. F. (2018). Cryptochrome-related abiotic stress responses in plants. *Frontiers in Plant Science*, *9,* 1897-1897. https://doi.org/10.3389/fpls.2018.01897

Dagon, K., & Schrag, D. P. (2017). Regional climate variability under model simulations of solar geoengineering. *Journal of Geophysical Research: Atmospheres, 122(22)*, 12,106-112,121. 10.1002/2017JD027110

Dagon, K., & Schrag, D. P. (2019). Quantifying the effects of solar geoengineering on vegetation. *Climatic Change,* 153(1-2), 235-251. https://doi.org/10.1007/s10584-019-02387-9

Dahl, R. A. (1998). *On democracy*. Yale University Press.

Dai, Z., Burns, E. T., Irvine, P. J., Tingley, D. H., Xu, J., & Keith, D. W. (2021). Elicitation of US and Chinese expert judgments show consistent views on solar geoengineering. *Humanities & Social Sciences Communications*, *8(1*), 1-9. https://doi.org/10.1057/s41599-020-00694-6

Dannenberg, A., Lumkowsky, M., Carlton, E. K., & Victor, D. G. (2023). Naming and shaming as a strategy for enforcing the Paris Agreement: The role of political institutions and public concern. *Proceedings of the National Academy of Sciences, 120(40)*, e2305075120. https://doi.org/doi:10.1073/pnas.2305075120

Dannenberg, A., & Zitzelsberger, S. (2019). Climate experts' views on geoengineering depend on their beliefs about climate change impacts. *Nature Climate Change, 9(10)*, 769-775. https://doi.org/10.1038/s41558-019-0564-z

Davies, G. (2010). Framing the social, political, and environmental risks and benefits of geoengineering: balancing the hard-to-imagine against the hard-to-measure. *Tulsa Law Review, 46*, 261.

Debnath, R., Reiner, D. M., Sovacool, B. K., Müller-Hansen, F., Repke, T., Alvarez, R. M., & Fitzgerald, S. D. (2023). Conspiracy spillovers and geoengineering. *Iscience*, 26(3). 10.1016/j.isci.2023.106166

Delanoë, J., & Hogan, R. J. (2008). A variational scheme for retrieving ice cloud properties from combined radar, lidar, and infrared radiometer. *Journal of Geophysical Research: Atmospheres, 113(D7)*.

Dell, M., Jones, B. F., & Olken, B. A. (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics*, *4(3*), 66-95. https://doi.org/10.1257/mac.4.3.66

Demarsy, E., Goldschmidt-Clermont, M., & Ulm, R. (2018). Coping with 'dark sides of the sun' through photoreceptor signaling. *Trends in Plant Science, 23(3)*, 260-271. https://doi.org/10.1016/j.tplants.2017.11.007

Deuzé, J. L., Bréon, F. M., Devaux, C., Goloub, P. H., Herman, M., Lafrance, B.,...Tanré, D. (2001). Remote sensing of aerosols over land surfaces from POLDER-ADEOS-1 polarized measurements. *Journal of Geophysical Research: Atmospheres, 106(D5)*, 4913-4926. 10.1029/2000JD900364

Diamond, M. S., Director, H. M., Eastman, R., Possner, A., & Wood, R. (2020). Substantial cloud brightening from shipping in subtropical low clouds. *AGU Advances, 1(1)*, e2019AV000111. https://doi.org/10.1029/2019AV000111

Diamond, M. S., Gettelman, A., Lebsock, M. D., McComiskey, A., Russell, L. M., Wood, R., & Feingold, G. (2022). To assess marine cloud brightening's technical feasibility, we need to know what to study---and when to stop. *Proceedings of the National Academy of Sciences - PNAS, 119(4)*. https://doi.org/10.1073/pnas.2118379119

Diffenbaugh, N. S., & Burke, M. (2019). Global warming has increased global economic inequality. *Proceedings of the National Academy of Sciences - PNAS, 116(20)*, 9808-9813. https://doi.org/10.1073/pnas.1816020116

Dipu, S., Quaas, J., Quaas, M., Rickels, W., Mülmenstädt, J., & Boucher, O. (2021). Substantial climate response outside the target area in an idealized experiment of regional radiation management. *Climate (Basel), 9(4),* 66. https://doi.org/10.3390/cli9040066

Convention on Biological Diversity. (2012). *Climate-related geoengineering, XI/20, Decision adopted by the Conference of the Parties to the Convention on Biological Diversity at its eleventh meeting.*

Doney, S. C., Fabry, V. J., Feely, R. A., & Kleypas, J. A. (2009). Ocean acidification: the other CO2 problem. *Annual Review of Marine Science, 1,* 169-192. https://doi.org/10.1146/annurev.marine.010908.163834

Drieskens, E., & van Schaik, L. G. (2014). *The EU and effective multilateralism: Internal and external reform practices*. Routledge. https://doi.org/10.4324/9781315881553

Duffey, A., Irvine, P., Tsamados, M., & Stroeve, J. (2023). Solar geoengineering in the Polar Regions: A review. *Earth's Future, 11(6)*, e2023EF003679. https://doi.org/10.1029/2023EF003679

Dunworth, T. (2008). Towards a culture of legality in international organizations: The case of the OPCW. *International Organizations Law Review*, 5, 119. 10.1163/157237408X327759

Dupont, P.-E. (2014). Compliance with treaties in the context of nuclear non-proliferation: assessing claims in the case of Iran. *Journal of Conflict and Security Law, 19(2)*, 161-210. 10.1093/jcsl/krt017

Durand, M., Murchie, E. H., Lindfors, A. V., Urban, O., Aphalo, P. J., & Robson, T. M. (2021). Diffuse solar radiation and canopy photosynthesis in a changing environment. *Agricultural and Forest Meteorology*, *311*, 108684. https://doi.org/10.1016/j.agrformet.2021.108684

Dusenge, M. E., Duarte, A. G., & Way, D. A. (2019). Plant carbon metabolism and climate change: elevated CO2 and temperature impacts on photosynthesis, photorespiration and respiration. *The New Phytologist, 221(1)*, 32-49. https://doi.org/10.1111/nph.15283

Dykema, J. A., Keith, D. W., & Keutsch, F. N. (2016). Improved aerosol radiative properties as a foundation for solar geoengineering risk assessment. *Geophysical Research Letters, 43(14)*, 7758-7766. https://doi.org/10.1002/2016GL069258

References

Eastham, S. D., Keith, D. W., & Barrett, S. R. H. (2018). Mortality tradeoff between air quality and skin cancer from changes in stratospheric ozone. *Environmental Research Letters, 13(3)*, 34035. https://doi.org/10.1088/1748-9326/aaad2e

Eastham, S. D., Weisenstein, D. K., Keith, D. W., & Barrett, S. R. H. (2018). Quantifying the impact of sulfate geoengineering on mortality from air quality and UV-B exposure. *Atmospheric Environment (1994), 187*, 424-434. https://doi.org/10.1016/j.atmosenv.2018.05.047

Ellery, A. (2017). Low-cost space-based geoengineering: an assessment based on self-replicating manufacturing of in-situ resources on the Moon. *International Journal of Environmental and Ecological Engineering, 10(2)*, 278-285. doi.org/10.5281/zenodo.1129952

Emmerling, J., & Tavoni, M. (2017). Climate engineering and abatement: A 'flat' relationship under uncertainty. *Environmental and Resource Economics, 69(2)*, 395-415. https://doi.org/10.1007/s10640-016-0104-5

Emmerling, J., & Tavoni, M. (2018). Exploration of the interactions between mitigation and solar radiation management in cooperative and non-cooperative international governance settings. *Global Environmental Change, 53*, 244-251. https://doi.org/10.1016/j.gloenvcha.2018.10.006

English, J. M., Toon, O. B., & Mills, M. J. (2012). Microphysical simulations of sulfur burdens from stratospheric sulfur geoengineering. *Atmospheric Chemistry & Physics, 12(10)*, 4775-4793. https://doi.org/10.5194/acp-12-4775-2012

Erice, G., Aranjuelo, I., Irigoyen, J. J., & Sánchez-Díaz, M. (2007). Effect of elevated CO_2, temperature and limited water supply on antioxidant status during regrowth of nodulated alfalfa. *Physiologia Plantarum*, *130(1),* 33-45. https://doi.org/10.1111/j.1399-3054.2007.00889.x

Evans, J., Stride, E., Edirisinghe, M., Andrews, D., & Simons, R. (2010). Can oceanic foams limit global warming? *Climate Research*, 42(2), 155-160.

Eyring, V., Bony, S., Meehl, G. A., Senior, C., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organisation. *Geoscientific Model Development, 8(5)*, 10539-10583. https://doi.org/10.5194/gmdd-8-10539-2015

Fan, Y., Tjiputra, J., Muri, H., Lombardozzi, D., Park, C.-E., Wu, S., & Keith, D. (2021). Solar geoengineering can alleviate climate change pressures on crop yields. *Nature Food*, 2(5), 373-381. https://doi.org/10.1038/s43016-021-00278-w

Farias, D. B. L., & Roger, C. (2023). Differentiation in environmental treaty making: Measuring provisions and how they reshape the depth--participation dilemma. *Global Environmental Politics, 23(1)*, 117-132. https://doi.org/10.1162/glep_a_00686

Fasullo, J.T., Tilmes, S., Richter, J.H., Kravitz, B., MacMartin, D.G., Mills, M.J. and Simpson, I.R. (2018). Persistent polar ocean warming in a strategically geoengineered climate. *Nature Geoscience, 11(12)*, 910-914. 10.1038/s41561-018-0249-7

Fasullo, J.T. and Richter, J.H. (2023). *Scenario and model dependence of strategic solar climate intervention in CESM*. Authorea Preprints**.** 10.1002/essoar.10511796.2

Fasullo, J. T., & Richter, J. H. (2023). Dependence of strategic solar climate intervention on background scenario and model physics. *Atmospheric Chemistry & Physics, 23(1)*, 163-182. https://doi.org/10.5194/acp-23-163-2023

Fawzy, S., Osman, A. I., Doran, J., & Rooney, D. W. (2020). Strategies for mitigation of climate change: a review. *Environmental Chemistry Letters, 18(6)*, 2069-2094. https://doi.org/10.1007/s10311-020-01059-w

Fielding, M. D., Chiu, J. C., Hogan, R. J., & Feingold, G. (2013). 3D cloud reconstructions: Evaluation of scanning radar scan strategy with a view to surface shortwave radiation closure. *Journal of Geophysical Research: Atmospheres, 118(16)*, 9153-9167. https://doi.org/10.1002/jgrd.50614

Feingold, G., Ghate, V. P., & Russell, L. M. (2022). *DOE-NOAA Marine cloud brightening workshop*. https://doi.org/10.2172/1902730

Fenn, J., Helm, J. F., Höfele, P., Kulbe, L., Ernst, A., & Kiesel, A. (2023). Identifying key-psychological factors influencing the acceptance of yet emerging technologies--A multi-method-approach to inform climate policy. *PLOS Climate, 2(6)*, e0000207. https://doi.org/10.1371/journal.pclm.0000207

Fernald, F. G., Herman, B. M., & Reagan, J. A. (1972). Determination of aerosol height distributions by lidar. *Journal of Applied Meteorology and Climatology*, 11(3), 482-489. https://doi.org/10.1175/1520-0450(1972)011%3C0482:DOAHDB%3E2.0.CO;2

Ferraro, A. J., Charlton-Perez, A. J., & Highwood, E. J. (2015). Stratospheric dynamics and midlatitude jets under geoengineering with space mirrors and sulfate and titania aerosols. *Journal of Geophysical Research: Atmospheres, 120(2)*, 414-429. https://doi.org/10.1002/2014JD022734

Ferraro, A. J., & Griffiths, H. G. (2016). Quantifying the temperature-independent effect of stratospheric aerosol geoengineering on global-mean precipitation in a multi-model ensemble. *Environmental Research Letters, 11(3),* 34012-34021. https://doi.org/10.1088/1748-9326/11/3/034012

Field, L., Ivanova, D., Bhattacharyya, S., Mlaker, V., Sholtz, A., Decca, R.,...Katuri, K. (2018). Increasing Arctic sea ice albedo using localized reversible geoengineering. *Earth's Future*, *6*, 882--901. https://doi.org/10.1029/2018EF000820

Findeisen, W. (1938) Die kolloidmeteorologischen Vorgänge bei der Niederschlagsbildung (Colloidal meteorological processes in the formation of precipitation). *Meteorologische Zeitschrift, 24(4)*, 443-454. https://doi.org/10.1127/metz/2015/0675

Finus, M., & Furini, F. (2023). Global climate governance in the light of geoengineering: A shot in the dark? *Journal of Environmental Economics and Management, 122*, 102854. https://doi.org/10.1016/j.jeem.2023.102854

Flament, T., Trapon, D., Lacour, A., Dabas, A., Ehlers, F., & Huber, D. (2021). Aeolus L2A aerosol optical properties product: standard correct algorithm and Mie correct algorithm. *Atmospheric Measurement Techniques, 14(12)*, 7851-7871. https://doi.org/10.5194/amt-14-7851-2021

Flegal, J. A., & Gupta, A. (2018). Evoking equity as a rationale for solar geoengineering research? Scrutinizing emerging expert visions of equity. *International Environmental Agreements: Politics, Law and Economics, 18(1)*, 45-61. https://doi.org/10.1007/s10784-017-9377-6

Fleming, J. R. (2012). Will geoengineering bring security and peace? What does history tell us? *Sicherheit und Frieden (S+F)/Security and Peace*, 200-204. 10.5771/0175-274x-2012-4-200

Fleming, J. R., & Love, E. A. (2012). Healthy lakes and vibrant economies: linking history, sense of place, and watershed protection in the Belgrade Lakes region. *Maine Policy Review, 21(1)*, 90-94. https://doi.org/10.53558/LUIK8319

Florin, M.-V., Rouse, P., Hubert, A.-M., Honegger, M., & Reynolds, J. (2020). International governance issues on climate engineering Information for policymakers. EPFL International Risk Governance Center (IRGC). DOI:10.5075/epfl-irgc-277726

Flyvbjerg, Bent. (2014). What you should know about megaprojects and why: An overview. *Project Management Journal 45(2)*: 6--19. https://doi.org/10.1002/pmj.21409

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.L., Frame, D.,...Wild, M. (2023). The Earth's energy budget, climate feedbacks and climate sensitivity. In *C. Intergovernmental Panel on Climate (Ed.), Climate Change 2021 -- The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 923-1054). Cambridge University Press. https://doi.org/10.1017/9781009157896.009

Forster, E. J., Healey, J. R., Dymond, C., & Styles, D. (2021). Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. *Nature Communications*, *12(1)*, 3831. https://doi.org/10.1038/s41467-021-24084-x

Fraser, N. (2005). Reframing global justice. *New Left Review, 36*, 69.

French, J. R., Friedrich, K., Tessendorf, S. A., Rauber, R. M., Geerts, B., Rasmussen, R. M.,...Blestrud, D. R. (2018). Precipitation formation from orographic cloud seeding. *Proceedings of the National Academy of Sciences, 115(6)*, 1168-1173. https://doi.org/10.1073/pnas.1716995115

Frumhoff, P. C., & Stephens, J. C. (2018). Towards legitimacy of the solar geoengineering research enterprise. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376(2119)*, 20160459. https://doi.org/10.1098/rsta.2016.0459

Fyfe, J. C., Gillett, N. P., & Zwiers, F. W. (2013). Overestimated global warming over the past 20 years. *Nature Climate Change, 3(9)*, 767-769. 10.1038/nclimate1972

Gannon, K. E., & Hulme, M. (2018). Geoengineering at the "edge of the world": Exploring perception and environment through the Haida Salmon Restoration Corporation, *Geography and Environment, 5(1*), e00054. https://doi.org/10.1002/geo2.54

Gao, R.-S., Rosenlof, K. H., Kärcher, B., Tilmes, S., Toon, O. B., Maloney, C., & Yu, P. (2021). Toward practical stratospheric aerosol albedo modification: Solar-powered lofting. *Science Advances, 7(20*), eabe3416. https://doi.org/doi:10.1126/sciadv.abe3416

Gardiner, S. (2010). Is 'arming the future' with geoengineering really the lesser evil? Some doubts about the ethics of intentionally manipulating the climate system. In S. Gardiner, S. Caney, D. Jamieson, & H. Shue (Eds.), *Climate ethics: Essential readings* (pp. 284 --312). Oxford: Oxford University Press.

Gardiner, S. M. (2011a). *A perfect moral storm*. Oxford: Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195379440.001.0001

Gardiner, S. M. (2011b). Some early ethics of geoengineering the climate: A commentary on the values of the Royal Society report. *Environmental Values*, *20*(2), 163--188. https://doi.org/10.3197/096327111X12997574391689

Gardiner, S. M. (2013a). Why geoengineering is not a 'global public good', and why it is ethically misleading to frame it as one. *Climatic Change*, *121*(3), 513--525. https://doi.org/10.1007/s10584-013-0764-x

Gardiner, S.M. (2013b). The desperation argument for geoengineering. *Political Science & Politics, 46*(1), 28-33.

Gardiner, S. M., & Fragnière, A. (2018). The Tollgate Principles for the governance of geoengineering: Moving beyond the Oxford Principles to an ethically more robust approach. *Ethics, Policy & Environment, 21(2)*, 143-174. https://doi.org/10.1080/21550085.2018.1509472

Gardiner, S. M., McKinnon, C., & Fragnière, A. (Eds.). (2020). *The ethics of "geoengineering" the global climate: Justice, legitimacy and governance*. Routledge. https://doi.org/10.4324/9781003049012

Garrison, J. (1995). An evaluation of the effect of volcanic eruption on the solar radiation at six Canadian stations. *Solar Energy*, 55(6), 513-525. https://doi.org/10.1016/0038-092X(95)00066-Z

Gasparini, B., & Lohmann, U. (2016). Why cirrus cloud seeding cannot substantially cool the planet. *Journal of Geophysical Research: Atmospheres, 121(9)*, 4877-4893. https://doi.org/10.1002/2015JD024666

Gasparini, B., McGraw, Z., Storelvmo, T., & Lohmann, U. (2020). To what extent can cirrus cloud seeding counteract global warming? *Environmental Research Letters, 15(5)*, 054002. https://doi.org/10.1088/1748-9326/ab71a3

Gasparrini, A., Guo, Y., Sera, F., Vicedo-Cabrera, A. M., Huber, V., Tong, S.,...Armstrong, B. (2017). Projections of temperature-related excess mortality under climate change scenarios. *Lancet Planet Health, 1(9)*, e360-e367. https://doi.org/10.1016/s2542-5196(17)30156-0

Gazzotti, P., Emmerling, J., Marangoni, G., Castelletti, A., Wijst, K.-I. v. d., Hof, A., & Tavoni, M. (2021). Persistent inequality in economically optimal climate policies. *Nature Communications*, *12(1)*, 3421-3421. https://doi.org/10.1038/s41467-021-23613-y

Geden, O. (2016). The Paris Agreement and the inherent inconsistency of climate policymaking. *Wiley Interdisciplinary Reviews: Climate Change, 7(6)*, 790-797. https://doi.org/10.1002/wcc.427

Geden, O. (2015). Policy: Climate advisers must maintain integrity. *Nature*, 521(7550), 27-28. 10.1038/521027a

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy, 31(8-9)*, 1257-1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Ghidoni, R., Abatayo, A. L., Bosetti, V., Casari, M., & Tavoni, M. (2023). Governing climate geoengineering: Side payments are not enough. *Journal of the Association of Environmental and Resource Economists, 10(5)*, 1149-1177. https://doi.org/10.1086/724286

Giannakaki, E., Balis, D. S., Amiridis, V., & Kazadzis, S. (2007). Optical and geometrical characteristics of cirrus clouds over a Southern European lidar station. *Atmospheric Chemistry and Physics, 7(21)*, 5519-5530. https://doi.org/10.5194/acp-7-5519-2007

Gibbons, R., & Robinson, T. (2021). Twenty-five years safer? Assessing the IAEA's Model Additional Protocol and its role in international politics. *The Non-proliferation Review, 28(4-6)*, 297-318. https://doi.org/10.1080/10736700.2022.2064516

Gilabert, P., & Lawford-Smith, H. (2012). Political feasibility: A conceptual exploration. *Political Studies, 60(4)*, 809-825. https://doi.org/10.1111/j.1467-9248.2011.00936.x

Gkikas, A., Gialitaki, A., Binietoglou, I., Marinou, E., Tsichla, M., Siomos, N.,...Proestakis, E. (2023). First assessment of Aeolus Standard Correct Algorithm particle backscatter coefficient retrievals in the eastern Mediterranean. *Atmospheric Measurement Techniques*, 16(4), 1017-1042. https://doi.org/10.5194/amt-16-1017-2023

Glassmeier, F., Hoffmann, F., Johnson, J. S., Yamaguchi, T., Carslaw, K. S., & Feingold, G. (2021). Aerosol-cloud-climate cooling overestimated by ship-track data. *Science, 371(6528)*, 485-489. https://doi.org/10.1126/science.abd3980

Glienke, S., Irvine, P. J., & Lawrence, M. G. (2015). The impact of geoengineering on vegetation in experiment G1 of the GeoMIP. *Journal of Geophysical Research: Atmospheres, 120(19)*, 10-196. 10.1002/2015JD024202

Goddard, P. B., Kravitz, B., MacMartin, D. G., & Wang, H. (2022). The shortwave radiative flux response to an injection of sea salt aerosols in the Gulf of Mexico. *Journal of Geophysical Research: Atmospheres, 127(21)*, e2022JD037067. https://doi.org/10.1029/2022JD037067

Goes, M., Tuana, N., & Keller, K. (2011). The economics (or lack thereof) of aerosol geoengineering. *Climatic Change*, 109(3-4), 719-744. https://doi.org/10.1007/s10584-010-9961-z

Goeschl, T., Heyen, D., & Moreno-Cruz, J. (2013). The intergenerational transfer of solar radiation management capabilities and atmospheric carbon stocks. *Environmental & Resource Economics, 56(1)*, 85-104. https://doi.org/10.1007/s10640-013-9647-x

Goodin, R. E. (1989). Stars to steer by: the political impact of moral values. *Journal of Public Policy, 9(3)*, 241-259. doi:10.1017/S0143814X0000845X

Goodman, A. H., & Henderson-Sellers, A. (1988). Cloud detection and analysis: A review of recent progress. *Atmospheric Research, 21(3-4)*, 203-228. https://doi.org/10.1016/0169-8095(88)90027-0

Gostin, L. O., Habibi, R., & Meier, B. M. (2020). Has global health law risen to meet the COVID-19 challenge? Revisiting the International Health Regulations to prepare for future threats. *The Journal of Law, Medicine & Ethics, 48(2)*, 376-381. 10.1177/1073110520935354

Govindasamy, B., & Caldeira, K. (2000). Geoengineering Earth's radiation balance to mitigate CO2-induced climate change. *Geophysical Research Letters, 27(14),* 2141-2144. https://doi.org/10.1029/1999GL006086

Gramstad, K., & Tjøtta, S. (2010). *Geoengineering - a part of climate change policies.*

Grant, N., Hawkes, A., Mittal, S., & Gambhir, A. (2021). Confronting mitigation deterrence in low-carbon scenarios. *Environmental Research Letters, 16(6),* 064099. 10.1088/1748-9326/ac0749

Grasso, M. (2019). Sulfur in the sky with diamonds: an inquiry into the feasibility of solar geoengineering. *Global Policy, 10(2),* 217-226. https://doi.org/10.1111/1758-5899.12646

Gregory, R., Satterfield, T., & Hasell, A. (2016). Using decision pathway surveys to inform climate engineering policy choices. *Proceedings of the National Academy of Sciences, 113(3),* 560-565. https://doi.org/doi:10.1073/pnas.1508896113

Grieco, J., Powell, R., & Snidal, D. (1993). The relative-gains problem for international cooperation. *American Political Science Review, 87(3),* 729-743. https://doi.org/10.2307/2938747

Grieger, K. D., Felgenhauer, T., Renn, O., Wiener, J., & Borsuk, M. (2019). Emerging risk governance for stratospheric aerosol injection as a climate management technology. *Environment Systems and Decisions, 39*, 371-382. 10.1007/s10669-019-09730-6

Gruber, S., Blahak, U., Haenel, F., Kottmeier, C., Leisner, T., Muskatel, H.,...Vogel, B. (2019). A process study on thinning of Arctic winter cirrus clouds with high-resolution ICON-ART simulations. *Journal of Geophysical Research: Atmospheres, 124(11)*, 5860-5888. https://doi.org/10.1029/2018JD029815

Gryspeerdt, E., Quaas, J., Goren, T., Klocke, D., & Brueck, M. (2018). An automated cirrus classification. *Atmospheric Chemistry and Physics, 18(9*), 6157-6169. https://doi.org/10.5194/acp-18-6157-2018

Gupta, A. (2010). Transparency to what end? Governing by disclosure through the Biosafety Clearing House. *Environment and Planning C: Government and Policy, 28(1)*, 128-144. https://doi.org/10.1068/c08137

Gupta, A. (2010b). Transparency as contested political terrain: who knows what about the global GMO trade and why does it matter? *Global Environmental Politics, 10(3)*, 32-52. 10.1162/GLEP_a_00013

References

Gupta, A., Biermann, F., van Driel, E., Bernaz, N., Jayaram, D., Kim, R. E.,...Wewerinke-Singh, M. (2024). Towards a Non-Use Regime on Solar Geoengineering: Lessons from International Law and Governance. *Transnational Environmental Law*, 1-32. doi:10.1017/S2047102524000050

Gupta, A., & Möller, I. (2019). De facto governance: how authoritative assessments construct climate engineering as an object of governance. *Environmental Politics, 28(3)*, 480-501. https://doi.org/10.1080/09644016.2018.1452373

Gupta, A., Möller, I., Biermann, F., Jinnah, S., Kashwan, P., Mathur, V.,...Nicholson, S. (2020). Anticipatory governance of solar geoengineering: conflicting visions of the future and their links to governance proposals. *Current Opinion in Environmental Sustainability, 45*, 10-19. https://doi.org/10.1016/j.cosust.2020.06.004

Guston, D. H. (2014). Understanding 'anticipatory governance'. *Social Studies of Science, 44(2)*, 218-242. https://doi.org/10.1177/0306312713508669

Hale, B. (2012). The world that would have been: Moral hazard arguments against geoengineering. In C. Preston (Ed.), *Reflecting sunlight: The ethics of solar radiation management* (pp. 113--131). Lanham, MD: Rowman and Littlefield.

Hamilton, C. (2013). No, we should not just 'at least do the research'. *Nature, 496 (7444)*, 139-139. 10.1038/496139a

Hamilton, C. (2013). The ethical foundations of climate engineering. In W.C.G. Burns & A.L. Strauss (Eds.), *Climate change engineering: Philosophical perspectives, legal Issues, and governance frameworks* (pp. 39-58). Cambridge University Press. 10.1017/CBO9781139161824.004

Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G. A.,. . . Zhang, S. (2005). Efficacy of climate forcings. *Journal of Geophysical Research: Atmospheres, 110(D18)*. 10.1029/2005JD005776

Harding, A., & Moreno-Cruz, J. B. (2016). Solar geoengineering economics: From incredible to inevitable and half-way back. *Earth's Future, 4(12)*, 569-577. https://doi.org/10.1002/2016EF000462

Harding, A. R., Belaia, M., & Keith, D. W. (2023). The value of information about solar geoengineering and the two-sided cost of bias. *Climate Policy, 23(3)*, 355-365. https://doi.org/10.1080/14693062.2022.2091509

Harding, A. R., Ricke, K., Heyen, D., MacMartin, D. G., & Moreno-Cruz, J. (2020). Climate econometric models indicate solar geoengineering would reduce inter-country income inequality. *Nature Communications, 11(1)*, 227-227. https://doi.org/10.1038/s41467-019-13957-x

Harrison, D. P. (2024). An overview of environmental engineering methods for reducing coral bleaching stress. *Oceanographic Processes of Coral Reefs*, 403-418. 10.1201/9781003320425-31

Hartzell-Nichols, L. (2012). Precaution and solar radiation management. *Ethics, Policy & Environment*, 15(2), 158-171. https://doi.org/10.1080/21550085.2012.685561

Hasekamp, O. P., Fu, G., Rusli, S. P., Wu, L., Di Noia, A., Brugh, J. A. D.,...van Amerongen, A. (2019). Aerosol measurements by SPEXone on the NASA PACE mission: expected retrieval capabilities. *Journal of Quantitative Spectroscopy and Radiative Transfer, 227*, 170-184. https://doi.org/10.1016/j.jqsrt.2019.02.006

Hathaway, O., & Shapiro, S. J. (2011). Outcasting: enforcement in domestic and international law. *Yale Law Journal, 121*, 252-469.

Haywood, J. M., Jones, A., Bellouin, N., & Stephenson, D. (2013). Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nature Climate Change, 3(7)*, 660-665. 10.1038/nclimate1857

Haywood, J. M., Jones, A., Jones, A. C., Halloran, P., & Rasch, P. J. (2023). Climate intervention using marine cloud brightening (MCB) compared with stratospheric aerosol injection (SAI) in the UKESM1 climate model. *Atmospheric Chemistry & Physics, 23(24)*, 15305-15324. https://doi.org/10.5194/acp-23-15305-2023

Heath, J. (1998). Stomata of trees growing in CO_2-enriched air show reduced sensitivity to vapour pressure deficit and drought. *Plant, Cell and Environment, 21(11)*, 1077-1088. https://doi.org/10.1046/j.1365-3040.1998.00366.x

Heckendorn, P., Weisenstein, D., Fueglistaler, S., Luo, B. P., Rozanov, E., Schraner, M., ... & Peter, T. (2009). The impact of geoengineering aerosols on stratospheric temperature and ozone. *Environmental Research Letters, 4(4)*, 045108. 10.1088/1748-9326/4/4/045108

Henneberger, J., Ramelli, F., Spirig, R., Omanovic, N., Miller, A. J., Fuchs, C.,...Kanji, Z. A. (2023). Seeding of supercooled low stratus clouds with a UAV to study microphysical ice processes: An introduction to the CLOUDLAB project. *Bulletin of the American Meteorological Society, 104 (11)*, E1962-E1979. 10.1175/BAMS-D-22-0178.1

Henry, M., Haywood, J., Jones, A., Dalvi, M., Wells, A., Visioni, D.,...Tye, M. R. (2023). Comparison of UKESM1 and CESM2 simulations using the same multi-target stratospheric aerosol injection strategy. *Atmospheric Chemistry and Physics, 23(20)*, 13369-13385. https://doi.org/10.5194/acp-23-13369-2023

Hernandez-Jaramillo, D. C., Harrison, L., Kelaher, B., Ristovski, Z., & Harrison, D. P. (2023). Evaporative cooling does not prevent vertical dispersion of effervescent seawater aerosol for brightening clouds. *Environmental Science & Technology, 57(49)*, 20559-20570. https://doi.org/10.1021/acs.est.3c04793

Heutel, G., Juan Moreno, C., & Shayegh, S. (2015). *Solar geoengineering, uncertainty, and the price of carbon*. Cambridge: National Bureau of Economic Research. 10.1016/j.jeem.2017.11.002

Heutel, G., Moreno-Cruz, J., & Ricke, K. (2016). Climate engineering economics. *Annual Review of Resource Economics, 8(1),* 99-118. https://doi.org/10.1146/annurev-resource-100815-095440

Heyen, D., Horton, J., & Moreno-Cruz, J. (2019). Strategic implications of counter-geoengineering: Clash or cooperation? *Journal of Environmental Economics and Management, 95*, 153-177. https://doi.org/10.1016/j.jeem.2019.03.005

Heyen, D., & Lehtomaa, J. (2021). Solar geoengineering governance: a dynamic framework of farsighted coalition formation. *Oxford Open Climate Change, 1(1)*. https://doi.org/10.1093/oxfclm/kgab010

Heyen, D., Wiertz, T., & Irvine, P. J. (2015). Regional disparities in SRM impacts: The challenge of diverging preferences. *Climatic Change, 133(4)*, 557-563. https://doi.org/10.1007/s10584-015-1526-8

Heymsfield, A. J., Thompson, G., Morrison, H., Bansemer, A., Rasmussen, R. M., Minnis, P., Wang, Z., & Zhang, D. (2011). Formation and spread of aircraft-induced holes in clouds. *Science, 333(6038)*, 77-81. 10.1126/science.1202851

Heyward, C. (2013). Situating and abandoning geoengineering: A typology of five responses to dangerous climate change. *Political Science & Politics, 46(1)*, 23--27. https://doi.org/10.1017/S1049096512001436

Heyward, C. (2017). Ethics and climate adaptation. In S.M. Gardiner & A. Thompson (Eds.), *The Oxford Handbook of Environmental Ethics* (pp. 474-486). Oxford University Press. 10.1093/oxfordhb/9780199941339.013.42

Heyward, C. (2014). Benefiting from climate geoengineering and corresponding remedial duties: The case of unforeseeable harms. *Journal of Applied Philosophy, 31(4)*, 405-419. 10.1111/japp.12075 ISSN 0264-3758.

Heyward, C. (2021). Is the beneficiary pays principle essential in climate justice? *Norsk filosofisk tidsskrift, 56(2-3)*, 125-136. https://doi.org/10.18261/issn.1504-2901-2021-02-03-07

Heyward, C. (2019). Normative issues of geoengineering technologies. In T.M. Letcher (Ed.), *Managing global warming* (pp. 639-657). Academic Press. https://doi.org/10.1016/B978-0-12-814104-5.00021-1

Heyward, C., & Rayner, S. (2015). Uneasy expertise: geoengineering, social science, and democracy in the Anthropocene. In M. Heazle & J. Kane (Eds.), *Policy legitimacy, science and political authority* (pp. 101-121). Routledge.

Himmelsbach, R. (2017). How scientists advising the European Commission on research priorities view climate engineering proposals. *Science and Public Policy, 45(1)*, 124-133. https://doi.org/10.1093/scipol/scx053

Hirasawa, H., Hingmire, D., Singh, H., Rasch, P. J., & Mitra, P. (2023). Effect of regional marine cloud brightening interventions on climate tipping elements. *Geophysical Research Letters, 50(20)*, e2023GL104314. https://doi.org/10.1029/2023GL104314

Hofmann, D. J., Rosen, J. M., Pepin, T. J., & Pinnick, R. G. (1975). Stratospheric aerosol measurements I: Time variations at northern midlatitudes. *Journal of the Atmospheric Sciences, 32(7)*, 1446-1456. https://doi.org/10.1175/1520-0469(1975)032<1446:SAMITV>2.0.CO;2

Honegger, M., Michaelowa, A., & Pan, J. (2021). Potential implications of solar radiation modification for achievement of the Sustainable Development Goals. *Mitigation and Adaptation Strategies for Global Change, 26(5)*, 21. https://doi.org/10.1007/s11027-021-09958-1

Hornigold, T. (2021). *Trade-offs inherent in solar geoengineering peak-shaving strategies*. arXiv preprint arXiv:2108.00096. https://doi.org/10.48550/arXiv.2108.00096

Hornsey, M. J., & Fielding, K. S. (2020). Understanding (and reducing) inaction on climate change. *Social Issues and Policy Review*, *14*(1), 3-35. https://doi.org/10.1111/sipr.12058

Horton, J. B. (2015). The emergency framing of solar geoengineering: Time for a different approach. *The Anthropocene Review*, *2*(2), 147-151. 10.1177/2053019615579922

Horton, J. B., Brent, K., Dai, Z., Felgenhauer, T., Geden, O., McDonald, J.,...Xu, J. (2023). Solar geoengineering research programs on national agendas: a comparative analysis of Germany, China, Australia, and the United States. *Climatic Change, 176(4)*, 37. https://doi.org/10.1007/s10584-023-03516-1

Horton, J. B., Parker, A., & Keith, D. (2014). Liability for solar geoengineering: historical precedents, contemporary innovations, and governance possibilities. *NYU Environmental Law Journal, 22*, 225-273.

Horton, J. B., Reynolds, J. L., Buck, H. J., Callies, D., Schäfer, S., Keith, D. W., & Rayner, S. (2018). Solar Geoengineering and Democracy. Global Environmental Politics, 18(3), 5-24. https://doi.org/10.1162/glep_a_00466

Hourdequin, M. (2019). Geoengineering justice: The role of recognition. *Science, Technology, & Human Values, 44(3)*, 448--477. https://doi.org/10.1177/0162243918802893

Hubert, A.-M. (2021). A code of conduct for responsible geoengineering research. *Global Policy, 12(S1)*, 82-96. https://doi.org/10.1111/1758-5899.12845

References

Hulme, M. (2014). Can science fix climate change? A case against climate engineering. John Wiley & Sons.

Hussain, A., Sipra, H. F., Waheed, A., & Ukhurebor, K. E. (2024). Exploring the academic perceptions of climate engineering in developing countries. *Atmósfera, 38*. https://doi.org/10.20937/ATM.53264

Huynh, H. N., & McNeill, V. F. (2024). The potential environmental and climate impacts of stratospheric aerosol injection: a review. *Environmental Science: Atmospheres*, 4(2), 114-143. https://doi.org/10.1039/d3ea00134b

Iles, C. E., & Hegerl, G. C. (2015). Systematic change in global patterns of streamflow following volcanic eruptions. *Nature Geoscience, 8(11)*, 838-842. 10.1038/ngeo2545

Illingworth, A. J., Barker, H., Beljaars, A., Ceccaldi, M., Chepfer, H., Clerbaux, N., Cole, J., Delanoë, J., Domenech, C., & Donovan, D. P. (2015). The EarthCARE satellite: The next step forward in global measurements of clouds, aerosols, precipitation, and radiation. *Bulletin of the American Meteorological Society, 96(8)*, 1311-1332. https://doi.org/10.1175/BAMS-D-12-00227.1

Initiative, S. R. M. G. (2011). *Solar radiation management: The governance of research*. London: The Royal Society. Retrieved from: https://royalsociety.org/-/media/policy/projects/solar-radiation-governance/des2391_srmgi-report_web.pdf

IPCC. (2023). Summary for policymakers. In *Climate change 2021 -- The physical science basis: Working Group I contribution to the sixth assessment report of the Intergovernmental Panel on Climate Change* (pp. 3-32). Cambridge University Press. https://doi.org/10.1017/9781009157896.001

Ipsos, M. (2010). *Experiment Earth? Report on a public dialogue on geoengineering*. Ipsos Mori.

IRS & Airbus (2020). *International Planetary Sun Shield (IPSS) - gigasails in space. IPSS High-level concept.* Bremen, Germany: The Institute of Space Systems (IRS) and Airbus Defence & Space.

Irvine, P., Emanuel, K., He, J., Horowitz, L. W., Vecchi, G., & Keith, D. (2019). Halving warming with idealized solar geoengineering moderates key climate hazards. *Nature Climate Change, 9(4)*, 295-299. https://doi.org/10.1038/s41558-019-0398-8

Irvine, P. J., & Keith, D. W. (2020). Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards. *Environmental Research Letters, 15(4)*, 044011. 10.1088/1748-9326/ab76de

Irvine, P. J., Kravitz, B., Lawrence, M. G., Gerten, D., Caminade, C., Gosling, S. N.,...Smith, S. J. (2017). Towards a comprehensive climate impacts assessment of solar geoengineering. *Earth's Future, 5(1),* 93-106. https://doi.org/10.1002/2016EF000389

Irvine, P. J., Kravitz, B., Lawrence, M. G., & Muri, H. (2016). An overview of the Earth system science of solar geoengineering. Wiley interdisciplinary reviews. *Climate Change, 7(6)*, 815-833. https://doi.org/10.1002/wcc.423

Irvine, P. J., Ridgwell, A., & Lunt, D. J. (2010). Assessing the regional disparities in geoengineering impacts. *Geophysical Research Letters, 37(18)*. https://doi.org/10.1029/2010GL044447

Irvine, P. J., Ridgwell, A., & Lunt, D. J. (2011). Climatic effects of surface albedo geoengineering. *Journal of Geophysical Research: Atmospheres, 116(D24)*. https://doi.org/10.1029/2011JD016281

J., R. (2005). *Political liberalism* (2^nd^ ed.). Columbia University Press.

Jacob, D. J. (2000). Heterogeneous chemistry and tropospheric ozone. *Atmospheric Environment, 34(12*), 2131-2159. https://doi.org/10.1016/S1352-2310(99)00462-8

Jamieson, D. (1996). Ethics and intentional climate change. *Climatic Change, 33(3)*, 323-336. https://doi.org/10.1007/BF00142580

Jamieson, D. (2013). Some whats, whys and worries of geoengineering. *Climatic Change, 121(3)*, 527--537. https://doi.org/10.1007/s10584-013-0862-9

Jamieson, D. (2020). Ethics and intentional climate change. In A. Maynard & J. Stilgoe (Eds.), *The ethics of nanotechnology, geoengineering, and clean energy* (pp. 247-260). Routledge. https://doi.org/10.4324/9781003075028

Jaross, G., Bhartia, P. K., Chen, G., Kowitt, M., Haken, M., Chen, Z.,...Kelly, T. (2014). OMPS Limb Profiler instrument performance assessment. *Journal of Geophysical Research: Atmospheres, 119(7)*, 4399-4412. doi:10.1002/2013JD020472

Jasanoff, S., & Hurlbut, J. B. (2018). A global observatory for gene editing. *Nature, 555(7697)*, 435-437. 10.1038/d41586-018-03270-w

Ji, D., Fang, S., Curry, C. L., Kashimura, H., Watanabe, S., Cole, J. N. S.,...Moore, J. C. (2018). Extreme temperature and precipitation response to solar dimming and stratospheric aerosol geoengineering. *Atmospheric Chemistry and Physics, 18(14)*, 10133-10156. https://doi.org/10.5194/acp-18-10133-2018

Jia, H., Ma, X., Yu, F., & Quaas, J. (2021). Significant underestimation of radiative forcing by aerosol--cloud interactions derived from satellite-based methods. *Nature Communications, 12(1)*, 3649. https://doi.org/10.1038/s41467-021-23888-1

Jin, X., Cao, L., & Zhang, J. (2022). Effects of solar radiation modification on the ocean carbon cycle: An earth system modeling study. *Atmospheric and Oceanic Science Letters, 15(3)*, 100187. https://doi.org/10.1016/j.aosl.2022.100187

Jinnah, S., Nicholson, S. and Flegal, J., (2020). Toward legitimate governance of solar geoengineering research: a role for sub-state actors. In S. M. Gardiner, C. McKinnon, A. Fragnière (eds.), *The ethics of "geoengineering" the global climate* (pp. 133-152). Routledge. 10.1080/21550085.2018.1562526

Jobin, M., & Siegrist, M. (2020). Support for the deployment of climate engineering: a comparison of ten different technologies. *Risk Analysis, 40(5)*, 1058-1078. https://doi.org/10.1111/risa.13462\ \ Jones, A., Haywood, J. M., Scaife, A. A., Boucher, O., Henry, M., Kravitz, B.,...Visioni, D. The impact of stratospheric aerosol intervention on the North Atlantic and quasi-biennial oscillations in the Geoengineering Model Intercomparison Project (GeoMIP) G6sulfur experiment. *Atmospheric Chemistry and Physics, 22*, 2999--3016, https://doi.org/10.5194/acp-22-2999-2022

Jones, A., Haywood, J., & Boucher, O. (2009). Climate impacts of geoengineering marine stratocumulus clouds. *Journal of Geophysical Research: Atmospheres, 114(D10)*. https://doi.org/10.1029/2008JD011450

Jones, A. C., Haywood, J. M., Dunstone, N., Emanuel, K., Hawcroft, M. K., Hodges, K. I., & Jones, A. (2017). Impacts of hemispheric solar geoengineering on tropical cyclone frequency. *Nature Communications, 8(1)*, 1382-1310. https://doi.org/10.1038/s41467-017-01606-0

Junge, C. E., Chagnon, C. W., & Manson, J. E. (1961). A world-wide stratospheric aerosol layer. *Science, 133(3463),* 1478-1479. 10.1126/science.133.3463.1478.a

Kahn, R. A., Gaitley, B. J., Garay, M. J., Diner, D. J., Eck, T. F., Smirnov, A., & Holben, B. N. (2010). Multiangle Imaging SpectroRadiometer global aerosol product assessment by comparison with the Aerosol Robotic Network. *Journal of Geophysical Research: Atmospheres, 115(D23)*. https://doi.org/10.1029/2010JD014601

Kalkuhl, M., & Wenz, L. (2020). The impact of climate conditions on economic production. Evidence from a global panel of regions. *Journal of Environmental Economics and Management, 103, 102360.* https://doi.org/10.1016/j.jeem.2020.102360

Karlsson, K. G., Stengel, M., Meirink, J. F., Riihelä, A., Trentmann, J., Akkermans, T.,...Hollmann, R. (2023). CLARA-A3: The third edition of the AVHRR-based CM SAF climate data record on clouds, radiation and surface albedo covering the period 1979 to 2023. *Earth System Science Data Discussions*, *2023*, 1-42. https://doi.org/10.5194/essd-15-4901-2023

Kawamoto, K., Nakajima, T., & Nakajima, T. Y. (2001). A global determination of cloud microphysics with AVHRR remote sensing. *Journal of Climate, 14(9)*, 2054-2068. https://doi.org/10.1175/1520-0442(2001)014%3C2054:AGDOCM%3E2.0.CO;2

Keith, D. (2013). *A case for climate engineering*. MIT Press.

Keith, D., & Irvine, P. (2021). The US can't go it alone on solar geoengineering. *Policy Exchange, 1*, 38-45.

Keith, D. W. (2017). Toward a responsible solar geoengineering research program. *Issues in Science and Technology, 33(3)*, 71-77.

Keith, D. W., & Irvine, P. J. (2016). Solar geoengineering could substantially reduce climate risks---A research hypothesis for the next decade. *Earth's Future*, *4*(11), 549-559. https://doi.org/10.1002/2016EF000465

Keith, D. W., & MacMartin, D. G. (2015). A temporary, moderate and responsive scenario for solar geoengineering. *Nature Climate Change, 5(3)*, 201-206. DOI: 10.1038/NCLIMATE2493

Keith, D., Morton, O., Shyur, Y., Worden, P., & Wordsworth, R. (2022). *Reflections on a meeting about space-based solar geoengineering*. Harvard's Solar Geoengieering Research Program.

Keith, D. W., Weisenstein, D. K., Dykema, J. A., & Keutsch, F. N. (2016). Stratospheric solar geoengineering without ozone loss. *Proceedings of the National Academy of Sciences - PNAS, 113(52)*, 14910-14914. https://doi.org/10.1073/pnas.1615572113

Kelle, A. (2004). Assessing the effectiveness of security regimes---The Chemical Weapons Control Regime's first six years of operation. *International Politics, 41*, 221-242. http://dx.doi.org/10.1057/palgrave.ip.8800075

Keller, D. P., Feng, E. Y., & Oschlies, A. (2014). Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nature Communications, 5(1)*, 3304. https://doi.org/10.1038/ncomms4304

Kellogg, W. W., & Schneider, S. H. (1974). Climate stabilization: For better or for worse? Even if we could predict the future of our climate, climate control would be a hazardous venture. *Science, 186(4170)*, 1163-1172. DOI: 10.1126/science.186.4170.1163

Kennedy III, R. G., Roy, K. I., & Fields, D. E. (2013). Dyson Dots: Changing the solar constant to a variable with photovoltaic lightsails. *Acta Astronautica, 82(2)*, 225-237. https://doi.org/10.1016/j.actaastro.2012.10.022

Kent, G., & McCormick, M. (1984). SAGE and SAM II measurements of global stratospheric aerosol optical depth and mass loading. *Journal of Geophysical Research: Atmospheres, 89(D4)*, 5303-5314. https://doi.org/10.1029/JD089iD04p05303

Keohane, R. O. (2011). Global governance and legitimacy. *Review of International Political Economy, 18(1)*, 99-109. https://doi.org/10.1080/09692290.2011.545222

Keys, P. W. (2023). The plot must thicken: a call for increased attention to social surprises in scenarios of climate futures. *Environmental Research Letters, 18(8)*, 081003. DOI 10.1088/1748-9326/ace4e0

Keys P W, Barnes E A, Diffenbaugh N S, Hurrell J W and Bell C M 2022 Potential for perceived failure of stratospheric aerosol injection deployment. *Proceedings of the National Academy of Sciences, 119*, e2210036119 https://doi.org/10.1073/pnas.2210036119

Khaykin, S. M., Godin-Beekmann, S., Keckhut, P., Hauchecorne, A., Jumelet, J., Vernier, J.-P.,...Bhartia, P. K. (2017). Variability and evolution of the midlatitude stratospheric aerosol budget from 22 years of ground-based lidar and satellite observations. *Atmospheric Chemistry and Physics, 17(3)*, 1829-1845. https://doi.org/10.5194/acp-17-1829-2017

Kikstra, J.S., Nicholls, Z.R.J., Smith, C.J., Lewis, J. Lamboll, R.D., Byers, E.,...Riahi, K. The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures. *Geoscientific Model Development, 15(24)*, 9075-9109. https://doi.org/10.5194/gmd-15-9075-2022

Klaus, G., Ernst, A., & Oswald, L. (2020). Psychological factors influencing laypersons' acceptance of climate engineering, climate change mitigation and business as usual scenarios. *Technology in Society, 60*, 101222. https://doi.org/10.1016/j.techsoc.2019.101222

Klepper, G., & Rickels, W. (2012). The real economics of climate engineering. *Economics Research International, 2012*, 1-20. https://doi.org/10.1155/2012/316564

Knutti, R., & Hegerl, G. C. (2008). The equilibrium sensitivity of the Earth's temperature to radiation changes. *Nature Geoscience, 1(11)*, 735-743. https://doi.org/10.1038/ngeo337

Kolstad, C. D. (2007). Systematic uncertainty in self-enforcing international environmental agreements. *Journal of Environmental Economics and Management, 53(1)*, 68-79. https://doi.org/10.1016/j.jeem.2006.08.001

Korhonen, H., Carslaw, K. S., & Romakkaniemi, S. (2010). Enhancement of marine cloud albedo via controlled sea spray injections: A global model study of the influence of emission rates, microphysics and transport. *Atmospheric Chemistry and Physics, 10(9)*, 4133-4143. https://doi.org/10.5194/acp-10-4133-2010

Kosugi, T. (2013). Fail-safe solar radiation management geoengineering. *Mitigation and Adaptation Strategies for Global Change, 18*, 1141-1166. 10.1007/s11027-012-9414-2

Kotz, M., Levermann, A., & Wenz, L. (2022). The effect of rainfall changes on economic production. *Nature (London), 601(7892)*, 223-227. https://doi.org/10.1038/s41586-021-04283-8

Kotz, M., Wenz, L., Stechemesser, A., Kalkuhl, M., & Levermann, A. (2021). Day-to-day temperature variability reduces economic growth. *Nature Climate Change, 11(4)*, 319-325. https://doi.org/10.1038/s41558-020-00985-5

Kovilakam, M., Thomason, L., & Knepp, T. (2023). SAGE III/ISS aerosol/cloud categorization and its impact on GloSSAC. *Atmospheric Measurement Techniques, 16(10)*, 2709-2731. https://doi.org/10.5194/amt-16-2709-2023

Kovilakam, M., Thomason, L. W., Ernest, N., Rieger, L., Bourassa, A., & Millán, L. (2020). The global space-based stratospheric aerosol climatology (version 2.0): 1979--2018. *Earth System Science Data, 12(4)*, 2607-2634. https://doi.org/10.5194/essd-12-2607-2020

Krämer, M., Rolf, C., Luebke, A., Afchine, A., Spelten, N., Costa, A.,...Avallone, L. (2016). A microphysics guide to cirrus clouds -- Part 1: Cirrus types. *Atmospheric Chemistry and Physics, 16(5)*, 3463-3483. https://doi.org/10.5194/acp-16-3463-2016

Kravitz, B., Caldeira, K., Boucher, O., Robock, A., Rasch, P. J., Alterskjær, K.,. . .Yoon, J.-H. (2013). Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres, 118(15), 8320-8332. https://doi.org/10.1002/jgrd.50646

Kravitz, B., MacMartin, D. G., & Caldeira, K. (2012). Geoengineering: Whiter skies? Geophysical Research Letters, 39(11). https://doi.org/10.1029/2012GL051652

Kravitz, B., MacMartin, D. G., Mills, M. J., Richter, J. H., Tilmes, S., Lamarque, J. F., Tribbia, J. J., & Vitt, F. (2017). First simulations of designing stratospheric sulfate aerosol geoengineering to meet multiple simultaneous climate objectives. *Journal of Geophysical Research: Atmospheres, 122(23)*, 12,616-612,634. 10.1002/2017JD026874

Kravitz, B., MacMartin, D. G., Robock, A., Rasch, P. J., Ricke, K. L., Cole, J. N. S.,...Yoon, J.-H. (2014). A multi-model assessment of regional climate disparities caused by solar geoengineering. *Environmental Research Letters, 9(7),* 74013-74017. https://doi.org/10.1088/1748-9326/9/7/074013

Kravitz, B., MacMartin, D. G., Tilmes, S., Richter, J. H., Mills, M. J., Cheng, W,....Vitt, F. (2019). Comparing surface and stratospheric impacts of geoengineering with different SO2 injection strategies. *Journal of Geophysical Research: Atmospheres, 124(14)*, 7900-7918. https://doi.org/10.1029/2019JD030329

Kravitz, B., MacMartin, D. G., Visioni, D., Boucher, O., Cole, J. N. S., Haywood, J.,...Tilmes, S. (2021). Comparing different generations of idealized solar geoengineering simulations in the Geoengineering Model Intercomparison Project (GeoMIP). *Atmospheric Chemistry and Physics, 21(6)*, 4231-4247. https://doi.org/10.5194/acp-21-4231-2021

Kravitz, B., Rasch, P. J., Forster, P. M., Andrews, T., Cole, J. N., Irvine, P. J., Ji, D.,...Muri, H. (2013). An energetic perspective on hydrological cycle changes in the Geoengineering Model Intercomparison Project. *Journal of Geophysical Research: Atmospheres, 118(23)*, 13,087-013,102. https://doi.org/10.1002/2013JD020502

Kravitz, B., Robock, A., Tilmes, S., Boucher, O., English, J. M., Irvine, P. J.,...Muri, H. (2015). The geoengineering model intercomparison project phase 6 (GeoMIP6): Simulation design and preliminary results. *Geoscientific Model Development, 8(10)*, 3379-3392. https://doi.org/10.5194/gmd-8-3379-2015

Kremser, S., Thomason, L. W., von Hobe, M., Hermann, M., Deshler, T., Timmreck, C.,. . . Meland, B. (2016). Stratospheric aerosol---Observations, processes, and impact on climate. *Reviews of Geophysics, 54(2),* 278-335. https://doi.org/10.1002/2015RG000511

Krishnamohan, K.-P. S.-P., Bala, G., Cao, L., Duan, L., & Caldeira, K. (2019). Climate system response to stratospheric sulfate aerosols: sensitivity to altitude of aerosol layer. *Earth System Dynamics, 10(4)*, 885-900. https://doi.org/10.5194/esd-10-885-2019

Kristjánsson, J. E., Muri, H., & Schmidt, H. (2015). The hydrological cycle response to cirrus cloud thinning. *Geophysical Research Letters, 42(24)*, 10,807-810,815. 10.1002/2015GL066795

Laakso, A., Visioni, D., Niemeier, U., Tilmes, S., & Kokkola, H. (2023). Dependency of the impacts of geoengineering on the stratospheric sulfur injection strategy part 2: How changes in the hydrological cycle depend on injection rates and model? *EGUsphere, 2023*, 1-29.

Lafferty, K. D. (2009). The ecology of climate change and infectious diseases. *Ecology (Durham), 90(4)*, 888. https://doi.org/10.1890/08-0079.1

Langenbach, A., Baumgarten, G., Fiedler, J., Lübken, F.-J., von Savigny, C., & Zalach, J. (2019). Year-round stratospheric aerosol backscatter ratios calculated from lidar measurements above northern Norway. *Atmospheric Measurement Techniques, 12(7)*, 4065-4076. https://doi.org/10.5194/amt-12-4065-2019

Latham, J. (1990). Control of global warming? *Nature, 347(6291)*, 339-340. https://doi.org/10.1038/347339b0

Latham, J., Bower, K., Choularton, T., Coe, H., Connolly, P., Cooper, G.,. . . Wood, R. (2012). Marine cloud brightening. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 370(1974)*, 4217-4262. https://doi.org/doi:10.1098/rsta.2012.0086

Latham, J., Gadian, A., Fournier, J., Parkes, B., Wadhams, P., & Chen, J. (2014). Marine cloud brightening: regional applications. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372(2031)*, 20140053. https://doi.org/doi:10.1098/rsta.2014.0053

Latham, J., Rasch, P., Chen, C.-C., Kettles, L., Gadian, A., Gettelman, A.,...Choularton, T. (2008). Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 366(1882)*, 3969-3987. https://doi.org/doi:10.1098/rsta.2008.0137

Lauer, A., & Hamilton, K. (2013). Simulating clouds with global climate models: A comparison of CMIP5 results with CMIP3 and satellite data. *Journal of Climate, 26(11)*, 3823-3845. https://doi.org/10.1175/JCLI-D-12-00451.1

Lawford-Smith, H. (2013). Understanding political feasibility. Journal of Political Philosophy, 21(3)*, 243-259. https://doi.org/10.1111/j.1467-9760.2012.00422.x

Lawford-Smith, H., 2020. Democratic authority to geoengineer. In S. M. Gardiner, C. McKinnon, A. Fragnière (eds.), *The ethics of "geoengineering" the global climate* (pp. 189-206). Routledge.

Lawrence, M. G., Schäfer, S., Muri, H., Scott, V., Oschlies, A., Vaughan, N. E.,...Scheffran, J. (2018). Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals. *Nature Communications, 9(1)*, 3734. https://doi.org/10.1038/s41467-018-05938-3

Leakey, A. D. B., Ainsworth, E. A., Bernacchi, C. J., Rogers, A., Long, S. P., & Ort, D. R. (2009). Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany, 60(10)*, 2859-2876. https://doi.org/10.1093/jxb/erp096

Lee, H., Muri, H., Ekici, A., Tjiputra, J., & Schwinger, J. (2021b). The response of terrestrial ecosystem carbon cycling under different aerosol-based radiation management geoengineering. *Earth System Dynamics, 12(1)*, 313-326. https://doi.org/10.5194/esd-12-313-2021

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J. P.,...Jones, C. (2021a). Future global climate: scenario-based projections and near-term information. In *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change* (pp. 553-672). Cambridge University Press.

Lee, W., MacMartin, D., Visioni, D., & Kravitz, B. (2020). Expanding the design space of stratospheric aerosol geoengineering to include precipitation-based objectives and explore trade-offs. *Earth System Dynamics, 11(4)*, 1051-1072. https://doi.org/10.5194/esd-11-1051-2020

Lenton, T. M. (2012). Arctic climate tipping points. *Ambio, 41(1),* 10-22. https://doi.org/10.1007/s13280-011-0221-x

References

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., & Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences, 105(6)*, 1786-1793. https://doi.org/doi:10.1073/pnas.0705414105

Lenton, T. M., & Vaughan, N. E. (2009). The radiative forcing potential of different climate geoengineering options. *Atmospheric Chemistry and Physics, 9(15)*, 5539-5561. https://doi.org/10.5194/acp-9-5539-2009

Levy, R. C., Mattoo, S., Munchak, L. A., Remer, L. A., Sayer, A. M., Patadia, F., & Hsu, N. C. (2013). The Collection 6 MODIS aerosol products over land and ocean. *Atmospheric Measurement Techniques, 6(11)*, 2989-3034. https://doi.org/10.5194/amt-6-2989-2013

Lin, A. C. (2015). The missing pieces of geoengineering research governance. *Minnesota Law Review, 100,* 2509.

Llewellyn, E. J., Lloyd, N. D., Degenstein, D. A., Gattinger, R. L., Petelina, S. V., Bourassa, A. E.,... Nordh, L. (2004). The OSIRIS instrument on the Odin spacecraft. *Canadian Journal of Physics, 82(6)*, 411-422. https://doi.org/10.1139/p04-005

Lloyd, N. D., & Oppenheimer, M. (2014). On the design of an international governance framework for geoengineering. *Global Environmental Politics, 14(2)*, 45-63. https://doi.org/10.1162/GLEP_a_00228

Lockley, A., MacMartin, D., & Hunt, H. (2020). An update on engineering issues concerning stratospheric aerosol injection for geoengineering. *Environmental Research Communications, 2(8)*, 82001. https://doi.org/10.1088/2515-7620/aba944

Lobell, D. B., & Field, C. B. (2007). Global scale climate--crop yield relationships and the impacts of recent warming. *Environmental Research Letters*, 2(1), 014002. 10.1088/1748-9326/2/1/014002

Lohmann, U., Spichtinger, P., Jess, S., Peter, T. and Smit, H. (2008), Cirrus cloud formation and ice supersaturated regions in a global climate model. *Environmental Research Letters, 3(045022)*, 10.1088/1748-9326/3/4/045022

Long, J. C., & Winickoff, D. E. (2010). Governing geoengineering research: Principles and process. *Governing, 1(5),* 60-62.

Loughman, R., Bhartia, P. K., Chen, Z., Xu, P., Nyaku, E., & Taha, G. (2018). The ozone mapping and profiler suite (OMPS) limb profiler (LP) version 1 aerosol extinction retrieval algorithm: Theoretical basis. *Atmospheric Measurement Techniques, 11(5)*, 2633-2651. 10.5194/amt-11-2633-2018

Low, S., Baum, C. M., & Sovacool, B. K. (2022). Undone science in climate interventions: Contrasting and contesting anticipatory assessments by expert networks. *Environmental Science & Policy, 137*, 249-270. https://doi.org/10.1016/j.envsci.2022.08.026

Low, S., Baum, C. M., & Sovacool, B. K. (2022). Taking it outside: exploring social opposition to 21 early-stage experiments in radical climate interventions. *Energy Research & Social Science, 90*, 102594. https://doi.org/10.1016/j.erss.2022.102594

Lunt, D. J., Ridgwell, A., Valdes, P. J., & Seale, A. (2008). "Sunshade World": A fully coupled GCM evaluation of the climatic impacts of geoengineering. *Geophysical Research Letters, 35(12)*. https://doi.org/10.1029/2008GL033674

Lunt, D. J. (2012). Sunshades for solar radiation management. In T. Lenton & N. Vaughan (Eds.), *Geoengineering responses to climate change* (pp. 9-20). New York: Springer. 10.1007/978-1-4614-5770-1_2

Maalick, Z., Korhonen, H., Kokkola, H., Kühn, T., & Romakkaniemi, S. (2014). Modelling artificial sea salt emission in large eddy simulations. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372(2031), 20140051. https://doi.org/doi:10.1098/rsta.2014.0051

MacMartin, D. G., & Kravitz, B. (2019). Mission-driven research for stratospheric aerosol geoengineering. *Proceedings of the National Academy of Sciences, 116(4)*, 1089-1094. https://doi.org/10.1073/pnas.1811022116

MacMartin, D. G., Kravitz, B., Tilmes, S., Richter, J. H., Mills, M. J., Lamarque, J. F.,...Vitt, F. (2017). The climate response to stratospheric aerosol geoengineering can be tailored using multiple injection locations. *Journal of Geophysical Research: Atmospheres, 122(23),* 12,574-512,590. https://doi.org/10.1002/2017JD026868.

MacMartin, D. G., Ricke, K. L., & Keith, D. W. (2018). Solar geoengineering as part of an overall strategy for meeting the 1.5 C Paris target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376(2119),* 20160454. https://doi.org/10.1098/rsta.2016.0454

MacMartin, D. G., Caldeira, K., & Keith, D. W. (2014). Solar geoengineering to limit the rate of temperature change. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372(2031)*, 20140134. https://doi.org/10.1098/rsta.2014.0134

MacMartin, D. G., Visioni, D., Kravitz, B., Richter, J. H., Felgenhauer, T., Lee, W. R.,...Sugiyama, M. (2022). Scenarios for modeling solar radiation modification. *Proceedings of the National Academy of Sciences, 119(33)*, e2202230119. https://doi.org/doi:10.1073/pnas.2202230119

Macnaghten, P., & Szerszynski, B. (2013). Living the global social experiment: An analysis of public discourse on solar radiation management and its implications for governance. *Global Environmental Change, 23(2)*, 465-474. https://doi.org/10.1016/j.gloenvcha.2012.12.008

Madronich, S., Tilmes, S., Kravitz, B., MacMartin, D.G., Richter J.H. (2018). Response of surface ultraviolet and visible radiation to stratospheric SO2 injections. *Atmosphere. 9(11)*, 432. https://doi.org/10.3390/atmos9110432

Mahajan, A., Tingley, D., & Wagner, G. (2019). Fast, cheap, and imperfect? US public opinion about solar geoengineering. *Environmental Politics, 28(3)*, 523-543. https://doi.org/10.1080/09644016.2018.1479101

Maheswaran, T., Acker, D., & Fasoulas, S. (2022). The international planetary sunshade-an umbrella project to foster international collaboration to mitigate global warming. *Proceedings of the 73rd IAC*. 10.1088/1742-6596/2526/1/012113

Mahfouz, N. G. A., Hill, S. A., Guo, H., & Ming, Y. (2023). The radiative and cloud responses to sea salt aerosol engineering in GFDL models. *Geophysical Research Letters, 50(2)*, e2022GL102340. https://doi.org/10.1029/2022GL102340

Maki, M., Kim, Y., Kobori, T., Hirano, K., Lee, D. I., & Iguchi, M. (2021). Analyses of three-dimensional weather radar data from volcanic eruption clouds. *Journal of Volcanology and Geothermal Research*, 412, 107178. 10.1016/j.jvolgeores.2021.107178

Mamalakis, A., Barnes, E. A., & Hurrell, J. W. (2023). Using explainable artificial intelligence to quantify "climate distinguishability" after stratospheric aerosol injection. *Geophysical Research Letters*, 50, e2023GL106137. https://doi.org/10.1029/2023GL106137

Manney, G. L., Harwood, R. S., MacKenzie, I. A., Minschwaner, K., Allen, D. R., Santee, M. L.,...Fuller, R. A. (2009). Satellite observations and modeling of transport in the upper troposphere through the lower mesosphere during the 2006 major stratospheric sudden warming. *Atmospheric Chemistry and Physics, 9(14),* 4775-4795. https://doi.org/10.5194/acp-9-4775-2009

Manney, G. L., Millán, L. F., Santee, M. L., Wargan, K., Lambert, A., Neu, J. L.,...Read, W. G. (2022). Signatures of anomalous transport in the 2019/2020 Arctic stratospheric polar vortex. *Journal of Geophysical Research: Atmospheres, 127(20)*, e2022JD037407. 10.1029/2022JD037407

Manoussi, V., Xepapadeas, A., & Emmerling, J. (2018). Climate engineering under deep uncertainty. *Journal of Economic Dynamics & Control, 94*, 207-224. https://doi.org/10.1016/j.jedc.2018.06.003

Marbach, T., Fougnie, B., Lang, R., Lacan, A., Munro, R., & Schlüssel, P. (2018). The multiview polarimeter 3MI: preparation and overview of the in-flight characterization (conference presentation). In *Sensors, systems and next-generation satellites* (XXII, 10785, p. 107850I). SPIE. https://doi.org/10.1117/12.2325387

Marchant, B., Platnick, S., Meyer, K., & Wind, G. (2020). Evaluation of the MODIS Collection 6 multilayer cloud detection algorithm through comparisons with CloudSat Cloud Profiling Radar and CALIPSO CALIOP products. *Atmospheric Measurement Techniques, 13(6)*, 3263-3275. https://doi.org/10.5194/amt-13-3263-2020

Mathur, V., & Roy, A. (2019). Perspectives from India on geoengineering. *Current Science, 116(1)*, 40-46. 10.18520/cs/v116/i1/40-46

Matloff, G., Bangs, C., & Johnson, L. (2014). *Harvesting space for a greener earth*. New York: Springer. 10.1007/978-1-4614-9426-3

Mauldin Iii, L. E., Zaun, N. H., McCormick, J. M. P., Guy, J. H., & Vaughn, W. R. (1985). Stratospheric Aerosol and Gas Experiment II Instrument: A functional description. *Optical Engineering, 24(2)*, 242307-242307. https://doi.org/10.1117/12.7973473

McClellan, J., Keith, D. W., & Apt, J. (2012). Cost analysis of stratospheric albedo modification delivery systems. *Environmental Research Letters, 7(3)*, 34019-34018. https://doi.org/10.1088/1748-9326/7/3/034019

McCormick, M. P., Hamill, P., Pepin, T. J., Chu, W. P., Swissler, T. J., & McMaster, L. R. (1979). Satellite studies of the stratospheric aerosol. *Bulletin of the American Meteorological Society, 60(9)*, 1038-1046. https://doi.org/10.1175/1520-0477(1979)060<1038:SSOTSA>2.0.CO;2

McCormack, C. G., Born, W., Irvine, P. J., Achterberg, E. P., Amano, T., Ardron, J.,...Sutherland, W. J. (2016). Key impacts of climate engineering on biodiversity and ecosystems, with priorities for future research. *Journal of Integrative Environmental Sciences, 13(2-4)*, 103-128. https://doi.org/10.1080/1943815X.2016.1159578

McCusker, K. E., Armour, K. C., Bitz, C. M., & Battisti, D. S. (2014). Rapid and extensive warming following cessation of solar radiation management. *Environmental Research Letters, 9(2)*, 024005. doi:10.1088/1748-9326/9/2/024005

McInnes, C. R. (2010). Space-based geoengineering: challenges and requirements. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 224(3)*, 571-580. https://doi.org/10.1243/09544062JMES1439

McKinnon, C. (2019). Sleepwalking into lock-in? Avoiding wrongs to future people in the governance of solar radiation management research. *Environmental Politics, 28(3)*, 441-459.

McKinnon, C. (2020). The Panglossian politics of the geoclique. *Critical Review of International Social and Political Philosophy, 23(5)*, 584--599. https://doi.org/10.1080/09644016.2018.1450344

McLaren, D. (2016a). Mitigation deterrence and the "moral hazard" of solar radiation management. *Earth's Future, 4(12)*, 596-602. https://doi.org/10.1002/2016EF000445

McLaren, D. (2016b). Framing out justice. In C. Preston (Ed.), *Climate justice and geoengineering: ethics and policy in the atmospheric anthropocene* (pp. 139-160). London: Rowman & Littlefield.

McLaren, D. P. (2018). Whose climate and whose ethics? Conceptions of justice in solar geoengineering modelling. *Energy Research & Social Science, 44*, 209-221. https://doi.org/10.1016/j.erss.2018.05.021

McLaren, D. (2023). Governing emerging solar geoengineering: A role for risk-risk evaluation? *Georgetown Journal of International Affairs, 24(2)*, 234-243. 10.1353/gia.2023.a913651

McLaren, D., & Corry, O. (2021b). The politics and governance of research into solar geoengineering. *Wiley Interdisciplinary Reviews: Climate Change, 12(3)*, e707. https://doi.org/10.1002/wcc.707

McLaren, D., & Corry, O. (2023). Our way of life is not up for negotiation!": Climate interventions in the shadow of societal security. *Global Studies Quarterly, 3(3)*, ksad037. https://doi.org/10.1093/isagsq/ksad037

McLaren, D., & Corry, O. (2021a). Clash of geofutures and the remaking of planetary order: Faultlines underlying conflicts over geoengineering governance. *Global Policy, 12*, 20-33. https://doi.org/10.1111/1758-5899.12863

McLaren, D., Parkhill, K. A., Corner, A., Vaughan, N. E., & Pidgeon, N. F. (2016). Public conceptions of justice in climate engineering: Evidence from secondary analysis of public deliberation. *Global Environmental Change, 41*, 64-73. https://doi.org/10.1016/j.gloenvcha.2016.09.002

Mengis, N., Martin, T., Keller, D. P., & Oschlies, A. (2016). Assessing climate impacts and risks of ocean albedo modification in the Arctic. *Journal of Geophysical Research: Oceans, 121(5)*, 3044-3057. https://doi.org/10.1002/2015JC011433

Menk, L., Terzi, S., Zebisch, M., Rome, E., Lückerath, D., Milde, K., & Kienberger, S. (2022). Climate change impact chains: a review of applications, challenges, and opportunities for climate risk and vulnerability assessments. *Weather, Climate, and Society, 14(2)*, 619-636. https://doi.org/10.1175/WCAS-D-21-0014.1

Mercado, L. M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., & Cox, P. M. (2009). Impact of changes in diffuse radiation on the global land carbon sink. *Nature, 458(7241),* 1014-1017. 10.1038/nature07949

Mercer, A. M., Keith, D. W., & Sharp, J. D. (2011). Public understanding of solar radiation management. *Environmental Research Letters, 6(4)*, 44006. 10.1088/1748-9326/6/4/044006

Merk, C., Klaus, G., Pohlers, J., Ernst, A., Ott, K., & Rehdanz, K. (2019). Public perceptions of climate engineering: Laypersons' acceptance at different levels of knowledge and intensities of deliberation. *GAIA-Ecological Perspectives for Science and Society, 28(4)*, 348-355. https://doi.org/10.14512/gaia.28.4.6

Merk, C., & Pönitzsch, G. (2017). The role of affect in attitude formation toward new technologies: The case of stratospheric aerosol injection. *Risk Analysis, 37(12)*, 2289-2304. https://doi.org/10.1111/risa.12780

Merk, C., Pönitzsch, G., Kniebes, C., Rehdanz, K., & Schmidt, U. (2015). Exploring public perceptions of stratospheric sulfate injection. *Climatic Change, 130(2),* 299-312. https://doi.org/10.1007/s10584-014-1317-7

Merk, C., Pönitzsch, G., & Rehdanz, K. (2016). Knowledge about aerosol injection does not reduce individual mitigation efforts. *Environmental Research Letters, 11(5)*, 054009. 10.1088/1748-9326/11/5/054009

Merk, C., Pönitzsch, G., & Rehdanz, K. (2019). Do climate engineering experts display moral-hazard behaviour? *Climate Policy, 19(2)*, 231-243. https://doi.org/10.1080/14693062.2018.1494534

Merk, C., & Wagner, G. (2024). Presenting balanced geoengineering information has little effect on mitigation engagement. *Climatic Change, 177(1)*, 11. https://doi.org/10.1007/s10584-023-03671-5

References

Millard-Ball, A. (2012). The Tuvalu Syndrome: Can geoengineering solve climate's collective action problem? *Climatic Change, 110(3-4)*, 1047-1066. https://doi.org/10.1007/s10584-011-0102-0

Miralles, D. G., Gentine, P., Seneviratne, S. I., & Teuling, A. J. (2019). Land--atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges. *Annals of the New York Academy of Sciences, 1436(1),* 19-35. https://doi.org/10.1111/nyas.13912

Mishchenko, M. I., Dlugach, J. M., Lacis, A. A., Travis, L. D., & Cairns, B. (2019). Retrieval of volcanic and man-made stratospheric aerosols from orbital polarimetric measurements. *Optics Express, 27(4),* A158-A170. https://doi.org/10.1364/OE.27.00A158

Mitchell, D. L., & Finnegan, W. (2009). Modification of cirrus clouds to reduce global warming. *Environmental Research Letters, 4(4),* 8. doi:10.1088/1748-9326/4/4/045102

Mitchell, D. L., Garnier, A., Avery, M., & Erfani, E. (2016). CALIPSO observations of the dependence of homo-and heterogeneous ice nucleation in cirrus clouds on latitude, season and surface condition. *Atmospheric Chemistry and Physics Discussions*, 1-60. https://doi.org/10.5194/acp-2016-1062

Mitchell, D. L., Garnier, A., Pelon, J., & Erfani, E. (2018). CALIPSO (IIR--CALIOP) retrievals of cirrus cloud ice-particle concentrations. *Atmospheric Chemistry and Physics, 18(23),* 17325-17354. https://doi.org/10.5194/acp-18-17325-2018

Mittiga, R. (2022). Political legitimacy, authoritarianism, and climate change. *American Political Science Review, 116(3),* 998-1011. 10.1017/S0003055421001301

Moch, J. M., Mickley, L. J., Eastham, S. D., Lundgren, E. W., Shah, V., Buonocore, J. J.,...Tai, A. P. K. (2023). Overlooked long-term atmospheric chemical feedbacks alter the impact of solar geoengineering: Implications for tropospheric oxidative capacity. *AGU Advances, 4(5)*, n/a. https://doi.org/10.1029/2023AV000911

Möller, I. (2020). Political perspectives on geoengineering: Navigating problem definition and institutional fit. *Global Environmental Politics*, 20 (2): 57--82. https://doi.org/10.1162/glep_a_00547

Möller, I. (2023). *The emergence of geoengineering: How knowledge networks form governance objects*. Cambridge University Press. https://doi.org/10.1017/9781009049696

Montjoie, M. (2015). Treaty implementation applied to conventions on nuclear safety. *Nuclear Law Bulletin*, 96, 9. https://doi.org/10.1787/16097378

Moore, J. C., Jevrejeva, S., & Grinsted, A. (2010). Efficacy of geoengineering to limit 21st century sea-level rise. *Proceedings of the National Academy of Sciences, 107(36),* 15699-15703. https://doi.org/10.1073/pnas.1008153107

Moore, J. C., Yue, C., Zhao, L., Guo, X., Watanabe, S., & Ji, D. (2019). Greenland ice sheet response to stratospheric aerosol injection geoengineering. *Earth's Future, 7(12),* 1451-1463. https://doi.org/10.1029/2019EF001393

Moreno-Cruz, J. B. (2015). Mitigation and the geoengineering threat. *Resource and Energy Economics, 41*, 248-263. https://doi.org/10.1016/j.reseneeco.2015.06.001

Moreno-Cruz, J. B., & Keith, D. W. (2013). Climate policy under uncertainty: A case for solar geoengineering. *Climatic Change, 121(3),* 431-444. https://doi.org/10.1007/s10584-012-0487-4

Moreno-Cruz, J. B., Ricke, K. L., & Keith, D. W. (2012). A simple model to account for regional inequalities in the effectiveness of solar radiation management. *Climatic Change, 110(3-4)*, 649-668. https://doi.org/10.1007/s10584-011-0103-z

Moreno-Cruz, J. B., & Smulders, S. (2017). Revisiting the economics of climate change: The role of geoengineering. *Research in Economics, 71(2),* 212-224. https://doi.org/10.1016/j.rie.2016.12.001

Morgan, M. G., Adams, P. J., & Keith, D. W. (2006). Elicitation of expert judgments of aerosol forcing. *Climatic Change, 75(1-2)*, 195-214. https://doi.org/10.1007/s10584-005-9025-y

Morgan, M. G., & Keith, D. W. (1995). Subjective judgments by climate experts. *Environmental Science & Technology, 29(10)*, 468A-476A. https://doi.org/10.1021/es00010a753

Morgan, M. G., & Ricke, K. (2010). *Cooling the earth through solar radiation management: The need for research and an approach to its governance*. An opinion piece for the International Risk Governance Council. Pittsburgh, PA: Carnegie Mellon University.

Moriarty, P., & Honnery, D. (2022). Renewable energy and energy reductions or solar geoengineering for climate change mitigation? *Energies (Basel), 15(19)*, 7315. https://doi.org/10.3390/en15197315

Moriyama, R., Sugiyama, M., Kurosawa, A., Masuda, K., Tsuzuki, K., & Ishimoto, Y. (2017). The cost of stratospheric climate engineering revisited. *Mitigation and Adaptation Strategies for Global Change, 22(8)*, 1207-1228. https://doi.org/10.1007/s11027-016-9723-y

Morrow, D.R., (2020). A mission-driven research program on solar geoengineering could promote justice and legitimacy. In S. M. Gardiner, C. McKinnon, A. Fragnière (eds.), *The ethics of "geoengineering" the global climate* (pp. 207-229). Routledge. https://doi.org/10.1080/13698230.2020.1694220

Morrow, D. R., Kopp, R. E., & Oppenheimer, M. (2013). *Political legitimacy in decisions about experiments in solar radiation management*. In W. C. G. Burns & A. L. Strauss (Eds.), *Climate change geoengineering: Philosophical perspectives, legal issues, and governance frameworks* (pp. 146--167). Cambridge: Cambridge University Press.

Moroney, C., Davies, R., & Muller, J. P. (2002). Operational retrieval of cloud-top heights using MISR data. *IEEE Transactions on Geoscience and Remote Sensing, 40(7)*, 1532-1540. 10.1109/TGRS.2002.801150

Müller-Hansen, F., Repke, T., Baum, C. M., Brutschin, E., Callaghan, M. W., Debnath, R.,...Minx, J. C. (2023). Attention, sentiments and emotions towards emerging climate technologies on Twitter. *Global Environmental Change*, 83, 102765. https://doi.org/10.1016/j.gloenvcha.2023.102765

Muri, H., Tjiputra, J., Otterå, O. H., Adakudlu, M., Lauvset, S. K., Grini, A.,...Kristjánsson, J. E. (2018). Climate response to aerosol geoengineering: A multimethod comparison. *Journal of Climate, 31(16)*, 6319-6340. https://doi.org/10.1175/JCLI-D-17-0620.1

Nakajima, T., & King, M. D. (1990). Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part I: Theory. *Journal of Atmospheric Sciences, 47(15)*, 1878-1893. https://doi.org/10.1175/1520-0469

National Academies of Sciences, E., & Medicine. (2021). *Reflecting sunlight: Recommendations for solar geoengineering research and research governance*. The National Academies Press. https://doi.org/doi:10.17226/25762

Neale, R. E., Lucas, R. M., Byrne, S. N., Hollestein, L., Rhodes, L. E., Yazar, S.,...Olsen, C. M. (2023). The effects of exposure to solar radiation on human health. *Photochemical & Photobiological Sciences*, 22(5), 1011-1047. https://doi.org/10.1007/s43630-023-00375-8

Nelson, J. P., Selin, C. L., & Scott, C. T. (2021). Toward anticipatory governance of human genome editing: a critical review of scholarly governance discourse. *Journal of Responsible Innovation, 8(3)*, 382-420. https://doi.org/10.1080/23299460.2021.1957579

Newell, R. G., Prest, B. C., & Sexton, S. E. (2021). The GDP-temperature relationship: Implications for climate change damages. *Journal of Environmental Economics and Management, 108,* 102445. https://doi.org/10.1016/j.jeem.2021.102445

Nicholson, S., Jinnah, S., & Gillespie, A. (2018). Solar radiation management: A proposal for immediate polycentric governance. *Climate Policy, 18(3)*, 322-334. https://doi.org/10.1080/14693062.2017.1400944

Niemeier, U., Schmidt, H., Alterskjær, K., & Kristjánsson, J. E. (2013). Solar irradiance reduction via climate engineering: Impact of different techniques on the energy balance and the hydrological cycle. *Journal of Geophysical Research: Atmospheres, 118(21)*, 11,905-911,917. https://doi.org/10.1002/2013JD020445

Niemeier, U., & Timmreck, C. (2015). What is the limit of climate engineering by stratospheric injection of SO 2? *Atmospheric Chemistry and Physics, 15(16)*, 9129-9141. https://doi.org/10.5194/acp-15-9129-2015

Niemeier, U., Schmidt, H., & Timmreck, C. (2011). The dependency of geoengineered sulfate aerosol on the emission strategy. *Atmospheric Science Letters, 12(2)*, 189-194. https://doi.org/10.1002/asl.304

Norby, R. J., DeLucia, E. H., Gielen, B., Calfapietra, C., Giardina, C. P., King, J. S.,...Ceulemans, R. (2005). Forest response to elevated CO2 is conserved across a broad range of productivity. *Proceedings of the National Academy of Sciences - PNAS, 102(50)*, 18052-18056. https://doi.org/10.1073/pnas.0509478102

Nordhaus, W. D. (1992). An optimal transition path for controlling greenhouse gases. *Science (American Association for the Advancement of Science), 258(5086)*, 1315-1319. https://doi.org/10.1126/science.258.5086.1315

Obahoundje, S., Nguessan-Bi, V. H., Diedhiou, A., Kravitz, B., & Moore, J. C. (2023). Implication of stratospheric aerosol geoengineering on compound precipitation and temperature extremes in Africa. *Science of the Total Environment, 863,* 160806. 10.1016/j.scitotenv.2022.160806

Odoulami, R. C., New, M., Wolski, P., Guillemet, G., Pinto, I., Lennard, C.,....Tilmes, S. (2020). Stratospheric aerosol geoengineering could lower future risk of 'Day Zero' level droughts in Cape Town. *Environmental Research Letters, 15(12)*, 124007. 10.1088/1748-9326/abbf13

Oksanen, A.-A. (2023). Dimming the midnight sun? Implications of the Sámi Council's intervention against the SCoPEx project. *Frontiers in Climate, 5*. https://doi.org/10.3389/fclim.2023.994193

Oldham, P., Szerszynski, B., Stilgoe, J., Brown, C., Eacott, B., & Yuille, A. (2014). Mapping the landscape of climate engineering. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372(2031)*, 20140065. https://doi.org/10.1098/rsta.2014.0065

Olmo, F. J., Tovar, J., Alados-Arboledas, L., Okulov, O., & Ohvril, H. O. (1999). A comparison of ground level solar radiative effects of recent volcanic eruptions. *Atmospheric Environment (1994), 33(28)*, 4589-4596. https://doi.org/10.1016/S1352-2310(99)00271-X

Omanovic, N., Ferrachat, S., Fuchs, C., Henneberger, J., Miller, A. J., Ohneiser, K.,...Zhang, H. (2024). Evaluating the Wegener-Bergeron-Findeisen process in ICON in large-eddy mode with in-situ observations from the CLOUDLAB project. *EGUsphere, 2024*, 1-28. https://doi.org/10.5194/acp-24-6825-2024

Omar, A., Vaughan, M., Liu, Z., Hu, Y., Reagan, J., & Winker, D. (2007). Extinction-to-backscatter ratios of lofted aerosol layers observed during the first three months of CALYPSO measurements. *2007 IEEE International Geoscience and Remote Sensing Symposium*. 10.1109/IGARSS.2007.4423976

Omar, A. H., Winker, D. M., & Won, J.-G. (2004). Aerosol models for the CALIPSO lidar inversion algorithms. *Laser Radar Technology for Remote Sensing* 10.1117/12.511067

Oomen, J. (2021). Ways of seeing intervention and control. In J. Oomen (Ed.), Imagining climate engineering: Dreaming of the designer climate. Routledge. https://doi.org/10.4324/9781003043553-6

Oreskes, N., Shrader-Frechette, K., & Belitz, K. (1994). Verification, validation, and confirmation of numerical models in the Earth sciences. *Science, 263(5147*), 641--646. https://doi.org/10.1126/science.263.5147.641

Osman, M., McLachlan, S., Fenton, N., Neil, M., Löfstedt, R., & Meder, B. (2020). Learning from behavioural changes that fail. *Trends in Cognitive Sciences*, *24*(12), 969--980. https://doi.org/10.1016/j.tics.2020.09.009

Otto, S., Kaiser, F. G., & Arnold, O. (2014). The critical challenge of climate change for psychology. *European Psychologist*, *19*(2), 96--106. https://doi.org/10.1027/1016-9040/a000182

Owen, R. (2014). Solar radiation management and the governance of hubris. In R.M. Harrison & R. Hester (Eds.), *Geoengineering of the climate system: Issues in environmental science and technology*. Royal Society of Chemistry. https://doi.org/10.1039/9781782621225-00212

Packard, L. (2018). Designing an international liability regime to compensate victims of solar radiation management. *Environmental Claims Journal, 30(1)*, 71-86. https://doi.org/10.1080/10406026.2017.1403832

Page, E. A. (2012). The hidden costs of carbon commodification: emissions trading, political legitimacy and procedural justice. *Democratization, 19(5)*, 932-950. https://doi.org/10.1080/13510347.2012.709689

Pamplany, A. (2020). The Ethical Desirability of Geoengineering: Challenges to Justice. In T.F. Heston & S. Ray (Eds.), *Bioethics in medicine and society*. IntechOpen. 10.5772/intechopen.94889

Parker, A. (2014). Governing solar geoengineering research as it leaves the laboratory. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical, and Engineering Sciences,* 372(2031), 20140173. https://doi.org/10.1098/rsta.2014.0173

Parker, A., Horton, J. B., & Keith, D. W. (2018). Stopping solar geoengineering through technical means: A preliminary assessment of counter-geoengineering. *Earth's Future, 6(8)*, 1058-1065. https://doi.org/10.1029/2018EF000864

Parker, A., & Irvine, P. J. (2018). The risk of termination shock from solar geoengineering. *Earth's Future, 6(3)*, 456-467. https://doi.org/10.1002/2017EF000735

Parson, E. A., & Ernst, L. N. (2013). International governance of climate engineering. *Theoretical Inquiries in Law, 14(1),* 307-338. https://doi.org/10.1515/til-2013-015

Parson, E. A., & Keith, D. W. (2013). End the deadlock on governance of geoengineering research. *Science (American Association for the Advancement of Science), 339(6125)*, 1278-1279. https://doi.org/10.1126/science.1232527

References

Partanen, A.-I., Kokkola, H., Romakkaniemi, S., Kerminen, V.-M., Lehtinen, K. E. J., Bergman, T.,...Korhonen, H. (2012). Direct and indirect effects of sea spray geoengineering and the role of injected particle size. *Journal of Geophysical Research: Atmospheres, 117(D2)*. https://doi.org/10.1029/2011JD016428

Pasztor J., Harrison, N., Chen, Y., Ghosh, A., Jumeau, R., Nobres, C. & Reynolds, J. (2019). *Geoengineering: the need for governance*. Carnegie Climate Geoengineering Governance Initiative (C2G2). Retrieved from: https://www.c2g2.net/the-need-for-governance/

Pearson, J., Oldson, J., & Levin, E. (2006). Earth rings for planetary environment control. *Acta Astronautica, 58(1)*, 44-57. https://doi.org/10.1016/j.actaastro.2005.03.071

Pierce, J. R., Weisenstein, D. K., Heckendorn, P., Peter, T., & Keith, D. W. (2010). Efficient formation of stratospheric aerosol for climate engineering by emission of condensible vapor from aircraft. *Geophysical Research Letters, 37(18*). https://doi.org/10.1029/2010GL043975

Penner, J. E., Zhou, C., & Liu, X. (2015). Can cirrus cloud seeding be used for geoengineering? *Geophysical Research Letters, 42(20*), 8775-8782. https://doi.org/10.1002/2015GL065992

Pezzoli, P., Emmerling, J., & Tavoni, M. (2023). SRM on the table: The role of geoengineering for the stability and effectiveness of climate coalitions. *Climatic Change, 176(10)*, 141. https://doi.org/10.1007/s10584-023-03604-2

Pfrommer, T., Goeschl, T., Proelss, A., Carrier, M., Lenhard, J., Martin, H.,... Schmidt, H. (2019). Establishing causation in climate litigation: Admissibility and reliability. *Climatic Change, 152(1)*, 67-84. 10.1007/s10584-018-2362-4

Pidgeon, N., Parkhill, K., Corner, A., & Vaughan, N. (2013). Deliberating stratospheric aerosols for climate geoengineering and the SPICE project. *Nature Climate Change, 3(5)*, 451-457. 10.1038/nclimate1807

Pinnick, R. G., Rosen, J. M., & Hofmann, D. J. (1976). Stratospheric aerosol measurements III: Optical model calculations. *Journal of the Atmospheric Sciences, 33(2)*, 304-314. https://doi.org/10.1175/1520-0469(1976)033<0304:SAMIOM>2.0.CO;2

Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L., & Levin, S. A. (2013). Marine taxa track local climate velocities. *Science, 341(6151)*, 1239-1242. DOI: 10.1126/science.1239352

Pitari, G., Aquila, V., Kravitz, B., Robock, A., Watanabe, S., Cionni, I.,...Tilmes, S. (2014). Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres, 119(5)*, 2629-2653. https://doi.org/10.1002/2013JD020566

Platnick, S., Meyer, K. G., King, M. D., Wind, G., Amarasinghe, N., Marchant, B.,...Riedi, J. (2016). The MODIS cloud optical and microphysical products: Collection 6 updates and examples from Terra and Aqua. *IEEE Transactions on Geoscience and Remote Sensing, 55(1)*, 502-525. 10.1109/TGRS.2016.2610522

Plazzotta, M., Seferian, R., & Douville, H. (2019). Impact of solar radiation modification on allowable CO2 emissions: What can we learn from multimodel simulations? *Earth's Future, 7(6)*, 664-676. https://doi.org/10.1029/2019EF001165

Plummer, D., Nagashima, T., Tilmes, S., Archibald, A., Chiodo, G., Fadnavis, S.,...Lamarque, J.-F. (2021). CCMI-2022: A new set of Chemistry-Climate Model Initiative (CCMI) community simulations to update the assessment of models and support upcoming ozone assessment activities. *SPARC Newsletter, 57*, 22-30.

Polvani, L. M., Banerjee, A., & Schmidt, A. (2019). Northern Hemisphere continental winter warming following the 1991 Mt. Pinatubo eruption: reconciling models and observations. *Atmospheric Chemistry and Physics, 19(9)*, 6351-6366. https://doi.org/10.5194/acp-19-6351-2019

Pomerantz, M., Akbari, H., Berdahl, P., Konopacki, S., Taha, H., & Rosenfeld, A. (1999). Reflective surfaces for cooler buildings and cities. *Philosophical Magazine B, 79(9)*, 1457-1476. https://doi.org/10.1080/13642819908216984

Pope, F. D., Braesicke, P., Grainger, R., Kalberer, M., Watson, I., Davidson, P., & Cox, R. (2012). Stratospheric aerosol particles and solar-radiation management. *Nature Climate Change, 2(10)*, 713-719. 10.1038/NCLIMATE1528

Preston, C. (2013). Ethics and geoengineering: Reviewing the moral issues raised by solar radiation management and carbon dioxide removal. *Wiley Interdisciplinary Reviews: Climate Change, 4*. https://doi.org/10.1002/wcc.198

Preston, C., & Carr, W. (2020). Recognitional justice, climate engineering, and the care approach. In S. M. Gardiner, C. McKinnon & A. Fragnière (eds.), *The ethics of "geoengineering" the global climate* (pp. 79-94). Routledge. https://doi.org/10.1080/21550085.2018.1562527

Proctor, J., Hsiang, S., Burney, J., Burke, M., & Schlenker, W. (2018). Estimating global agricultural effects of geoengineering using volcanic eruptions. *Nature (London), 560(7719)*, 480-483. https://doi.org/10.1038/s41586-018-0417-3

Proelss, A., & Steenkamp, R. C. (2022). Geoengineering: Methods, associated risks and international liability. In P. Gailhofer, D. Krebs, A. Proelss, K. Schmalenbach, R. Verheyen (Eds.), Corporate liability for transboundary environmental harm: An international and transnational perspective. Springer International Publishing. https://doi.org/10.1007/978-3-031-13264-3_9

Oxford Geoengineering Programme (2018). *The principles*. Oxford Geoengineering Programme. Retrieved from: http://www.geoengineering.ox.ac.uk/oxford-principles/principles/

Quaas, J., Quaas, M. F., Boucher, O., & Rickels, W. (2016). Regional climate engineering by radiation management: Prerequisites and prospects. *Earth's Future, 4(12)*, 618-625. https://doi.org/10.1002/2016EF000440

Quaas, M. F., Quaas, J., Rickels, W., & Boucher, O. (2017). Are there reasons against open-ended research into solar radiation management? A model of intergenerational decision-making under uncertainty. *Journal of Environmental Economics and Management, 84*, 1-17. https://doi.org/10.1016/j.jeem.2017.02.002

Rabitz, F. (2016). Going rogue? Scenarios for unilateral geoengineering. *Futures: the Journal of Policy, Planning and Futures Studies, 84*, 98-107. https://doi.org/10.1016/j.futures.2016.11.001

Rabitz, F. (2019). Governing the termination problem in solar radiation management. *Environmental Politics, 28(3)*, 502-522. https://doi.org/10.1080/09644016.2018.1519879

Rai, N., Morales, L. O., & Aphalo, P. J. (2021). Perception of solar UV radiation by plants: photoreceptors and mechanisms. *Plant Physiology, 186(3)*, 1382-1396. https://doi.org/10.1093/plphys/kiab162

Raimi, K. T., Wolske, K. S., Hart, P. S., & Campbell-Arvai, V. (2020). The Aversion to Tampering with Nature (ATN) Scale: Individual differences in (dis)comfort with altering the natural world. *Risk Analysis, 40(3)*, 638--656. https://doi.org/10.1111/risa.13414

Raimi, K. T., Maki, A., Dana, D., & Vandenbergh, M. P. (2019). Framing of geoengineering affects support for climate change mitigation. *Environmental Communication, 13(3)*, 300-319. https://doi.org/10.1080/17524032.2019.1575258

Rasch, P. J., Latham, J., & Chen, C.-C. J. (2009). Geoengineering by cloud seeding: influence on sea ice and climate system. *Environmental Research Letters, 4,* 045112. https://doi.org/10.1088/1748-9326/4/4/045112

Rauber, R. M., Geerts, B., Xue, L., French, J., Friedrich, K., Rasmussen, R. M.,...Parkinson, S. (2019). Wintertime orographic cloud seeding---A review. *Journal of Applied Meteorology and Climatology, 58(10)*, 2117-2140. https://doi.org/10.1175/JAMC-D-18-0341.1

Rayner, S., Heyward, C., Kruger, T., Pidgeon, N., Redgwell, C., & Savulescu, J. (2013). The Oxford Principles. *Climatic Change, 121(3)*, 499-512. https://doi.org/10.1007/s10584-012-0675-2

Reichwein, D., Hubert, A.-M., Irvine, P. J., Benduhn, F., & Lawrence, M. G. (2015). State responsibility for environmental harm from climate engineering. *Climate Law, 5(2-4)*, 142-181. https://doi.org/10.1163/18786561-00504003

Reisinger, A., & Geden, O. (2023). Temporary overshoot: Origins, prospects, and a long path ahead. *One Earth, 6(12),* 1631-1637. https://doi.org/10.1016/j.oneear.2023.11.008

Reynolds, D., Scourse, J., Halloran, P., Nederbragt, A., Wanamaker, A. D., Butler, P.,...Knudsen, K. (2016). Annually resolved North Atlantic marine climate over the last millennium. *Nature Communications, 7(1)*, 13502. https://doi.org/10.1038/ncomms13502

Reynolds, J. L. (2015). An economic analysis of liability and compensation for harm from large-scale field research in solar climate engineering. *Climate Law, 5(2-4)*, 182-209. doi 10.1163/18786561-00504004

Reynolds, J. L. (2019a). *The governance of solar geoengineering: Managing climate change in the anthropocene*. Cambridge University Press. https://doi.org/10.1017/9781316676790

Reynolds, J. L. (2019b). Solar geoengineering to reduce climate change: A review of governance proposals. *Proceedings of the Royal Society. A, Mathematical, Physical, and Engineering Sciences, 475(2229)*, 20190255-20190255. https://doi.org/10.1098/rspa.2019.0255

Reynolds, J. L. (2022). Linking solar geoengineering and emissions reductions: Strategically resolving an international climate change policy dilemma. *Climate Policy, 22(3)*, 285-300. https://doi.org/10.1080/14693062.2021.1993125

Reynolds, J. L., & Fleurke, F. (2013). Climate engineering research: A precautionary response to climate change? *Carbon & Climate Law Review, 7(2)*, 101-107. https://doi.org/10.21552/CCLR/2013/2/251

Reynolds, J. L., & Parson, E. A. (2020). Nonstate governance of solar geoengineering research. *Climatic Change, 160(2)*, 323-342. https://doi.org/10.1007/s10584-020-02702-9

Richter, J., Visioni, D., MacMartin, D., Bailey, D., Rosenbloom, N., Lee, W.,...Lamarque, J.-F. (2022). Assessing responses and impacts of solar climate intervention on the Earth system with stratospheric aerosol injection (ARISE-SAI): protocol and initial results from the first simulations. *Geoscientific Model Development, 15*, 8221--8243https://doi.org/10.5194/gmd-15-8221-2022

Richter, J. H., Tilmes, S., Mills, M. J., Tribbia, J. J., Kravitz, B., MacMartin, D. G.,...Lamarque, J. F. (2017). Stratospheric dynamical response and ozone feedbacks in the presence of SO2 injections. *Journal of Geophysical Research: Atmospheres, 122(23)*, 12,557-512,573. https://doi.org/10.1002/2017jd026912

Ricke, K., Wan, J. S., Saenger, M., & Lutsko, N. J. (2023). Hydrological consequences of solar geoengineering. *Annual Review of Earth and Planetary sciences, 51(1)*, 447-470. https://doi.org/10.1146/annurev-earth-031920-083456

Ricke, K. L., Moreno-Cruz, J. B., & Caldeira, K. (2013). Strategic incentives for climate geoengineering coalitions to exclude broad participation. *Environmental Research Letters, 8(1),* 14021-14028. https://doi.org/10.1088/1748-9326/8/1/014021

Rickels, W., Klepper, G., Dovern, J., Betz, G., Brachatzek, N., Cacean, S.,...Hoose, C. (2011). *Large-scale intentional interventions into the climate system. Assessing the climate engineering debate*. Scoping report conducted on behalf of the German Federal Ministry of Education and Research (BMBF). Kiel Earth Institute.

Rickels, W., Quaas, M. F., Ricke, K., Quaas, J., Moreno-Cruz, J., & Smulders, S. (2020). Who turns the global thermostat and by how much? *Energy Economics, 91*, 104852. https://doi.org/10.1016/j.eneco.2020.104852

Rickels, W., Quaas, M. F., Ricke, K., Quaas, J., Moreno Cruz, J., & Smulders, S. (2018). Turning the global thermostat-who, when, and how much? *Kiel Working Paper*, 2110.

Rickels, W., Merk, C., Reith, F., Keller, D. P., & Oschlies, A. (2019). (Mis) conceptions about modeling of negative emissions technologies. *Environmental Research Letters, 14(10),* 104004. 10.1088/1748-9326/ab3ab4

Rizos, K., Gkikas, A., Proestakis, E., Georgiou, T., Amiridis, V., Marinou, E.,...Retscher, C. (2023). Development and validation of an enhanced aerosol product for Aeolus (L2A+). *Environmental Sciences Proceedings, 26(1),* 91. https://doi.org/10.3390/environsciproc2023026091

Robock, A. (2000). Volcanic eruptions and climate. *Reviews of Geophysics, 38(2),* 191-219. https://doi.org/10.1029/1998RG000054

Robock, A., Bunzl, M., Kravitz, B., & Stenchikov, G. L. (2010). A test for geoengineering? *Science, 327(5965),* 530-531. https://doi.org/10.1126/science.1186237

Robock, A., Oman, L., & Stenchikov, G. L. (2008). Regional climate responses to geoengineering with tropical and Arctic SO2 injections. *Journal of Geophysical Research - Atmospheres, 113(D16)*, D16101-n/a. https://doi.org/10.1029/2008JD010050

Rockwood, L. (2018). *Evaluation of the impact of the Model Additional Protocol on non-nuclear-weapon states with comprehensive safeguards agreements*. Swedish Radiation Safety Authority, Vienna.

Rollins, A. W., Thornberry, T. D., Gao, R. S., Smith, J. B., Sayres, D. S., Sargent, M. R.,..Fahey, D. W. (2014). Evaluation of UT/LS hygrometer accuracy by intercomparison during the NASA MACPEX mission. *Journal of Geophysical Research: Atmospheres, 119(4)*, 1915-1935. https://doi.org/10.1002/2013JD020817

Rosen, J. M. (1964). The vertical distribution of dust to 30 kilometers. *Journal of Geophysical Research, 69(21)*, 4673-4676. 10.1029/JZ069i021p04673

Rosenthal, S., Irvine, P. J., Cummings, C. L., & Ho, S. S. (2023). Exposure to climate change information predicts public support for solar geoengineering in Singapore and the United States. *Scientific Reports, 13(1)*, 19874. https://doi.org/10.1038/s41598-023-46952-w

Ross, A., & Damon Matthews, H. (2009). Climate engineering and the risk of rapid climate change. *Environmental Research Letters, 4(4)*, 045103. https://doi.org/10.1088/1748-9326/4/4/045103

Rothe, D. (2017). Seeing like a satellite: Remote sensing and the ontological politics of environmental security. *Security Dialogue, 48(4),* 334-353. 10.1177/0967010617709399

Royal Society. (2009). *Geoengineering the climate: Science, governance and uncertainty* (RS Policy document, 10/29). London: Royal Society.

Russell, L. M., Sorooshian, A., Seinfeld, J. H., Albrecht, B. A., Nenes, A., Ahlm, L.,. . . Wonaschütz, A. (2013). Eastern Pacific Emitted Aerosol Cloud Experiment. *Bulletin of the American Meteorological Society, 94(5)*, 709-729. https://doi.org/10.1175/BAMS-D-12-00015.1

Sagemueller, I. (2005). Non-compliance procedures under the Cartagena Protocol: a wise decision for a soft approach. *New Zealand Journal of Environmental Law, 9*, 163.

Salter, S., Sortino, G., & Latham, J. (2008). Sea-going hardware for the cloud albedo method of reversing global warming. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 366(1882)*, 3989-4006. https://doi.org/doi:10.1098/rsta.2008.0136

Sánchez, J.-P., & McInnes, C. R. (2015). Optimal sunshade configurations for space-based geoengineering near the Sun-Earth L1 point. *PLOS ONE, 10(8)*, e0136648. https://doi.org/10.1371/journal.pone.0136648

Schäfer, S., Lawrence, M., Stelzer, H., Born, W., Low, S., Aaheim, A.,...Carius, A. (2015). *The European transdisciplinary assessment of climate engineering (EuTRACE): Removing greenhouse gases from the atmosphere and reflecting sunlight away from Earth*.

Scharpf, F. (1999). *Governing in Europe: Effective and democratic?* Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198295457.001.0001

Scheer, D., & Renn, O. (2014). Public perception of geoengineering and its consequences for public debate. *Climatic Change, 125*, 305-318. 10.1007/s10584-014-1177-1

Scheffran, J. (2019). The entwined Cold War roots of missile defense and climate geoengineering. *Bulletin of the Atomic Scientists, 75(5),* 222-228. https://doi.org/10.1080/00963402.2019.1654256

Schenuit, F., Gilligan, J., & Viswamohanan, A. (2021). A scenario of solar geoengineering governance: Vulnerable states demand, and act. *Futures, 132*, 102809. https://doi.org/10.1016/j.futures.2021.102809

Schelling, T. C. (1996). The economic diplomacy of geoengineering. *Climatic Change, 33(3),* 303-307. https://doi.org/10.1007/BF00142578

Schloss, C. A., Nuñez, T. A., & Lawler, J. J. (2012). Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. *Proceedings of the National Academy of Sciences, 109(22)*, 8606-8611. https://doi.org/10.1073/pnas.1116791109

Schmidt, A., Carslaw, K., Mann, G., Rap, A., Pringle, K., Spracklen, D.,...Forster, P. (2012). Importance of tropospheric volcanic aerosol for indirect radiative forcing of climate. *Atmospheric Chemistry and Physics, 12(16)*, 7321-7339. https://doi.org/10.5194/acp-12-7321-2012

Schneider, S. H. (1996). Geoengineering: Could---or should---we do it? *Climatic Change, 33(3*), 291-302. https://doi.org/10.1007/BF00142577

Schneider, T., Lan, S., Stuart, A., & Teixeira, J. (2017). Earth system modeling 2.0: A blueprint for models that learn from observations and targeted high-resolution simulations. Geophysical Research Letters, 44, 12,396--12,417. https://doi.org/10.1002/2017GL076101

Schultz, D. M., Volkert, H., Antonescu, B., & Davies, H. C. (2020). Defender and expositor of the Bergen methods of synoptic analysis: Significance, history, and translation of Bergeron's (1928) "Three-dimensionally combining synoptic analysis". *Bulletin of the American Meteorological Society, 101(12)*, E2078-E2094. https://doi.org/10.1175/BAMS-D-20-0021.1

Schuster, B. G. (1970). Detection of tropospheric and stratospheric aerosol layers by optical radar (lidar). *Journal of Geophysical Research, 75(15)*, 3123-3132. https://doi.org/10.1029/JC075i015p03123

Schwarz-Herion, O. (2018). The impact of the climate change discussion on society, science, culture, and politics: From the limits to growth via the Paris Agreement to a binding global policy? In A. Omran & O. Schwarz-Herion (Eds.), *The impact of climate change on our life: The questions of sustainability* (pp. 1-32). Springer. https://doi.org/10.1007/978-981-10-7748-7

Scott, K. N. (2013). International law in the Anthropocene: Responding to the geoengineering challenge. *Michigan Journal of International Law, 34(2),* 309.

Seidel, D. J., Feingold, G., Jacobson, A. R., & Loeb, N. (2014). Detection limits of albedo changes induced by climate engineering. *Nature Climate Change, 4(2),* 93-98. https://doi.org/10.1038/nclimate2076

Seitz, R. (2011). Bright water: hydrosols, water conservation and climate change. *Climatic Change, 105(3-4),* 365-381. https://doi.org/10.1007/s10584-010-9965-8

Seneviratne, S. I., Phipps, S. J., Pitman, A. J., Hirsch, A. L., Davin, E. L., Donat, M. G.,...Kravitz, B. (2018). Land radiative management as contributor to regional-scale climate adaptation and mitigation. *Nature Geoscience, 11(2),* 88-96. doi:10.1038/s41561-017-0057-5

Shearer, M. P., Potter, C., Vahey, R. A., Connell, N. D., & Gronvall, G. K. (2022). BWC assurance: increasing certainty in BWC compliance. *Nonproliferation Review, 29(1-3),* 47-75. 10.1080/10736700.2023.2178099

Shue, H. (2017). Responsible for what? Carbon producer CO2 contributions and the energy transition. *Climatic Change, 144(4), 591*-596. https://doi.org/10.1007/s10584-017-2042-9

Simpson, I., Tilmes, S., Richter, J., Kravitz, B., MacMartin, D., Mills, M. J., Fasullo, J., & Pendergrass, A. G. (2019). The regional hydroclimate response to stratospheric sulfate geoengineering and the role of stratospheric heating. *Journal of Geophysical Research: Atmospheres, 124(23)*, 12587-12616. https://doi.org/10.1029/2019JD031093

Simpson, I. R., Tilmes, S., Richter, J. H., Kravitz, B., MacMartin, D. G., Mills, M. J.,...Pendergrass, A. G. (2019). The regional hydroclimate response to stratospheric sulfate geoengineering and the role of stratospheric heating. *Journal of Geophysical Research: Atmospheres, 124(23)*, 12587-12616. https://doi.org/10.1029/2019JD031093

Simpson, J. J., & Gobat, J. I. (1996). Improved cloud detection for daytime AVHRR scenes over land. *Remote Sensing of Environment, 55(1),* 21-49. https://doi.org/10.1016/0034-4257(95)00188-3

Smith, C. J., Crook, J. A., Crook, R., Jackson, L. S., Osprey, S. M., & Forster, P. M. (2017). Impacts of stratospheric sulfate geoengineering on global solar photovoltaic and concentrating solar power resource. *Journal of Applied Meteorology and Climatology, 56(5)*, 1483-1497. https://doi.org/10.1175/JAMC-D-16-0298.1

Smith, P. T. (2018). Legitimacy and non-domination in solar radiation management research. *Ethics, Policy & Environment, 21(3)*, 341--361. https://doi.org/10.1080/21550085.2018.1562528

Smith, P. T. (2020). Legitimacy and non-domination in solar radiation management research. In S. M. Gardiner, C. McKinnon & A. Fragnière (eds.), *The ethics of "geoengineering" the global climate* (pp. 112-132). Routledge.

Smith, W. (2020). The cost of stratospheric aerosol injection through 2100. *Environmental Research Letters, 15,* 114004. https://doi.org/10.1088/1748-9326/aba7e7

Smith, W., Bhattarai, U., Bingaman, D. C., Mace, J. L., & Rice, C. V. (2022). Review of possible very high-altitude platforms for stratospheric aerosol injection. *Environmental Research Communications, 4(3)*, 031002. 10.1088/2515-7620/ac4f5d

Smith, W., Bhattarai, U., MacMartin, D. G., Lee, W. R., Visioni, D., Kravitz, B., & Rice, C. V. (2022). A subpolar-focused stratospheric aerosol injection deployment scenario. *Environmental Research Communications, 4,* 095009. https://doi.org/10.1088/2515-7620/ac8cd3

Smith, W., & Henly, C. (2021). Updated and outdated reservations about research into stratospheric aerosol injection. *Climatic Change,* 164(3-4), 39. https://doi.org/10.1007/s10584-021-03017-z

Smith, W., & Wagner, G. (2018). Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. *Environmental Research Letters, 13(12)*, 124001. https://doi.org/10.1088/1748-9326/aae98d

Sofieva, V. F., Szelag, M., Tamminen, J., Fussen, D., Bingen, C., Vanhellemont, F.,...Pohl, C. (2023). Multi-wavelength dataset of aerosol extinction profiles retrieved from GOMOS stellar occultation measurements. *Atmospheric Measurement Techniques Discussions*, 2023, 1-18. https://doi.org/10.5194/amt-17-3085-2024

Sonntag, S., Ferrer González, M., Ilyina, T., Kracher, D., Nabel, J.E.M.S., Niemeier, U.,...Schmidt, H. (2018), Quantifying and comparing effects of climate engineering methods on the Earth system. *Earth's Future, 6,* 149-168. https://doi.org/10.1002/2017EF000620

Sourdeval, O., Gryspeerdt, E., Krämer, M., Goren, T., Delanoë, J., Afchine, A.,...Quaas, J. (2018). Ice crystal number concentration estimates from lidar--radar satellite remote sensing--Part 1: Method and evaluation. *Atmospheric Chemistry and Physics, 18(19),* 14327-14350. https://doi.org/10.5194/acp-18-14327-2018

Sovacool, B. K., Baum, C., & Low, S. (2023). The next climate war? Statecraft, security, and weaponization in the geopolitics of a low-carbon future. *Energy Strategy Reviews, 45*, 101031. 10.1016/j.esr.2022.101031

Sovacool, B. K., Baum, C. M., Cantoni, R., & Low, S. (2023). Actors, legitimacy, and governance challenges facing negative emissions and solar geoengineering technologies. *Environmental Politics*, 1-26. 10.1080/09644016.2023.2210464

Sovacool, B.K., Baum, C.M., Low, S., & Fritz, L. (2023). Coral reefs, cloud forests and climate protection: Radical interventions for geoengineering and ecosystem restoration in Australia's Wet Tropics and Great Barrier Reef. *PLOS Climate, 2(10),* e0000221. https://doi.org/10.1371/journal.pclm.0000221

Sovacool, B. K., Baum, C. M., & Low, S. (2022). Determining our climate policy future: Expert opinions about negative emissions and solar radiation management pathways. *Mitigation and Adaptation Strategies for Global Change, 27(8),* 58-58. https://doi.org/10.1007/s11027-022-10030-9

Sovacool, B. K., Baum, C. M., Low, S., & Fritz, L. (2023). Coral reefs, cloud forests and radical climate interventions in Australia's Wet Tropics and Great Barrier Reef. *PLOS Climate, 2(10),* e0000221.

Sovacool, B.K., Baum, C.M., Cantoni, R., & Low, S. (2024). Actors, legitimacy, and governance challenges facing negative emissions and solar geoengineering technologies. *Environmental Politics, 33(2),* 340-365. https://doi.org/10.1080/09644016.2023.2210464

Stavins, R. N., & Stowe, R. C. (2019). *Governance of the deployment of solar geoengineering*. Harvard Project on Climate Agreements, Cambridge: Harvard University. Retrieved from harvard_project_sg_governance_briefs_volume_feb_2019.pdf

Steffek, J. (2015). The output legitimacy of international organizations and the global public interest. *International Theory, 7(2),* 263-293. https://doi.org/10.1017/S1752971915000044

Stenchikov, G., Robock, A., Ramaswamy, V., Schwarzkopf, M. D., Hamilton, K., & Ramachandran, S. (2002). Arctic Oscillation response to the 1991 Mount Pinatubo eruption: Effects of volcanic aerosols and ozone depletion. *Journal of Geophysical Research: Atmospheres, 107(D24),* ACL 28-21-ACL 28-16. https://doi.org/10.1029/2002JD002090

Stephens, J. C., Kashwan, P., McLaren, D., & Surprise, K. (2023). The dangers of mainstreaming solar geoengineering: A critique of the National Academies Report. *Environmental Politics, 32(1),* 157-166. https://doi.org/10.1080/09644016.2021.1989214

Stephens, J. C., & Surprise, K. (2020). The hidden injustices of advancing solar geoengineering research. *Global Sustainability*, *3*, e2. https://doi.org/10.1017/sus.2019.28

Stevens, B., Acquistapace, C., Hansen, A., Heinze, R., Klinger, C., Klocke, D.,... Zängl, G. (2020). The added value of large-eddy and storm-resolving models for simulating clouds and precipitation. *Journal of the Meteorological Society of Japan. Ser. II, 98(2),* 395-435. https://doi.org/10.2151/jmsj.2020-021

Stilgoe, J. (2015). *Experiment Earth: Responsible innovation in geoengineering*. Routledge. https://doi.org/10.4324/9781315849195

Stilgoe, J., Owen, R., & Macnaghten, P. (2013). Developing a framework for responsible innovation. *Research Policy, 42(9*), 1568-1580. https://doi.org/10.1016/j.respol.2013.05.008

Stilgoe, J., & O'Donovan, C. (2023). Trials and tribulations: Who learns what from urban experiments with self-driving vehicles?. In F. Cugurullo, F. Caprotti, M. Cook, A. Karvonen, P. McGuirk, S. Marvin (Eds.), *Artificial intelligence and the city* (pp. 38-52). Routledge. http://dx.doi.org/10.2139/ssrn.4603654

Stjern, C. W., Muri, H., Ahlm, L., Boucher, O., Cole, J. N., Ji...Lenton, A. (2018). Response to marine cloud brightening in a multi-model ensemble. *Atmospheric Chemistry and Physics, 18(2),* 621-634. https://doi.org/10.5194/acp-18-621-2018

Stjern, C. W., Muri, H., Ahlm, L., Boucher, O., Cole, J. N. S., Ji, D.,...Kristjánsson, J. E. (2018). Response to marine cloud brightening in a multi-model ensemble. *Atmospheric Chemistry and Physics*, 18(2), 621-634. https://doi.org/10.5194/acp-18-621-2018

Stjern, C. W., Kristjánsson, J. E., & Hansen, A. W. (2009). Global dimming and global brightening---An analysis of surface radiation and cloud cover data in northern Europe. *International Journal of Climatology: A Journal of the Royal Meteorological Society, 29(5)*, 643-653. https://doi.org/10.1002/joc.1735

Storelvmo, T., Kristjánsson, J. E., & Lohmann, U. (2008). Aerosol influence on mixed-phase clouds in CAM-Oslo. *Journal of the Atmospheric Sciences, 65(10)*, 3214-3230. https://doi.org/10.1175/2008JAS2430.1

Storelvmo, T., Kristjansson, J. E., Muri, H., Pfeffer, M., Barahona, D., & Nenes, A. (2013). Cirrus cloud seeding has potential to cool climate. *Geophysical Research Letters, 40(1)*, 178-182. https://doi.org/10.1029/2012GL054201

Storelvmo, T., and N. Herger (2014), Cirrus cloud susceptibility to the injection of ice nuclei in the upper troposphere, *Journal of Geophysical Research: Atmospheres, 119*, 2375--2389. https://doi.org.10.1002/2013JD020816

Strong, A. L., Cullen, J. J., & Chisholm, S. W. (2009). Ocean fertilization: Science, policy, and commerce. *Oceanography*, 22(3), 236-261. https://doi.org/10.5670/oceanog.2009.83

Struck, C. (2007). *The feasibility of shading the greenhouse with dust clouds at the stable lunar Lagrange points*. Retrieved from https://arxiv.org/abs/astro-ph/0701513

Sugiyama, M., Asayama, S., & Kosugi, T. (2020). The North--South divide on public perceptions of stratospheric aerosol geoengineering? A survey in six Asia-Pacific countries. *Environmental Communication, 14(5)*, 641-656. https://doi.org/10.1080/17524032.2019.1699137

Sugiyama, M., Asayama, S., Kosugi, T., Ishii, A., Emori, S., Adachi, J.,...Hibi, Y. (2017). Transdisciplinary co-design of scientific research agendas: 40 research questions for socially relevant climate engineering research. *Sustainability Science, 12*, 31-44. 10.1007/s11625-016-0376-2

Sun, H., Bourguet, S., Eastham, S., & Keith, D. (2023). Optimizing injection locations relaxes altitude-lifetime trade-off for stratospheric aerosol injection. *Geophysical Research Letters, 50(16*), e2023GL105371. https://doi.org/10.1029/2023GL105371

Surprise, K., & Sapinski, J. P. (2023). Whose climate intervention? Solar geoengineering, fractions of capital, and hegemonic strategy. *Capital & Class*, *47*(4), 539-564. https://doi.org/10.1177/03098168221114386

Sutter, J., Jones, A., Frölicher, T., Wirths, C., & Stocker, T. (2023). Climate intervention on a high-emissions pathway could delay but not prevent West Antarctic Ice Sheet demise. *Nature Climate Change, 13(9)*, 951-960. https://doi.org/10.1038/s41558-023-01738-w

Svoboda, T. (2015). Geoengineering, agent-regret, and the lesser of two evils argument. *Environmental Ethics, 37(2),* 207-220. 10.5840/enviroethics201537218

Svoboda, T. (2017). *The ethics of climate engineering: Solar radiation management and non-ideal justice.* Taylor & Francis. https://doi.org/10.4324/9781315468532

Szapudi, I. (2023). Solar radiation management with a tethered sun shield. *Proceedings of the National Academy of Sciences, 120(32),* e2307434120. https://doi.org/10.1073/pnas.2307434120

Szerszynski, B., Kearnes, M., Macnaghten, P., Owen, R., & Stilgoe, J. (2013). Why solar radiation management geoengineering and democracy won't mix. *Environment and Planning. A, 45(12),* 2809-2816. https://doi.org/10.1068/a45649

Tackett, J. L., Kar, J., Ientom, M. A., Getzewich, B. J., Kim, M.-H., Vernier, J.-P.,...Winker, D. M. (2023). The CALIPSO version 4.5 stratospheric aerosol subtyping algorithm. *Atmospheric Measurement Techniques, 16(3),* 745-768. https://doi.org/10.5194/amt-16-745-2023

Taha, H., Konopacki, S., & Gabersek, S. (1999). Impacts of large-scale surface modifications on meteorological conditions and energy use: A 10-region modeling study. *Theoretical and Applied Climatology, 62*, 175-185. https://doi.org/10.1007/s007040050082

Talberg, A., Thomas, S., Christoff, P., & Karoly, D. (2018). How geoengineering scenarios frame assumptions and create expectations. *Sustainability Science, 13(4),* 1093-1104. https://doi.org/10.1007/s11625-018-0527-8

Tang, A. (2023). The slippery slopes of climate engineering research. *Global Environmental Change, 80,* 102674. https://doi.org/10.1016/j.gloenvcha.2023.102674

Tanré, D., Bréon, F. M., Deuzé, J. L., Dubovik, O., Ducos, F., François, P., ... Waquet, F. (2011). Remote sensing of aerosols by using polarized, directional and spectral measurements within the A-Train: the PARASOL mission. *Atmospheric Measurement Techniques, 4(7),* 1383-1395. https://doi.org/10.5194/amt-4-1383-2011

Teller, E., Wood, L., & Hyde, R. (1996). *Global warming and ice ages: I. Prospects for physics-based modulation of global change.*

Tessendorf, S. A., Bruintjes, R. T., Weeks, C., Wilson, J. W., Knight, C. A., Roberts, R. D.,...Freney, E. (2012). The Queensland cloud seeding research program. *Bulletin of the American Meteorological Society, 93(1)*, 75-90. doi:10.1175/Bams-D-11-00060.1

Tew, Y. L., Tan, M. L., Liew, J., Chang, C. K., & Muhamad, N. (2023). A review of the effects of solar radiation management on hydrological extremes. *IOP Conference Series: Earth and Environmental Science. 10.1088/1755-1315/1238/1/012030*

Thompson, R. C., Swan, S. H., Moore, C. J., & vom Saal, F. S. (2009). Our plastic age. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526)*, 1973-1976. https://doi.org/doi:10.1098/rstb.2009.0054

Tilmes, S., Fasullo, J., Lamarque, J.-F., Marsh, D. R., Mills, M., Alterskjær, K.,...Watanabe, S. (2013). The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres, 118(19),* 11,036-011,058. https://doi.org/10.1002/jgrd.50868

Tilmes, S., Garcia, R. R., Kinnison, D. E., Gettelman, A., & Rasch, P. J. (2009). Impact of geoengineered aerosols on the troposphere and stratosphere. *Journal of Geophysical Research: Atmospheres, 114(D12)*. https://doi.org/10.1029/2008JD011420

Tilmes, S., Jahn, A., Kay, J. E., Holland, M., & Lamarque, J. F. (2014). Can regional climate engineering save the summer Arctic sea ice? *Geophysical Research Letters, 41(3)*, 880-885. 10.1002/2013GL058731

Tilmes, S., MacMartin, D. G., Lenaerts, J. T. M., van Kampenhout, L., Muntjewerf, L., Xia, L.,...Robock, A. (2020). Reaching 1.5 and 2.0°C global surface temperature targets using stratospheric aerosol geoengineering. *Earth System Dynamics, 11(3),* 579-601. https://doi.org/10.5194/esd-11-579-2020

Tilmes, S., Richter, J. H., Kravitz, B., MacMartin, D. G., Glanville, A. S., Visioni, D., Kinnison, D. E., & Müller, R. (2021). Sensitivity of total column ozone to stratospheric sulfur injection strategies. *Geophysical Research Letters, 48(19*), e2021GL094058. https://doi.org/10.1029/2021GL094058

Tilmes, S., Rosenlof, K., Visioni, D., M. Bednarz, E. M., Felgenhauer, T., Smith, W.,...Thompson, C. (2024). Research criteria towards an interdisciplinary Stratospheric Aerosol Intervention Assessment. *Oxford Open Climate Change*, 4 (1), https://doi.org/10.1093/oxfclm/kgae010

Tilmes, S., Richter, J. H., Kravitz, B., MacMartin, D. G., Mills, M. J., Simpson, I. R.,...Ghosh, S. (2018). CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble Project. *Bulletin of the American Meteorological Society, 99(11),* 2361-2371. https://doi.org/10.1175/BAMS-D-17-0267.1

Tilmes, S., Richter, J. H., Mills, M. J., Kravitz, B., MacMartin, D. G., Garcia, R. R.,...Vitt, F. (2018). Effects of different stratospheric SO2 injection altitudes on stratospheric chemistry and dynamics. *Journal of Geophysical Research: Atmospheres, 123(9)*, 4654-4673. https://doi.org/10.1002/2017JD028146

Tilmes, S., Richter, J. H., Mills, M. J., Kravitz, B., MacMartin, D. G., Vitt, F.,...Lamarque, J.-F. (2017). Sensitivity of aerosol distribution and climate response to stratospheric SO2 injection locations. *Journal of Geophysical Research: Atmospheres, 122(23),* 12,591-512,615. https://doi.org/10.1002/2017JD026888

Tilmes, S., Sanderson, B. M., & O'Neill, B. C. (2016). Climate impacts of geoengineering in a delayed mitigation scenario. *Geophysical Research Letters, 43(15),* 8222-8229. https://doi.org/10.1002/2016GL070122

Tilmes, S., Visioni, D., Jones, A., Haywood, J., Séférian, R., Nabat, P.,...Niemeier, U. (2022). Stratospheric ozone response to sulfate aerosol and solar dimming climate interventions based on the G6 Geoengineering Model Intercomparison Project (GeoMIP) simulations. *Atmospheric Chemistry and Physics, 22(7),* 4557-4579. https://doi.org/10.5194/acp-22-4557-2022

Tingley, D., & Wagner, G. (2017). Solar geoengineering and the chemtrails conspiracy on social media. *Palgrave Communications, 3(1),* 12. https://doi.org/10.1057/s41599-017-0014-3

Tjiputra, J. F., Grini, A., & Lee, H. (2016). Impact of idealized future stratospheric aerosol injection on the large-scale ocean and land carbon cycles. *Journal of Geophysical Research: Biogeosciences, 121(1),* 2-27. https://doi.org/10.1002/2015JG003045

Todt, M. A., Asher, E., Hall, E., Cullis, P., Jordan, A., Xiong, K.,...Thornberry, T. (2023). Baseline Balloon Stratospheric Aerosol Profiles (B2SAP)---Systematic measurements of aerosol number density and size. *Journal of Geophysical Research: Atmospheres, 128(12),* e2022JD038041. *10.1029/2022JD038041*

Toll, V., Christensen, M., Quaas, J., & Bellouin, N. (2019). Weak average liquid-cloud-water response to anthropogenic aerosols. *Nature, 572(7767*), 51-55.

Tørstad, V. H. (2020). Participation, ambition and compliance: can the Paris Agreement solve the effectiveness trilemma? *Environmental Politics, 29(5),* 761-780. https://doi.org/10.1080/09644016.2019.1710322

Tracy, S. M., Moch, J. M., Eastham, S. D., & Buonocore, J. J. (2022). Stratospheric aerosol injection may impact global systems and human health outcomes. *Elementa, 10(1).* https://doi.org/10.1525/elementa.2022.00047

Trenberth, K. E., & Dai, A. (2007). Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. *Geophysical Research Letters, 34(15*). https://doi.org/10.1029/2007GL030524

Trickl, T., Adelwart, M., Khordakova, D., Ries, L., Rolf, C., Sprenger, M., Steinbrecht, W., & Vogelmann, H. (2023). Local comparisons of tropospheric ozone: vertical soundings at two neighbouring stations in southern Bavaria. Atmospheric Measurement Techniques Discussions, 2023, 1-40. https://doi.org/10.5194/amt-16-5145-2023

Trisos, C. H., Amatulli, G., Gurevitch, J., Robock, A., Xia, L., & Zambri, B. (2018). Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination. *Nature Ecology & Evolution, 2(3),* 475-482. https://doi.org/10.1038/s41559-017-0431-0

Trisos, C. H., Gabriel, C., Robock, A., & Xia, L. (2018). Chapter 24 - Ecological, agricultural, and health impacts of solar geoengineering. In Z. Zommers & K. Alverson (Eds.), *Resilience*: *The science of adaptation to climate change* (pp. 291-303). Elsevier. https://doi.org/10.1016/B978-0-12-811891-7.00024-4

Tsipiras, K., & Grant, W. J. (2022). What do we mean when we talk about the moral hazard of geoengineering? *Environmental Law Review*, *24*(1), 27--44. https://doi.org/10.1177/14614529211069839

Tully, C., Neubauer, D., & Lohmann, U. (2023). Assessing predicted cirrus ice properties between two deterministic ice formation parameterizations. *Geoscientific Model Development, 16(10),* 2957-2973. https://doi.org/10.5194/gmd-16-2957-2023

Tully, C., Neubauer, D., Omanovic, N., & Lohmann, U. (2022). Cirrus cloud thinning using a more physically based ice microphysics scheme in the ECHAM-HAM general circulation model. *Atmospheric Chemistry and Physics, 22(17*), 11455-11484. https://doi.org/10.5194/acp-22-11455-2022

Twomey, S. (1977). The influence of pollution on the shortwave albedo of clouds. *Journal of Atmospheric Sciences, 34(7)*, 1149-1152. https://doi.org/10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2

Tye, M. R., Dagon, K., Molina, M. J., Richter, J. H., Visioni, D., Kravitz, B., & Tilmes, S. (2022). Indices of extremes: geographic patterns of change in extremes and associated vegetation impacts under climate intervention. *Earth System Dynamics*, *13(3)*, 1233-1257. https://doi.org/10.5194/esd-13-1233-2022

UNESCO. (2023). *Report of the World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) on the ethics of climate engineering*. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000386677?posInSet=2&queryId=b6f89936-d78a-431d-9f59- 51212304ae5c

United Nations Environment Programme (2023). *One atmosphere: An independent expert review on solar radiation modification research and deployment*. Nairobi: United Nations Environment Programme

United Nations Human Rights Council. (2023). *Impact of new technologies for climate protection on the enjoyment of human rights*. Retrieved from https://www.ohchr.org/en/hr-bodies/hrc/advisory-committee/impact-of-new-technologies

UNFCCC. (2015). *The Paris Agreement*. Retrieved from https://unfccc.int/sites/default/files/english_paris_agreement.pdf

Urban, O., Janouš, D., Acosta, M., Czerný, R., Marková, I., Navrátil, M....Marek, M. V. (2007). Ecophysiological controls over the net ecosystem exchange of mountain spruce stand. Comparison of the response in direct vs. diffuse solar radiation. *Global Change Biology, 13(1*), 157-168. https://doi.org/10.1111/j.1365-2486.2006.01265.x

Urban, O., Klem, K., Holová, P., Šigut, L., Šprtová, M., Teslová-Navrátilová, P.,...Grace, J. (2014). Impact of elevated CO2 concentration on dynamics of leaf photosynthesis in Fagus sylvatica is modulated by sky conditions. *Environmental Pollution, 185*, 271-280. https://doi.org/10.1016/j.envpol.2013.11.009

Urpelainen, J. (2012). Geoengineering and global warming: a strategic perspective. *International Environmental Agreements: Politics, Law and Economics, 12(4),* 375-389. https://doi.org/10.1007/s10784-012-9167-0

Vattioni, S., Luo, B., Feinberg, A., Stenke, A., Vockenhuber, C., Weber, R.,...Keutsch, F. (2023). Chemical impact of stratospheric alumina particle injection for solar radiation modification and related uncertainties. *Geophysical Research Letters, 50(24),* e2023GL105889. https://doi.org/10.1029/2023GL105889

Vattioni, S., Stenke, A., Luo, B., Chiodo, G., Sukhodolov, T., Wunderlin, E., and T. Peter (2024a). Importance of microphysical settings for climate forcing by stratospheric SO2 injections as modeled by SOCOL-AERv2. *Geoscientific Model Development*, *17(10*), 4181--4197. https://doi.org/10.5194/gmd-17-4181-2024

Vattioni, S., Weber, R., Feinberg, A., Stenke, A., Dykema, J., Luo, B.,...Chiodo, G. (2024b). A fully coupled solid particle microphysics scheme for stratospheric aerosol injections within the aerosol-chemistry-climate-model SOCOL-AERv2, *EGUsphere preprint.* https://doi.org/10.5194/egusphere-2024-444

Vattioni, S., Weisenstein, D., Keith, D., Feinberg, A., Peter, T., & Stenke, A. (2019). Exploring accumulation-mode H 2 SO 4 versus SO 2 stratospheric sulfate geoengineering in a sectional aerosol--chemistry--climate model. *Atmospheric Chemistry and Physics, 19(7),* 4877-4897. https://doi.org/10.5194/acp-19-4877-2019

Vaughan, G., Wareing, D., & Ricketts, H. (2021). Measurement report: Lidar measurements of stratospheric aerosol following the 2019 Raikoke and Ulawun volcanic eruptions. *Atmospheric Chemistry and Physics, 21(7),* 5597-5604. https://doi.org/10.5194/acp-21-5597-2021

Vaughan, N. E., & Lenton, T. M. (2011). A review of climate geoengineering proposals. *Climatic Change, 109(3-4)*, 745-790. https://doi.org/10.1007/s10584-011-0027-7

Victor, D. G. (2008). On the regulation of geoengineering. *Oxford Review of Economic Policy, 24(2),* 322-336. https://doi.org/10.1093/oxrep/grn018

Villanueva, D., Possner, A., Neubauer, D., Gasparini, B., Lohmann, U., & Tesche, M. (2022). Mixed-phase regime cloud thinning could help restore sea ice. *Environmental Research Letters, 17(11),* 114057. 10.1088/1748-9326/aca16d

Virgoe, J. (2009). International governance of a possible geoengineering intervention to combat climate change. *Climatic Change, 95(1-2*), 103-119. https://doi.org/10.1007/s10584-008-9523-9

Visioni, D., Bednarz, E. M., Lee, W. R., Kravitz, B., Jones, A., Haywood, J. M., & MacMartin, D. G. (2023a). Climate response to off-equatorial stratospheric sulfur injections in three Earth system models -- Part 1: Experimental protocols and surface changes. *Atmospheric Chemistry and Physics, 23(1),* 663-685. https://doi.org/10.5194/acp-23-663-2023

Visioni, D., Kravitz, B., Robock, A., Tilmes, S., Haywood, J., Boucher, O.,...Xia, L. (2023b). Opinion: The scientific and community-building roles of the Geoengineering Model Intercomparison Project (GeoMIP)--past, present, and future. *Atmospheric Chemistry and Physics, 23(9),* 5149-5176. https://doi.org/10.5194/acp-23-5149-2023

Visioni, D., MacMartin, D. G., & Kravitz, B. (2021). Is turning down the sun a good proxy for stratospheric sulfate geoengineering? *Journal of Geophysical Research: Atmospheres, 126(5*), e2020JD033952. https://doi.org/10.1029/2020JD033952

Visioni, D., MacMartin, D. G., Kravitz, B., Boucher, O., Jones, A., Lurton, T.,...Niemeier, U. (2021). Identifying the sources of uncertainty in climate model simulations of solar radiation modification with the G6sulfur and G6solar Geoengineering Model Intercomparison Project (GeoMIP) simulations. *Atmospheric Chemistry and Physics, 21(13),* 10039-10063. https://doi.org/10.5194/acp-21-10039-2021

Visioni, D., MacMartin, D. G., Kravitz, B., Lee, W., Simpson, I. R., & Richter, J. H. (2020). Reduced poleward transport due to stratospheric heating under stratospheric aerosols geoengineering. *Geophysical Research Letters, 47(17),* e2020GL089470. https://doi.org/10.1029/2020GL089470

Visioni, D., MacMartin, D. G., Kravitz, B., Tilmes, S., Mills, M. J., Richter, J. H., & Boudreau, M. P. (2019). Seasonal injection strategies for stratospheric aerosol geoengineering. *Geophysical Research Letters, 46(13)*, 7790-7799. https://doi.org/10.1029/2019GL083680

Visioni, D., Pitari, G., Aquila, V., Tilmes, S., Cionni, I., Di Genova, G., & Mancini, E. (2017). Sulfate geoengineering impact on methane transport and lifetime: results from the Geoengineering Model Intercomparison Project (GeoMIP). *Atmospheric Chemistry and Physics, 17(18)*, 11209-11226. https://doi.org/10.5194/acp-17-11209-2017

Visioni, D., Slessarev, E., MacMartin, D. G., Mahowald, N. M., Goodale, C. L., & Xia, L. (2020). What goes up must come down: impacts of deposition in a sulfate geoengineering scenario. *Environmental Research Letters, 15(9),* 94063. https://doi.org/10.1088/1748-9326/ab94eb

Visschers, V. H. M., Shi, J., Siegrist, M., & Arvai, J. (2017). Beliefs and values explain international differences in perception of solar radiation management: insights from a cross-country survey. *Climatic Change, 142(3),* 531-544. https://doi.org/10.1007/s10584-017-1970-8

Wandinger, U., Floutsi, A. A., Baars, H., Haarig, M., Ansmann, A., Hünerbein, A.,...Mason, S. (2023). HETEAC--the Hybrid End-To-End Aerosol Classification model for EarthCARE. *Atmospheric Measurement Techniques, 16(10),* 2485-2510. https://doi.org/10.5194/amt-16-2485-2023

Wang, H., Rasch, P. J., & Feingold, G. (2011). Manipulating marine stratocumulus cloud amount and albedo: a process-modelling study of aerosol-cloud-precipitation interactions in response to injection of cloud condensation nuclei. *Atmospheric Chemistry and Physics, 11(9),* 4237-4249. https://doi.org/10.5194/acp-11-4237-2011

Ward, H. (2008). Liberal democracy and sustainability. *Environmental Politics, 17(3),* 386-409. https://doi.org/10.1080/09644010802055626

Ward, K. D. (2004). The BWC protocol mandate for failure. *The Nonproliferation Review, 11(2),* 183-199. 10.1080/10736700408436972

Wegener, A. (1911). *Thermodynamik der atmosphäre.* Leipzig: J.A. Barth. https://doi.org/10.1038/090031a0

Wehr, T., Kubota, T., Tzeremes, G., Wallace, K., Nakatsuka, H., Ohno, Y.,...Bernaerts, D. (2023). The EarthCARE mission -- science and system overview. Atmospheric Measurement Techniques, 16(15), 3581--3608. https://doi.org/10.5194/amt-16-3581-2023

Weisenstein, D. K., Keith, D. W., & Dykema, J. (2015). Solar geoengineering using solid aerosol in the stratosphere. *Atmospheric Chemistry and Physics, 15(20),* 11835-11859. https://doi.org/10.5194/acp-15-11835-2015

Weiss, E.B. (1989). *In fairness to future generations: International law, common patrimony, and intergenerational equity*. UN University.

Weitzman, M. L. (2015). A voting architecture for the governance of free-driver externalities, with application to geoengineering. *The Scandinavian Journal of Economics, 117(4)*, 1049-1068. https://doi.org/10.1111/sjoe.12120

Wendler, G. (1984). Effects of the El Chichón volcanic cloud on solar radiation received at Fairbanks, Alaska. *Bulletin of the American Meteorological Society, 65(3)*, 216-218. https://doi.org/10.1175/1520-0477(1984)065<0216:EOTECV>2.0.CO;2

Whyte, K. P. (2012). Now this! Indigenous sovereignty, political obliviousness and governance models for SRM research. *Ethics, Policy & Environment, 15(2)*, 172--187. https://doi.org/10.1080/21550085.2012.685570

Whyte, K. P. (2016). Is it colonial déjà vu? Indigenous peoples and climate injustice. In J. Adamson & M. Davies (Eds.), *Humanities for the environment* (pp. 102-119). London: Routledge. http://dx.doi.org/10.2139/ssrn.2925277

Whyte, K. (2018). Settler colonialism, ecology, and environmental injustice. *Environment and Society*, *9*(1), 125-144. https://doi.org/10.3167/ares.2018.090109

Whyte, K. P. (2018b). Indigeneity in geoengineering discourses: Some considerations. *Ethics, Policy & Environment*, *21*(3), 289--307. https://doi.org/10.1080/21550085.2018.1562529(https://doi.org/10.1080/21550085.2018.1562529)

Whyte, K. P. (2019). Way beyond the lifeboat: An indigenous allegory of climate justice. In K.-K. Bhavnani, J. Foran, P.A. Kurian & D. Munshi (Eds.) *Climate futures: Reimagining global climate justice* (pp. 11-20). London: Zed Books http://dx.doi.org/10.2139/ssrn.3003946

Wibeck, V., Hansson, A., & Anshelm, J. (2015). Questioning the technological fix to climate change--Lay sense-making of geoengineering in Sweden. *Energy Research & Social Science, 7*, 23-30. 10.1016/j.erss.2015.03.001

Wibeck, V., Hansson, A., Anshelm, J., Asayama, S., Dilling, L., Feetham, P. M., Hauser, R., Ishii, A., & Sugiyama, M. (2017). Making sense of climate engineering: a focus group study of lay publics in four countries. Climatic change, 145(1), 1-14. https://doi.org/10.1007/s10584-017-2067-0

Wieners, C. E., Hofbauer, B. P., de Vries, I. E., Honegger, M., Visioni, D., Russchenberg, H. W. J., & Felgenhauer, T. (2023). Solar radiation modification is risky, but so is rejecting it: a call for balanced research. *Oxford Open Climate Change, 3(1).* https://doi.org/10.1093/oxfclm/kgad002

Wigley, T. M. (2006). A combined mitigation/geoengineering approach to climate stabilization. *Science, 314(5798),* 452-454. doi: 10.1126/science.1131728

Winickoff, D. E., Flegal, J. A., & Asrat, A. (2015). Engaging the Global South on climate engineering research. *Nature Climate Change, 5(7),* 627-634. https://doi.org/10.1038/NCLIMATE2632

Winker, D. M., Vaughan, M. A., Omar, A., Hu, Y., Powell, K. A., Liu, Z.,...Young, S. A. (2009). Overview of the CALIPSO mission and CALIOP data processing algorithms. *Journal of Atmospheric and Oceanic Technology, 26(11),* 2310-2323. https://doi.org/10.1175/2009JTECHA1281.1

Winsberg, E. (2021). A modest defense of geoengineering research: A case study in the cost of learning. *Philosophy & Technology, 34(4),* 1109-1134. 10.1007/s13347-021-00452-9

Winter, G. (2011). Climate engineering and international law: Last resort or the end of humanity? *Review of European Community & International Environmental Law, 20(3),* 277-289. https://doi.org/10.1111/j.1467-9388.2012.00730.x

World Meteorological Organization. (2023). *State of the global climate 2022*.

Wolff, J. (2020). Fighting risk with risk: Solar radiation management, regulatory drift, and minimal justice. *Critical Review of International Social and Political Philosophy, 23(5),* 564--583. https://doi.org/10.1080/13698230.2020.1694214

Wong, P.-H. (2014). Maintenance required: The ethics of geoengineering and post-implementation scenarios. *Ethics, Policy & Environment, 17(2)*, 186--191. https://doi.org/10.1080/21550085.2014.926090

Wong, P.-H. (2016). Consenting to geoengineering. *Philosophy & Technology, 29(2),* 173--188. https://doi.org/10.1007/s13347-015-0203-1

Wood, R., Ackerman, T., Rasch, P., & Wanser, K. (2017). Could geoengineering research help answer one of the biggest questions in climate science? *Earth's Future, 5(7),* 659-663. https://doi.org/10.1002/2017EF000601

Wrana, F., Von Savigny, C., Zalach, J., & Thomason, L. W. (2021). Retrieval of stratospheric aerosol size distribution parameters using satellite solar occultation measurements at three wavelengths. *Atmospheric Measurement Techniques, 14(3),* 2345-2357.https://doi.org/10.5194/amt-14-2345-2021

Wright, M. J., Teagle, D. A. H., & Feetham, P. M. (2014). A quantitative evaluation of the public response to climate engineering. *Nature Climate Change, 4(2),* 106-110. https://doi.org/10.1038/nclimate2087

Xia, L., Nowack, P. J., Tilmes, S., & Robock, A. (2017). Impacts of stratospheric sulfate geoengineering on tropospheric ozone. *Atmospheric Chemistry and Physics, 17(19*), 11913-11928. https://doi.org/10.5194/acp-17-11913-2017

Xia, L., Robock, A., Tilmes, S., & Neely Iii, R. R. (2016). Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate. *Atmospheric Chemistry and Physics, 16(3),* 1479-1489. https://doi.org/10.5194/acp-16-1479-2016

Xie, M., Moore, J. C., Zhao, L., Wolovick, M., & Muri, H. (2022). Impacts of three types of solar geoengineering on the Atlantic Meridional Overturning Circulation. *Atmospheric Chemistry and Physics, 22(7),* 4581-4597. https://doi.org/10.5194/acp-22-4581-2022

Yin, R., & Ulm, R. (2017). How plants cope with UV-B: from perception to response. *Current Opinion in Plant Biology, 37,* 42-48. https://doi.org/10.1016/j.pbi.2017.03.013

Young, D. N. (2023). Considering stratospheric aerosol injections beyond an environmental frame: The intelligible 'emergency' techno-fix and preemptive security. *European Journal of International Security, 8(2),* 262-280. https://doi.org/10.1017/eis.2023.4

Young, A. H., Knapp, K. R., Inamdar, A., Hankins, W., & Rossow, W. B. (2018). The international satellite cloud climatology project H-Series climate data record product. *Earth System Science Data, 10(1),* 583-593. https://doi.org/10.5194/essd-10-583-2018

Yu, X., Moore, J. C., Cui, X., Rinke, A., Ji, D., Kravitz, B., & Yoon, J.-H. (2015). Impacts, effectiveness and regional inequalities of the GeoMIP G1 to G4 solar radiation management scenarios. *Global and Planetary Change*, *129*, 10-22. https://doi.org/10.1016/j.gloplacha.2015.02.010

Yuan, T., Remer, L. A., & Yu, H. (2011). Microphysical, macrophysical and radiative signatures of volcanic aerosols in trade wind cumulus observed by the A-Train. *Atmospheric Chemistry and Physics 11(14)*, 7119-7132. https://doi.org/10.5194/acp-11-7119-2011

Yuan, M., Zhang, L., Wang, Y., & Han, C. (2023). Polarimetric range extended target detection via adaptive range weighted feature extraction. *Remote Sensing, 15(11),* 2929. https://doi.org/10.3390/rs15112929

Yue, C., Jevrejeva, S., Qu, Y., Zhao, L., & Moore, J. C. (2023). Thermosteric and dynamic sea level under solar geoengineering. *npj Climate and Atmospheric Science, 6(1),* 135. https://doi.org/10.1038/s41612-023-00466-4

Yuval, J., & O'Gorman, P. A. (2020). Stable machine-learning parameterization of subgrid processes for climate modeling at a range of resolutions. *Nature Communications, 11(1),* 3295. https://doi.org/10.1038/s41467-020-17142-3

Zampieri, L., & Goessling, H. F. (2019). Sea ice targeted geoengineering can delay Arctic sea ice decline but not global warming. *Earth's Future, 7(12),* 1296-1306. https://doi.org/10.1029/2019EF001230

Zarnetske, P. L., Gurevitch, J., Franklin, J., Groffman, P. M., Harrison, C. S., Hellmann, J. J.,...Tilmes, S. (2021). Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth. *Proceedings of the National Academy of Sciences, 118(15),* e1921854118. https://doi.org/10.1073/pnas.1921854118

Zerefos, C. S., Eleftheratos, K., Kapsomenakis, J., Solomos, S., Inness, A., Balis, D.,...Amiridis, V. (2017). Detecting volcanic sulfur dioxide plumes in the Northern Hemisphere using the Brewer spectrophotometers, other networks, and satellite observations. *Atmospheric Chemistry and Physics, 17(1),* 551-574. https://doi.org/10.5194/acp-17-551-2017

Zhang, X., Dong, X., Xi, B., & Zheng, X. (2023). Aerosol properties and their influences on marine boundary layer cloud condensation nuclei over the Southern Ocean. *Atmosphere, 14(8),* 1246. https://doi.org/10.3390/atmos14081246

Zhang, Z., Zhu, Y., & Crabbe, M. J. C. (2023). Impacts of marine cloud brightening scheme on climatic extremes in the Tibetan Plateau. *Open Geosciences, 15(1*). https://doi.org/doi:10.1515/geo-2022-0500

Zhao, M., Cao, L., Bala, G., & Duan, L. (2021). Climate response to latitudinal and altitudinal distribution of stratospheric sulfate aerosols. *Journal of Geophysical Research: Atmospheres, 126(24),* e2021JD035379. https://doi.org/10.1029/2021JD035379

Zhu, P., Zhuang, Q., Ciais, P., Welp, L., Li, W., & Xin, Q. (2017). Elevated atmospheric CO2 negatively impacts photosynthesis through radiative forcing and physiology-mediated climate feedback. *Geophysical Research Letters, 44(4),* 1956-1963. https://doi.org/10.1002/2016GL071733

Zürn, M., & Schäfer, S. (2013). The paradox of climate engineering. *Global Policy, 4(3),* 266-277. https://doi.org/10.1111/gpol.12004

Zürn, M., & Stephen, M. (2010). The view of old and new powers on the legitimacy of international institutions. *Politics, 30(S1),* 91-101. https://doi.org/10.1111/j.1467-9256.2010.01388.x

Annexes

Background and main processes

Introduction

The College of Commissioners requested the Group of Chief Scientific Advisors to produce a Scientific Opinion on solar radiation modification. The overarching questions posed in the scoping paper, published in August 2023, were:

> How to address the risks and opportunities associated with research on Solar Radiation Modification and with its potential deployment? What are the options for a governance system for research and potential deployment taking into account different SRM technologies and their scale?

Responsibilities and working structure within the Scientific Advice Mechanism

The Group of Chief Scientific Advisors has produced its Scientific Opinion on SRM, which sets out evidence-based policy recommendations. The Advisors involved with the project have been Nebojša Nakićenović and Eric Lambin, as well as Naomi Ellemers and Nicole Grobert. The Science Policy, Advice and Ethics Unit at DG RTD has assisted the Advisors in the development of the Scientific Opinion.

SAPEA has been responsible for independently producing the evidence review report that informs the Scientific Opinion. Within SAPEA, Academia Europaea has served as lead Academy Network for the topic. Louise Edwards (Academia Europaea Cardiff) has coordinated the Report's development, alongside Rafael Carrascosa Marzo (Academia Europaea Cardiff) and the other SAPEA scientific policy officers. Céline Tschirhart, Scientific Policy Officer at ALLEA, coordinated the peer review.

SAM coordination team meetings, chaired by Nebojša Nakićenović, have included the co-chairs of the SAPEA working group, a Board member of Academia Europaea, and SAPEA staff members. Two meetings involved the European Group on Ethics in Science and New Technologies, which has produced a statement on the ethics of SRM.

Selection of experts

In autumn 2023, SAPEA set up an interdisciplinary working group, following the procedure laid down in the SAPEA quality assurance guidelines.

The two co-chairs of the working group, Johannes Quaas and Benjamin Sovacool, were proposed by the lead Academy Network, Academia Europaea. Following assessment of their declarations of interest, the co-chairs were approved by the SAPEA Board.

The call for nominations for the working group was issued by SAPEA in September 2023, describing the scope, timeline and areas of expertise required. Experts were also identified through desk research by the Academy Networks.

The selection committee for the working group met on 1 November 2023. The committee comprised:

- working group co-chairs (Johannes Quaas and Benjamin Sovacool)
- Board members of the lead Academy Network, Academia Europaea (Marja Makarow and Paolo Papale)
- President of YASAS (Helen Eenmaa), as a second Academy Network

SAPEA received a total of 101 nominations for the working group. The selection committee was asked to choose experts according to demonstrated excellence in one or more of the fields listed in the call for nominations. The areas of diversity taken into account included:

- interdisciplinarity, with all relevant disciplines and fields included
- broad geographical coverage of Europe, including Widening Countries
- participation of underrepresented gender
- inclusion of early- and mid-career researchers

The final working group of those who accepted the invitation from SAPEA, was 20 members, including the two co-chairs. 35% were female, 60% were mid-career researchers and a further 10% were early-career, making a total of 70% as EMCRs. 11 European countries and 1 non-European country were represented in the group. 3 experts came from Widening countries.

The composition of the working group was approved by the SAPEA Board. All working group members were required to complete the standard Declaration of Interests form of the European Commission, which were then assessed by SAPEA in accordance with SAPEA's quality guidelines. The completed DOIs were published alongside the evidence review report.

Evidence review process

Working group

The working group met ten times during the period from November 2023 to July 2024, via online meetings. Between meetings, they worked collectively online on successive drafts of the Report.

Expert workshop

An expert workshop was held online on 22 March 2024. Its purpose was to receive feedback on the draft evidence review report from the wider expert community. Invited experts from five European countries spoke at the workshop, with two contributors from the USA (see Annex 2 for details). In all, there were 45 participants.

The workshop started with a keynote presentation by an invited international expert. Each of the two main parts of the report was then introduced by the responsible co-chair, with feedback given by three discussants. A final session was dedicated to a critique of an early draft of the evidence-based policy options. The main points of feedback were considered by the working group at a dedicated meeting.

The report of the workshop is published separately, as a companion document to the evidence review report, and is available on the SAM website. The invited experts are listed in Annex 2.

Peer review

A double-blind peer review process was coordinated by the Scientific Policy Officer at ALLEA, in accordance with the SAPEA quality guidelines. Four reviewers (see Annex 2) provided feedback, representing a diverse and complementary range of disciplines (two for each of the main parts of the report). This fedback was systematically addressed by the working group. The main actions taken included the following:

- Areas of the report where the reviewers felt there were gaps and that information was missing were addressed, with additional literature cited.
- Chapter 6 was reviewed and revised extensively.
- Clarification of terms was provided, where this was flagged by the reviewers.
- The draft of the executive summary was developed considerably, in a collective effort by the working group.
- The risks and potential benefits of SRM were re-examined, with further consideration given to the challenges of risk framings and risk-risk trade-offs.

- The balance of arguments for and against the 'slippery slope' concept was re-examined.

The SAPEA Board approved the final outcome of the peer review process.

Plagiarism check

In accordance with the SAPEA Quality Guidelines, a plagiarism check on the final version of the evidence review report was run by Cardiff University using Turnitin software. The results were checked by the Scientific Policy Officer of ALLEA.

Publication

This evidence review report was been handed over to the Group of Chief Scientific Advisors and published on 9 December 2024. It is accompanied by the expert workshop report and the statement on the ethics of SRM by the European Group on Ethics in Science and New Technologies. All documents can be accessed on the SAM website.

Literature review

The review team at Cardiff University is made up of information specialists and methodologists. It undertook a preliminary literature review in October 2023, in response to a request from the SAM secretariat in the European Commission. This review was also provided to the working group at its first meeting in late November, for background information only. It included:

- a review of major reports, covering both grey and scientific literature
- a review of recent literature on technological, scientific, ethical and governance aspects of SRM
- an analysis of concepts and definitions used in the context of SRM

A rapid review was conducted on behalf of the European Group on Ethics in Science and New Technologies, to inform its work on a statement on the ethics of SRM. The work was undertaken by the review team at Cardiff University, in consultation with a member of the SAPEA working group.

For the evidence review report, the working group relied on its own knowledge of the literature and no additional requests were made to the Review Team.

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Working group

The working group members who wrote this report are listed at the start of the report.

Science writers

- Chad Baum, Aarhus University, Denmark
- Sean Low, Aarhus University, Denmark
- Livia Bianca Fritz, Aarhus University, Denmark

Peer reviewers

- Catriona McKinnon, University of Exeter, United Kingdom
- Ulrike Niemeier, Max-Planck-Institut für Meteorologie, Germany
- Stefan Schafer, Research Institute for Sustainability (RIFS), Germany
- Roland Séférian, National Centre for Meteorological Research, France

Expert workshop participants

- Dominic Lenzi, Twente University, Netherlands
- Duncan McLaren, University of California Los Angeles, United States
- Christine Merk, Kiel Institute for the World Economy, Germany
- Helene Muri, Norwegian University of Science & Technology, Norway
- Sebastian Oberthür, Brussels School of Governance, Belgium
- Keywan Riahi, International Institute for Applied Systems Analysis, Austria
- Alan Robock, Rutgers University, United States
- Isabelle Steinke, TU Delft, Netherlands
- Jean-Pascal van Ypersele, Université catholique de Louvain, Belgium

Members of the selection committee

- Marja Makarow, President of Academia Europaea, member of the SAPEA Board, Finland
- Paolo Papale, Class Chair of Exact Sciences, Academia Europaea
- Johannes Quaas, Leipzig University, Germany

- Benjamin Sovacool, Boston University, United States and University of Sussex, United Kingdom

SAPEA staff members

- Louise Edwards, Academia Europaea
- Rafael Carrascosa Marzo, Scientific Policy Officer, Academia Europaea Cardiff
- Céline Tschirhart, Scientific Policy Officer, ALLEA
- Toby Wardman, Head of Communications
- Alaa Jbour, Communications Manager
- Stephany Mazon, Scientific Policy Officer, YASAS
- Marie Franquin, Scientific Policy Officer, Euro-CASE (to month/year)
- Rúben Castro, Scientific Policy Officer, FEAM (to month/year)
- Rudolf Hielscher, Coordinator, acatech

Literature reviews, policy mapping and referencing

- Meg Kiseleva, Specialist Unit for Review Evidence, Cardiff University
- Frederico Rocha, European Information Service, Cardiff University
- Alice Sadler, Academia Europaea Cardiff
- Kate Bradbury, Cardiff University Library Services, Cardiff University
- Alison Weightman, Specialist Unit for Review Evidence, Cardiff University

Group of Chief Scientific Advisors to the European Commission

- Nebojša Nakićenović, Deputy Chair
- Eric Lambin, Member
- Naomi Ellemers, Member
- Nicole Grobert, Chair

Science Policy, Advice and Ethics Unit at DG RTD, European Commission

- Ingrid Zegers, Project Officer
- Bence Börcsök, Policy Officer
- Annabelle Ascher, Secretary to the Group of Chief Scientific Advisors
- Nikolaos Stilianakis, Policy Officer
- Jim Dratwa, team lead, European Group on Ethics in Science and New Technologies (EGE)
- Barbara Giovanelli, Policy Officer, European Group on Ethics in Science and New Technologies (EGE)

scientificadvice.eu
@EUScienceAdvice

Contact us
EC-SAM@ec.europa.eu

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