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Solar Radiation Management and Climate Engineering: An Essay[1]

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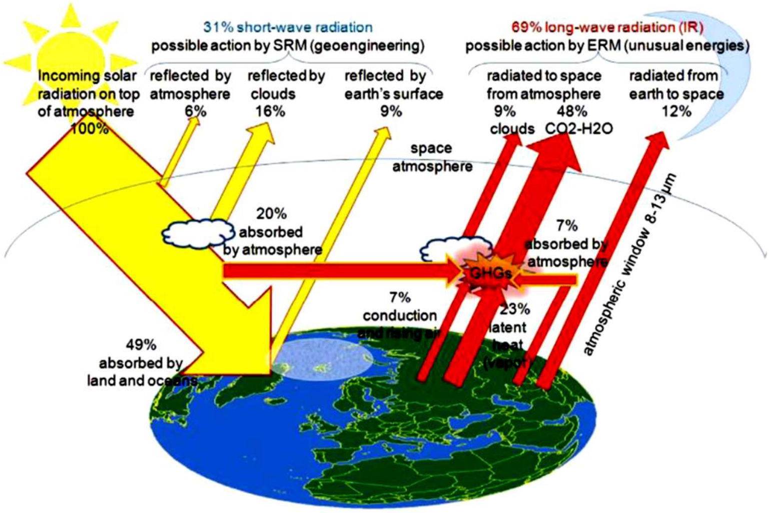

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[1] Copies or PDF file are available on request: Institut für Wirtschaftsinformatik, Leibniz Universität Hannover, Königsworther Platz 1, 30167 Hannover, Germany (www.iwi.uni-hannover.de). We summarize one Master thesis of the third author and two Bachelor theses of the second and fourth authors, all supervised by the first author.

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Abstract

We provide an overview of the governance design aspects Solar Radiation Management to mitigate the global climate change. Techniques to cool the global Earth climate reducing solar radiation are often not addressed in climate policy discourses due to their potential risk and uncertainties. To legitimize field experiments and find possible solutions for challenges of global regulation, it is necessary to engage in early deliberations and involve the global public. We have developed governance requirements based on literature and discussions to regulate stratospheric aerosol injection. A mini-lateral regime enables and short willingness of multilateral negotiations needed Solar Radiation Management and entailed global consequences. Low developed states are important since these are most affected by the consequences. A development of a regulatory mechanism mitigates or prevents risk. Research must be intensified, e.g., global climate simulations and labor and field experiments.

Keywords: Global Climate Change, Climate Engineering, Solar Radiation Management, Stratospheric Aerosol Injection, International Governance, Regulatory Mechanism

1 Introduction

Anthropogenic global warming and a series of subsequent changes in the climate system endanger the Earth. The effects are increasingly observable, with sea ice melting, heat waves, hurricanes and pandemics on the rise. In 2015, the Paris Agreement was adopted, exhorting that the Earth should not warm more than 2 °C above pre-industrial levels by the end of the century. According to UN Secretary-General António Guterres, the latest Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) is a "code red for mankind" (Guterres, 2021) and predicts warming of up to 3 °C with planned mitigation actions (IPCC, 2021). Concrete actions to reach the target are lacking and our thinking and actions are too slow. Greenhouse gases, mainly carbon dioxide (CO_2), must be significantly reduced and zero emissions targeted to slow the rise in average temperature. Familiar climate policy plans include switching to renewable energy and new mobility concepts, but it can be foreseen that these will not be implemented fast enough and will not be sufficient (UNEP, 2019). New, unconventional ideas are needed, such as Climate Engineering and the associated Solar Radiation Management. Artificial intervention in the climate, in the form of reflection of solar radiation or removal of CO_2, is intended to stop global warming (Keith, 2013). The IPCC also considers CO_2 removal in projections of the 1.5 °C increase target unless CO_2 emissions drop dramatically by 2030 (IPCC, 2018).

Technologies, which have been under active discussion for about fifteen years, bring with them a lot of research questions and uncertainties. Their perception is negatively loaded, mainly because a "natural" solution to the climate problem is more desirable. But the issue deserves closer scrutiny because we are running out of time to avert climate catastrophe and some of the Climate Engineering measures have a high potential (Keith and Caldeira, 2010). In particular, stratospheric aerosol injection offers unlimited potential (Keith, 2013). We address the following research questions:

RQ 1: How international governance can be designed to enable policy based Solar Radiation Management, particularly stratospheric aerosol injection management?

RQ 2: Which regulatory and technical measures reduce the stratospheric aerosol injection risk?

A formation of efficient governance for Solar Radiation Management is necessary to prevent or mitigate risk (Parson & Ernst, 2012). In particular, policy implications need to become more of a focus for governance research. Deployment is inevitably intertwined with climate policy and research on the feasibility, impacts, and potential risk of the techniques must be advanced and a legal framework for research developed (Horton, 2011). Finding institutions and standards that address the regulation of Solar Radiation Management is a difficult and lengthy process that must be started in a timely manner to prevent hasty regulation and to preserve international security. We first highlight the challenges of governance formation from which requirements are

derived. Based on various moral values and principles, existing institutions and regulations are assessed for their suitability for regulation and requirements for an international legal framework are defined. The extent to which public involvement is necessary and possible and how international disputes can be addressed are discussed. Our second focus is an under-researched aspect of Solar Radiation Management. An important one, because without regulatory and control mechanisms, deployment of technologies is negligent. Our focus is on a technical regulatory mechanism that supports risk minimization. Much of this can be estimated in advance through simulations: the extent to which these are valid and the uncertainties that exist in computer modeling are discussed. Research into the subsequent adjustment of stratospheric aerosol injection measures, is hardly part of the existing literature due to the risk of an abort response with devastating consequences. To provide approaches for research, scientific publications are analyzed that discuss ways to neutralize the effects of stratospheric aerosol injection measures.

2 Theoretical Background and Hypotheses

2.1 Climate Change and the Earth's Climate System

In 2020, the global mean temperature was 1.2 °C above pre-industrial levels and the decade from 2011-2020 was the warmest decade on record. The CO_2 concentration rose to 410 ppm (parts per million) and, like the temperature trend, indicates a steady increase in the future (WMO, 2021). To an increase in extreme events, the rising global average temperature has resulted in a rise in sea level, a threat to biodiversity and ecosystems, among other things. These consequences have a negative impact on food and water supplies, livelihoods and human health (IPCC, 2018). Anthropogenic greenhouse gas emissions, e.g., are driving ocean acidification, increasingly threatening the resilience and viability of natural ecosystems on whose existence mankind depends (Chapin et al., 2002). There is a high degree of dynamism between the impacts of climate change. E.g., rising sea levels lead to a higher incidence of storm surges and flooding. In the context of the relationships of climate change impacts, scientists also speak of so-called tipping points. These refer to a time when global warming has progressed to such an extent that certain climate processes can no longer be stopped. E.g., when permafrost soils melt, they release large amounts of carbon because they store almost twice as much CO_2 as the atmosphere (Lenton et al., 2008). CO_2 is both an amplifier and a trigger for global warming. This is because CO_2 emissions are directly related to the strength of the greenhouse gas effect. Trace gases absorb a large part of the infrared radiation emitted by the Earth, as a result they warm themselves and emit long-wave radiation back to the ground. In order not to exceed the 2 °C increase limit, the world must become climate-neutral by 2050, which means that no more emissions may be emitted. This requires above all a turnaround in the mobility and energy sectors. It is foreseeable that these efforts will not be made in time and that the effect will not be sufficient (Lenton and Vaughan, 2009).

2.2 Climate Engineering

Climate Engineering describes the targeted artificial climate intervention and includes various measures to counteract anthropogenic climate change. A basic distinction is made between Solar Radiation Management and CO_2 removal measures. Radiation management can be further subdivided into Solar Radiation Management and Thermal Radiation Management. The key difference between CO_2 removal and Solar Radiation Management is that the former targets the polluters of global warming, i.e. CO_2 and also other greenhouse gases, and the latter mitigates the main symptom of climate change, the rising average global temperature. Solar Radiation Management affects the Earth's radiation balance and is a subcategory of radiation management. In contrast to Thermal Radiation Management, which aims to increase longwave radiation, Solar Radiation Management reduces incoming shortwave solar radiation, i.e. incident solar radiation is thrown back into space (Keith, 2000). CO_2 removal deals with the removal of CO_2 from the atmosphere in order to reverse anthropogenic emissions. One can divide the measures into three categories. First, it is possible to increase CO_2 uptake capacity through, e.g., reforestation, coastal restoration, or ocean fertilization with iron, nitrogen, or phosphorus (DFG, 2013–2020). Second, there are the much less researched BECCS (Bioenergy with Carbon Capture and Storage) technologies, which produces energy and sequesters CO_2 burning biomass (Kemper, 2015). The IPCC's Fifth Assessment Report already highlights BECCS as an important method for achieving the 2 °C increase target (IPCC, 2014). Third, there are direct air capture technologies. CO_2 is extracted and captured directly from the air (Lenton and Vaughan, 2009). Following, CO_2 removal is not discussed in detail, since today none of the techniques is advanced enough to have the required removal capacities to negate the yearly emitted CO_2 (Battisti et al., 2009).

2.3 Solar Radiation Management

Solar Radiation Management affects the Earth's radiation balance balancing the radiative forcing from greenhouse gases. Radiative forcing is a parameter for changing the Earth's energy balance and is measured in W/m^2 (IPCC, 2013). Measures can be categorized according to where they are deployed. E.g., there are techniques that are intended to be used on the Earth's surface, in the stratosphere, in the troposphere, and in space (Shepherd, 2009). Reflectors can be deployed in space at altitudes above 400 km. They act as a "sunshade", either in the form of a thin film in Earth orbit or as a screen in solar orbit. E.g., due to logistical challenges of how to get the materials into orbit and how to fabricate such a large disk these Solar Radiation Management proposals are unrealistic (MacCracken, 2006). A stratospheric aerosol injection plans to inject aerosols into the stratosphere and thus at altitudes of 10 to 50 km (Robock, 2014). The atmospheric layer where weather phenomena occur is called the troposphere. It is also the place where the modification of cirrus clouds can take place (Latham et al., 2008). Measures that can be carried out at the Earth's surface include, e.g., modification of the Earth's surface albedo. Albedo stands for the "whiteness" or "brightness" of a surface. One implementation of this idea is to paint roofs white (Oleson et al., 2010). Currently, Solar Radiation Management techniques are in the computer modeling phase, but a first field experiment titled "SCoPEx" is planned for 2022 (Smith and Henly, 2021).

2.4 Stratospheric Aerosol Injection

The idea of cooling the climate with the help of aerosols in the stratosphere can be traced back to volcanic eruptions. In 1991, e.g., the volcano Pinatubo, Philippines, heavily erupted and injected 10 Mt S into the atmosphere, which likely caused the Earth to cool by 0.5 °C (Crutzen, 2006). In the past few years, research has intensified, but current research is almost exclusively in the context of computer simulations, theoretical studies, ethics, and social sciences (Caldeira and Bala, 2017). Aerosols reflect some of the sun's radiation back into space and enhance the properties of clouds to reflect shortwave radiation. The potential of these technologies is immense, e.g., global warming can be reversed under its application, totally. Crutzen (2006) estimates cooling at -0.75 W/m^2 (negative radiative forcing) per Mt S and estimate $ 25 billion cost to transport it to the stratosphere. Over the years, estimates for the amount of Sulfur needed have been revised upward and the expected residence time has been revised downward (Rickels et al., 2011). Aerosols must be indexed to the stratosphere because they have a longer life expectancy of one to two years there than, e.g., in the lower troposphere. A globally uniform application of aerosols is recommended, as several research studies have shown that this can reduce negative impacts, such as changes in precipitation and surface temperature (Kravitz et al., 2017). The amount of Sulfur needed depends on what the maximum global warming target is at the end of the century compared to pre-industrial levels. Current estimates suggest 12 Mt S per year to reduce radiative forcing by 2 W/m^2 and limit warming to 1.5 or 2 °C (Niemeier and Timmreck, 2015). Once injection is initiated, deployment must be continued to maintain the cooling effect (Parker and Irvine, 2018). Several approaches exist for conducting aerosol transport to altitudes of approximately 20 km. The least expensive, most efficient, but also most risky method is aerial dispersal. New efficient aircraft must be developed to be remotely controlled and to meet both the altitude requirements and the required payload capacities (Rasch et al., 2008).

3 Research Design

Our investigation of the research questions RQ 1 and RQ 2 is based on an extensive literature and WWW review. Our publications brought three typical criteria to ensure adequate, high-quality summary and analysis of those, i.e. relevance, precision, and methodological coherence. Six typical steps for the literature and WWW review proved useful, i.e. formulation of the problem, literature search, investigation of their receptivity, evaluation of quality, data extraction, and analysis and synthesis of data. The goal was to create new knowledge insights, interpret them and come to valid results and conclusions (Templier and Paré, 2015). Explaining the problem under investigation, the need for the research is emphasized. The purpose, process, and concept are explained in the process (Watson and Webster, 2002). In the context of our research questions, appropriate literature must be selected that offers different approaches to the topic. Especially in research around appropriate governance, it is important to clarify not only the tasks, goals, and moral values and principles, but also, e.g., the question of public involvement. Ethical, conceptual, political, technical and economic research areas overlap, so an extensive literature and WWW review was essential. The narrative literature and WWW review, which summarizes and compares multiple research findings and makes empirical claims, is appropriate to address the first research question RQ 1 given the large number of publications that provide suggestions for Solar Radiation Management governance. The investigation of a possible technical regulatory mechanism requires the creation of new approaches that go beyond the existing literature and provide a basis for future research. Thus, one can speak of a “developmental review” (Templier and Paré, 2015) that complements the narrative literature and WWW review.

4 Challenges for Research and Governance-Building, Tasks, and Goals

4.1 Environmental Risk of Stratospheric Aerosol Injection

The main reason why stratospheric aerosol injection has not yet reached the level of research and public acceptance that proponents hope for the risk multitude that the technologies entail, the extent of which can only be assessed to a limited extent. Only a few years ago did scientists begin to assess the negative impacts using simulation (Robock, 2016). Their accuracy is not assured due to lack of knowledge about microphysical properties and global distribution. The following negative impacts represent a consensus of various experts and their occurrence is very likely. It is likely that the Earth cools unevenly, so as the tropics cool, warming of more northern latitudes can occur simultaneously because atmospheric circulation can change (Benduhn and Niemeier, 2014). Stratospheric aerosol injection also impacts precipitation by causing regional differences and decreasing it in its entirety. Another concern is that Sulfur aerosols promote Ozone depletion because they act as catalysts for chemical reactions. This results in an increase in dangerous ultraviolet radiation (Heckendorn et al., 2009). Simulations estimate the effect to be only a few percent because, compared to the Pinatubo eruption, as a result of which damage to the Ozone layer was observed, high amounts of halogens cannot be applied during stratospheric aerosol injection (Benduhn and Niemeier, 2014).

4.2 Challenges of Governance Formation

The deployment of Solar Radiation Management technologies presents a particular challenge for a policy framework. First, there is still a high uncertainty risk, especially compared to traditional emissions reduction measures (Lloyd and Oppenheimer, 2014). This uncertainty, that extreme impacts are also possible, promotes bias among states in the context of discussing potential Climate Engineering deployments and increases the likelihood of international conflict (Parson and Ernst, 2013). The potential for political conflict is fostered by differential benefits. The higher private benefits and the larger the differences in negative impacts between states, the more likely negatively affected states will seek countermeasures (Dovern et al., 2015). How can an international consensus for deployment be found, if Solar Radiation Management has such regionally diverse and sometimes devastating consequences? What average temperature should be targeted and who decides? At this point, the legality of stratospheric aerosol injection also must be addressed. Without this, exploration or deployment is not debatable. Legality under international law must be assessed and whether existing treaties are violated. To date, no legal framework exists that regulates the use of stratospheric aerosol injection. In principle, any state is allowed to apply SO_2 aerosols, but just because it is legal does not mean it is an unrestricted right

(Horton et al., 2015). There will be large disagreement due to conflicting interests. After analyzing likely impacts of a Solar Radiation Management deployment, a country can object, if it fears to generate or receive more harm than benefit compared to other states. E.g., a coastal state can fear economic problems and food shortages if ocean acidification were to increase as a result of Climate Engineering. Not only interests are a reason for resistance, but also values such as religion, culture or philosophy (Szerszynski et al., 2013).

4.3 Tasks and Goals

Governance must protect against potential harms and risk and thus must enable research and development to assess that risk, but also discuss opportunities (Long et al., 2015). At the same time, it is necessary to involve the public to legitimize research, pursue accountability and ensure transparency (Nicholson et al., 2018), because potential risk is an important driver of public perception (Mercer et al., 2011). Transparent communication builds trust, if the information is understandable, a clearly identifiable actor can be named for the communication and sufficient fairly distributed resources exist for the information. In a communication program around Climate Engineering consequences and risk must be weighed first, because they can be put into perspective compared to the promising opportunities. The goal is not to create acceptance, but to help the public form judgments and opinions in such a way that they can be based on facts (Renn et al., 2011). The question arises to what extent the goals of public participation can be met. One suggestion is to educate within deliberative workshops about the consequences of anthropogenic climate change and explain possible options to combat it, including Solar Radiation Management (Bellamy, 2016). Another option is discourse within multiple focus groups that address possible political, technical, social and personal consequences (Macnaghten and Szerszynski, 2013). It is important to start the discourse as early as possible, before opinion formation becomes increasingly distant from the scientific and political process. The risk of moral hazard can be mitigated with education of society (Preston, 2013). Public involvement is also important during a deployment, e.g., the state implementing Solar Radiation Management measures must communicate potential risk to affected states. Constant information exchange to provide affected states with the most up-to-date information and receive feedback from them regarding damage is essential to best minimize and control damage (Flegal et al., 2019). In the early stages of project planning for a deployment, it is recommended to conduct a "Strategic Environmental Assessment", which can be found in the Espoo convention, to assess risk as early as possible. The assessment is conducted at the policy and planning level and includes the review of environmental impacts, the identification of assessment priorities and what mitigation measures are available (The European Parlament, 2001).

The main challenge in this process is the inclusion of vulnerable "Global South" states, such as Africa, which have the most to gain from the use of Solar Radiation

Management, but also the most to lose. Efficient implementation of public engagement policies faces several challenges. What opportunities developing countries have to make their voices heard or be more involved in the process will be explored in more detail in this discussion.

4.4 Moral Values and Principles

To transparency mentioned above, governance must be based on equity, flexibility, participation and accountability, the foundation of good governance. Equity concerns, on the one hand, the generational conflict, to what extent we owe it to future generations to stop climate change and what advantages and disadvantages follow for which generation through the use of Solar Radiation Management. But the governance of research and deployment must also be equitable. This is especially difficult because the balance of power and distribution of resources is very uneven around the world. Vulnerable populations must not be left out of the discussion. Anticipating and adapting to changing geopolitical circumstances and new information requires a high degree of flexibility. Governance institutions must evolve in parallel with research so that they do not lose touch with technological progress. Participation promotes responsible decision-making and is an integral part of democratic governance. Last, accountability serves to act in the public interest. Holding policymakers and researchers accountable means that the public guides governance and research decisions (Chhetri et al., 2018). The Oxford Principles, which were developed by a group of British academics, also refer to a part of these standards. The first principle states that Climate Engineering must be regulated as a public good. The goal is to promote the common good because there is a collective interest in a stable climate. At the same time, although benefits may vary, no one (or only very few) may be worse off than before the measures were taken. Or those who are particularly harmed are compensated. The ultimate interpretation offers many possibilities. Second, Rayner et al. (2013), also like Chhetri et al. (2018), emphasize the need for public participation in decision making, appealing to the "everyone affected" principle. E.g., all people affected by the impacts must to be carefully considered planning and conducting a field experiment. Questions arise whether to give veto rights to certain groups of people and how and whether to enable meaningful global participation in decision-making. The third principle calls for publication of all research plans and results to enable risk understanding. Even though the public has no direct decision-making power, it is a sign of recognition and no doubts of paternalism are raised. The fourth procedural standard proposed is independent of impact assessments. These can be conducted by funders, research organizations, governments, or international bodies. Implementing this accountability-based recommended course of action involves many decisions, such as which impacts to assess and how to ensure that the review body is independent. The final principle cited is the need for governance prior to the deployment of Solar Radiation Management measures. Especially if a large field experiment were to be conducted, the scale of which is equivalent to a deployment, the importance of this principle becomes apparent. The goal of the five principles is not to provide specific guidance for action, but to establish a framework for decision-making and the formation of a flexible architecture (Rayner et al., 2013).

4.5 Social, Legal, Environmental and Economic Responsibility

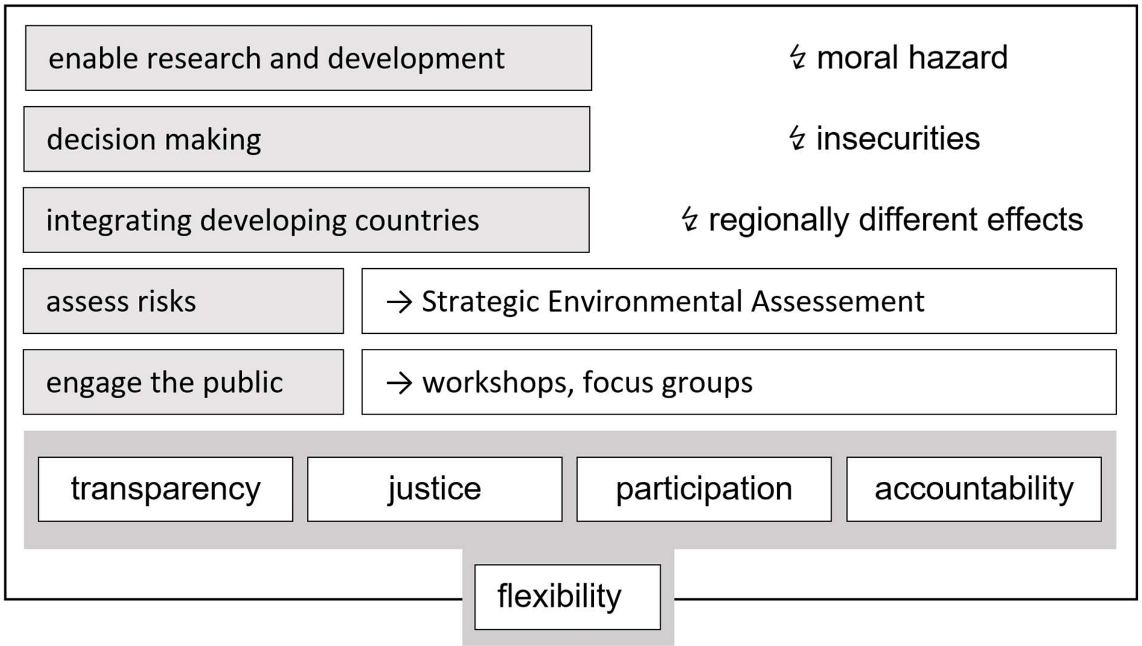
Climate Engineering is a question of intergenerational justice. The current generations on Earth are able to still live without severe constraints caused by the climate change. Leaving a planet behind that is not able to sustain the life of further generations is contradictory to the principle of intergenerational justice. Suppose there are Climate Engineering methods installed: What happens, if they conflict with other aims such as the 17 UN Sustainable Development Goals? Who has the power to evaluate whose life is more important, that of the current or that of the future generations? Is it okay to demand for constraints in the society to save the whole planet, which for many individuals is more of an abstract construct compared to their own life (DFG, 2013–2020)? Should it be allowed that a group of states, an organization or anyone else can make a choice that affects other nations or the whole planet (Hegerl and Solomon, 2009)? This question is even more important given the fact that the negative side-effects of Climate Engineering methods are more likely to affect these states which are already more affected by climate change. Even if there is an international collaboration regarding the implementation of Climate Engineering, how should voices be allocated? Another question is what the does society want to achieve with Climate Engineering? Should it be an alternative to mitigation, or should it be used to "buy time" for reducing CO_2 emissions and convert the energy and transportation sector to greener alternatives? It has different consequences for future generations. Is it okay to burden future generations with the maintenance of possibly large-scaled interferences in the climate system (Battisti et al., 2009)? Is there a difference between a deliberate modification of the climate and the right now happening unwittingly interference in the climate system through the emission of greenhouse gases? Should mankind be allowed to perform Climate Engineering at all? Answering these questions is beyond our scope. However, it is important to discuss them carefully and publicly and also both in theory and practice. Climate Engineering is also a question of legal nature. There is currently no legal framework to the topic of willfully modifying the climate system. Some individual methods are subject to already existing international treaties due to their nature of interference in the system. Already existing frameworks, e.g., the London Protocol for safety of marine ecosystems, can only be used to evaluate some of the methods, but not all (DFG, 2013–2020). As most of the Climate Engineering methods directly influence many other states globally, an internationally binding legal framework is needed in order to resolve upcoming issues with respect to the performed measures. Such a framework will be bound to several barriers. Not all of the side-effects of Climate Engineering can be foreseen, so there is the question of how to deal with them later on. The expected effects are very heterogeneously distributed across the planet. How can this be respected in the framework? Are financial compensations sufficient to offset the side-effects? If yes, how can they be measured and monetarized? Who is responsible in case of a legal dispute and how can it be guaranteed that the suffering of a country is triggered by a specific Climate Engineering method (Bodansky, 1996)? After a first willful modification of the climate, there can be a precedent case where weather events such as storms will be attributed to the methods in place and no longer be seen as normal phenomena. This opens a door to needless legal disputes that can be counterproductive in the effort to stop the climate change (DFG, 2013–2020). In order to coordinate research efforts and implement Climate Engineering methods, an international organization has been suggested. Although there are some examples for working international organizations like the International Atomic Energy Agency or the World Health Organization, which was able to eradicate smallpox through international collaboration, none of the existing ones has the power an international climate organization needs to efficiently work. Such an organization needs to be allowed to intervene within a country's sovereignty (Barrett, 2008; Battisti et al., 2009). Establishing such an organization is difficult. It is unlikely that states give up own decision-making power for a "global or multi-national goal". Even if some states join, what happens to the other who do not? It is obvious that they cannot be forced to join. As such, is it enough, if most of the Earth's states collaborate to be allowed to perform Climate Engineering? Another idea is to establish international legal guidelines inspired by already existing frameworks to allow every country its own research and implementation of methods. Blueprints for such guidelines are, e.g., the UN Environment Program for Weather Modification or the UN Framework Convention on Climate Change. Creating such a guideline is easier compared to the formation of an organization, but it has less power. There is still the need for a supervising body in order to prevent inefficient parallel research and control implemented Climate Engineering measures. There must be a legal handle for states who do not comply with the guidelines (Bodansky, 1996). While establishing an international framework for Climate Engineering is difficult, letting every country choose its own policy and actions is an alternative. Valuable resources, especially time, are lost, as the combination of efforts is more efficient. What happens, if one country starts to perform Climate Engineering and another suffers from it? Unilateral Climate Engineering projects can lead to political tension (Keith, 2000). There is a need for a legal background in the Climate Engineering research. Hubert suggests a Code of Conduct for Responsible Geoengineering Research. This can be a blueprint for establishing a legally binding framework in order to minimize risk and increase clarity about what is ethically allowed in Climate Engineering research. E.g., it highlights the importance of transparency within the research so that negative consequences can be better understood and possibly affected states can intervene before practical tests are done (Hubert and Reichwein, 2015). The lack of such a framework can reduce the effort in research as it is not clear if results are ever contributed to find a solution for climate change (Bodansky, 1996). As the cause of climate change, mankind has a responsibility towards the environment to counteract it in some way. Every negative effect of climate change must be carefully considered. Currently, global warming is the major concern, but the acidification of the oceans together with the changing weather system need to be regarded more intensely as well (Hegerl and Solomon, 2009). In order to completely reverse the climate change, mitigation efforts must not be reduced only because faster and easier methods weaken the worst symptoms. For the global environment, a restoration of the pre-industrial situation is the best (DFG, 2013–2020). A proper control and monitoring of the mitigation and Climate Engineering methods is needed. This is especially important for the latter and for Radiation Management measures in case of unforeseen side-effects to not worsen the situation for the environment (Battisti et al., 2009). If natural non-regenerative resources usage is reduced, the use of regenerative resources must not exceed the Earth's capacity to restore them in order not to increase the stress on the environmental ecosystems. The willful modification of the climate triggers extensive changes in some ecosystems taking away their natural character. With climate change this already happens and Climate Engineering can help to restore their natural character (Keith, 2000). It is clear that the worldwide economy will suffer from the effects of climate change. Given that several of its effects affect the whole planet, large amounts of money must be invested in finding a solution. This begins with a sufficient financial support for research efforts in mitigation techniques, CO_2 emission reduction and Climate Engineering and ends with the financial compensation of the people and states which suffer most from climate change. Comparing Climate Engineering mitigation cost and climate change cost, the more economical choice is to prevent the climate change from further damaging the planet (MacCracken, 2006). When it comes to financing Climate Engineering methods, there is the question of who should burden the cost? Depending on the selected methods, cost can easily exceed the capacity of rich countries or state unions. As industrialized countries are mainly responsible for the climate change it is justified that they pay most of the cost (Barrett, 2008). Economic arguments are often the basis for decision-making in societies and politics. But, it must be asked if this is useful also for the problem of climate change. Is the survival of the whole planet really monetizable, or is finding a solution regardless of cost and of negative impacts for the worldwide economy more logical?

4.6 Agreements and Conventions

The UN Framework Convention on Climate Change (UNFCCC) encourages parties to mitigate climate change and promotes research into new technologies (United Nations, 1992). At the same time, they are supposed to prevent transboundary environmental damage and developing and industrialized countries are supposed to make concerted efforts against climate change despite their different capabilities and responsibilities.

This also implies that industrialized countries make a larger contribution to the development of new technologies (UNFCCC, 2006). The Kyoto Protocol concluded under the UNFCCC is intended to facilitate the achievement of the ultimate goal. It calls on parties to advance research of innovative techniques, although this call can only be related to the development of CO_2 removal techniques (Bodansky, 2013). The Paris Agreement was adopted in 2015 as part of the 21st UN Climate Change Conference and includes three main climate policy goals: limiting global warming to a maximum of 2 °C, increasing adaptation to climate change, and climate-friendly finance. To ensure implementation of these, climate policy is composed of individual nationally determined contributions. Through these, states are given more autonomy to determine the level and form of commitments. This represents a new architecture of international cooperation in the fight against climate change, referred to as a bottom-up structure (Dröge, 2015). Under the Paris Agreement, Climate Engineering has not yet been discussed as a measure to achieve climate targets, although CO_2 removal has at least been included as a measure to reduce greenhouse gases. Solar Radiation Management measures are not compatible with the articles, but mechanisms can be used to provide transparency and public discourse (MacMartin et al., 2018). Parties to the Convention on Biological Diversity (CBD), on the other hand, have taken small and early steps to regulate Solar Radiation Management. In a moratorium, the parties are in favor of not implementing large-scale Climate Engineering measures for the time being, because efficient regulation and control mechanisms are still lacking. Only if risk to biodiversity and the environment has been sufficiently researched through scientific studies the moratorium can be lifted. However, they support small-scale field experiments, provided that also potential risk is considered, thus pointing to the need to fill the research gaps (Reynolds, 2019). In 2012, the parties to the convention additionally agreed to establish an information-sharing mechanism. The London Convention refers to the 1972 Convention for the Prevention of Marine Pollution, which was modernized in 1996 with the issuance of the London Protocol. In 2008 and 2010, the parties positioned themselves against methods of marine geoengineering, particularly ocean fertilization to increase carbon removal. In 2012, they explicitly banned the measures, except for approved, legitimate research. While the convention does not affect Solar Radiation Management, it is an example of international coordination of Climate Engineering measures (Talberg et al., 2018). The Convention on the Prohibition of Military or Any Hostile Use of Environmental Modification Techniques (ENMOD Convention) was concluded in 1977. Environmental modification techniques are defined as those that alter the structure or composition of the Earth through deliberate manipulation of natural processes. Given this definition, Solar Radiation Management measures fall under this term. States are prohibited in the first article from assisting other states, groups of states, or international organizations in the use of these if the effects of the techniques have severe and widespread adverse consequences for other states parties. If, on the other hand, the use is for peaceful purposes, the use may not be hindered, provided that it complies with the principles and rules of international law, in particular the principle of prevention (McGee et al., 2021). From this also follows the obligation in the convention to exchange information between states on peaceful modification techniques. Ultimately, the ENMOD Convention's prohibition on environmental modification techniques does not apply to Solar Radiation Management techniques unless they are used for hostile purposes (Bodle et al., 2012).

5 Discussion, Implications, and Recommendations



Above are the results and findings on the moral values and principles, challenges, tasks and goals of Solar Radiation Management governance. Transparency, justice, participation, accountability and comprehensive flexibility are the basic principles. The five tasks on the left are the most important issues that governance must address. To assess risk, the Strategic Environmental Assessment is recommended and to involve the public, workshops and focus groups are good options. The three most important challenges are moral hazard, uncertainties, and regionally different consequences and thus different interests of different states.

5.1 International Regime Structure

How can an international regime structure be created that meets the requirements that have been identified? Three approaches to this are discussed below: Unilateralism, Minilateralism, and Multilateralism. Unilateralism refers to any action that a state takes independently, with minimal involvement of other governments. It finds justification in the sovereignty of each state to act unilaterally. But, the actions of one state may directly affect another and thus conflict with the sovereignty of the other state. Consequently, unilateral action may be less desirable than multilateral action, which fosters mutual understanding and negotiation between states. Unilateralism can lead to international tension and conflict when one state must bear harm to the benefit of the acting state. It can also intend to promote common goals, especially in solving environmental problems, where multilateral action and international cooperation are often inefficient. At the same time, there is always a risk of instability in the international system (Böhringer et al., 2012). States can claim Solar Radiation Management interventions have harmed them and even imply disregard for their interests or hostile intentions. It is unlikely that a government can take Climate Engineering measures on its own without the objection of affected states. Focus of Solar Radiation Management governance must be on improving cooperation among states in decision-making, rule-making, and implementation (Urpelainen, 2012). By bringing in a small number of participants who can have the largest influence in resolving problems, minilateralism proposes a more responsive governance structure than multilateralism. The goal is largely exclusive agreements. In international climate policy this is an obvious approach because fewer than twenty states are responsible for more than 80% of the world's greenhouse gas emissions and these must make a larger contribution to emissions reductions. It is also predominantly these states that have the technical resources to produce innovations in the fight against climate change (Eckersley, 2012). In practice, it has been proven that the more states are involved in a negotiation, the less common interests can be found. From the perspective of climate policy, multilateral cooperation is difficult because the interests of the states are very different. High latitude states can welcome global warming, e.g., because it has a positive impact on their agriculture. A suitable number of participating states can be around twenty (Gosling and Naim, 2009). This is also evident in the distribution of greenhouse gas emissions responsibilities in the twenty members of the group of major industrialized and emerging countries (G20). Although coordinated action can be taken quickly with this small number, the legitimacy problem remains due to the exclusion of other states. In the case of the Solar Radiation Management, affected states possibly can be left out of the decision-making process (Zürn and Schäfer, 2013). Minilateralism seems impractical for Solar Radiation Management in the long term because the damage is global and states are inevitably disadvantaged. As a flexible and strong cooperation model, it can be used in the short term if a multilateral agreement is not achievable. It can also facilitate political dialogues that have a positive impact on the cooperation climate for multilateral negotiations. Especially, if sub-national and non-state actors form a vanguard alliance, they have a lot of potential in international climate politics (Brandi et al., 2015). Compared to minilateralism and unilateralism, multilateralism represents an inclusive approach to equal participation of states and thus enjoys higher legitimacy. Multilateral governance can allow for international oversight of Solar Radiation Management measures. International cooperation is essential, especially during implementation, because, e.g., termination shocks must be prevented. Such governance does not imply a global consensus of all states. Rather, potentially affected states can be included, including in particular the most vulnerable states (Parker, 2014). Since multilateralism is the most promising approach in the discussion of possible governance, the design of a decision-making process will also be addressed before concrete design options are discussed. After all, decision-making of a regulatory and operational nature in research and risk assessment is part of the main tasks of a governance system. In contrast to purely political decision making, governance must have a predominantly scientific character, because the assessment of planned climate interventions is necessarily based on the assessments of scientists. For the objectives and tasks, a decision-making process must be developed which processes, transparency and participation appear legitimate. In order to mitigate the expected climate change risk with the help of Climate Engineering measures and not cause larger negative consequences, decisions must be made competently and thoughtfully. This includes weighing at what point intervention is necessary, but also decisions that must be made reactively during the response to potential unforeseen impacts. Collaboration between political decision-makers and a technical or executive institution that monitors the deployment and its effects, as well as responds to unplanned events, is important to provide independent support. It is foreseeable that as the scale of interventions increases, scientific judgments will lose weight in decision making and regional and national interests will come to the fore (Parson and Ernst, 2013).

The UN Environment Programme (UNEP) was established in 1972 at the UN Conference on the Protection of the Environment. Its purpose is to provide general policy guidance for the implementation and coordination of environmental measures and to promote international environmental cooperation (Ivanova, 2007). Negotiating and regulating Solar Radiation Management measures within the UNEP framework is appropriate for several reasons. First, UNEP has experience of multilateral negotiations and in developing legal and policy instruments for international environmental protection. The organization can identify environmental challenges early and, providing scientific and policy input, develop moral values and principles that later lead to informed negotiations. Limited government power and potential conflicts with other UN bodies are obstacles (Burns, 2011). UNEP can mediate, bring together international institutions and coordinate discussions because of its central position in global environmental governance. Discussions on Solar Radiation Management can take place within the combined framework of the CBD, the London Agreement, and the UNFCCC. UNEP is also in a position to promote public involvement early on and relies on the principle of sharing information transparently (Nicholson et al., 2018). The UNFCCC is also a potential framework for regulation. It is the most experienced, inclusive and legitimate body to address the threats of climate change and the purpose of Solar Radiation Management measures align with the UNFCCC's objective. The convention can regulate research and deployment of Solar Radiation Management techniques in a new protocol with an adaptive management mechanism. This mechanism operates through a stepwise decision-making process that adapts to changing conditions (Lin, 2020). But the proposal seems unrealistic because of the high effort required in the negotiation process to adopt a binding document. Criticism is also expressed about the fact that the inclusion of Solar Radiation Management can distract from mitigation and adaptation efforts. The consensus-based decision-making processes and universal participation within the UNFCCC can also stand in the way of responsive action. It seems premature to include Solar Radiation Management measures in the portfolio of climate change mitigation strategies under the UNFCCC, but it also seems wrong to ban them (Virgoe, 2009). The high number of members is problematic, i.e. the UNFCCC currently has 197 member states, which makes it difficult for them to act. Lloyd and Oppenheimer (2014) advise against discourse at the UNFCCC and the UN General Assembly. Another criticism on their part is that the regimes are a less efficient mechanism due to the high heterogeneity. The researchers propose the design of a temporary international regime consisting of a small number of states to lead the research and deployment of Solar Radiation Management. Small groups have the advantage that decision making is easier and they are more realistic to implement. Lloyd and Oppenheimer propose a regime consisting of a maximum of thirty states, today. They establish other characteristics to ensure efficiency. They advocate a tie vote and a right of veto for members. Flexibility with regard to future reforms and weak legalization are intended to facilitate decision-making. It must be possible to increase the number of members as research progresses. It must also include states that cannot use Solar Radiation Management technologies themselves but are particularly affected by the consequences, such as Bangladesh. The regime exists with the goal of delaying the deployment of Solar Radiation Management and advancing research. It is important that it is an independent international organization with its own membership. It is also possible to have subsidiary scientific bodies responsible for technical assessment, as is the case with the UNFCCC. The practical legitimacy must also be guaranteed, i.e. that the members accept and comply with the moral values, rules, and principles. Because Solar Radiation Management involves highly uncertain conditions, states are reluctant to enter into strongly legalized commitments. In order to bind states to the commitments despite weak legalization, rules in case of non-compliance with the agreements and to choose a voting process that guarantees unambiguous agreements must be provided. Looking at past arms control treaties, it can be concluded that treaty negotiations must be early started. In this way, a more efficient treaty can be concluded before individual interests grow too strong and result in complex, rather inefficient treaties (Lloyd and Oppenheimer, 2014). An alternative is treatment under the CBD. This has already done preliminary work on Solar Radiation Management and offers a variety of treaties to prevent environmental damage. But the conference of the parties currently treats Solar Radiation Management only as a potential threat and does not address the opportunities of the techniques. The scope for developing such techniques is limited, if the CBD plays the lead role in regulating them. That the objectives of the CBD differ from those of the UNFCCC can lead to regime conflicts if a treaty is inconsistent with both (Parker, 2014). In contrast to the idea of regulating Solar Radiation Management measures within one regime, the techniques can be addressed separately in different pre-existing regimes. Their differing objectives make uniform regulation difficult and tend to promote inconsistency and fragmentation between particular regimes. On the other hand, Solar Radiation Management measures risk that cannot be adequately addressed by a single existing regime. Polycentric governance has key advantages, including the sharing of responsibilities and cost, the ability to leverage broad-based institutional resources, and broad participation. It is important to conduct all negotiations in one forum to ensure targeting (Biermann et al., 2009). In the debate about which legal framework is most appropriate, the dimension of the obligation must be taken into account. There is non-binding and binding law. For Solar Radiation Management governance, a binding framework agreement lends itself to establishing general moral values and principles and basic obligations, such as the obligation to avoid transboundary damage and to act prudently. Treaties are the primary forms of binding law, imposing obligations and conferring rights on contracting parties and some of them establish process mechanisms for interpreting and applying obligations and noncompliance. Binding law thus makes government commitments more credible because it increases noncompliance cost. As the need for regulation increases, it becomes less responsive because of the complexity of adopting changes and the time needed for them to take effect. Negotiation cost are reduced compared with nonbinding law. Nonbinding moral values and principles can also contribute to efficient enforcement and lawmaking because they still involve a good faith obligation. Accordingly, binding rules are more desirable, if the consequences of non-compliance are severe. Non-binding rules are preferred, if these consequences are weak and ambitious cooperation is sought (Dupuy, 1990). Non-binding rules also allow for faster response and results, which is beneficial in terms of expected findings (Reynolds, 2019). Uncertainty makes the formulation of precise rules fundamentally impossible, but adjusting the precision of contract provisions is a solution in dealing with uncertainty. Formulating less ambiguous content and wording of a binding instrument offer a rational adjustment to uncertainty and may increase the willingness of states to engage in collaborative (MacMartin and Kravitz, 2019).

Least developed countries most likely will suffer from a Climate Engineering effort. What opportunities do they have and how can they be more involved in the process? Least developed countries demand better participation in conferences and meetings, as well as financial resources needed to do so. This idea is pioneered by the IPCC model, where each working group has a co-chair from a "Global South" country. Under the Solar Radiation Management, this person represents the interests and concerns of these countries. The establishment of a global monitoring and approval mechanism in the United Nations can regulate or prohibit the activities of individual states. Because of the vast difference in access to scientific resources between North and South, the various interests are even more difficult to influence and it is foreseeable that attempts will be made to override "Global South" countries. The mechanism can include a veto power for African countries. E.g., at the UN General Assembly, developing country governments can stand united, generate an absolute majority and express their concerns about Climate Engineering within. Developing countries additionally have the options of having the legality of the measures reviewed by the International Court of Justice and raising the issue at conferences that regulate climate interventions. This court can issue advisory opinions, but in the context of Climate Engineering it is unlikely that a ruling can be reached. This is only possible, if the court's decision is unanimously agreed to (Biermann and Möller, 2019).

5.2 Liability Mechanism

Given the potential damage, the development of a liability mechanism is necessary to enable multilateral decision-making and to rebut objections to Solar Radiation Management measures. The construction of such a mechanism faces a variety of challenges, e.g., it has to be possible to assign damages to measures and clarify which types of damages are compensated and when. Already attributing extreme weather events to anthropogenic climate change is difficult, but attributing damages to Solar Radiation Management measures are even more complex (Reynolds, 2019). One basis for decisions under this regime is international law, which dictates that a state must pay damages if they harm another state through an act that violates international law. Strict liability has become standard in this regard, meaning that a state can also be liable for damages that occurred through no fault of their own. This seems practicable because proving fault in international legal proceedings is difficult anyway. This liability under international law leads to three conclusions established by Horton et al. (2014).

First, the characteristics of stratospheric aerosol injection suggest that state, rather than civil, liability provides an appropriate basis because there is currently no market for Solar Radiation Management s and few incentives for private firms. Markets play a minor role in state liability regimes. This is not likely to change in the future because there is little support for corporate participation in stratospheric aerosol injection for operational decision making by commercial private entities. The only liability regime currently based solely on state liability is the Convention on International Liability for Damage Caused by Space Objects. According to this, only states can claim damages. If more than one state is at fault, the convention provides for joint liability. While settlement is generally sought first, provision is made for the convening of a damage commission in the event that this is unsuccessful. There is no limit on the amount of damages. In general, the convention has been judged by legal scholars to be an efficient, well-designed instrument for a liability regime. Second, a compensation fund is useful because of the potentially very high cost that result from adverse consequences. The proposal for a fund goes back to the oil spill regime, which governs compensation for damages following oil spills. The regime, which is based on strict liability, has been convincing in its efficiency and flexibility, so that so far all claims for compensation from private and public groups have been met. It provides a model for the stratospheric aerosol injection liability regime because it is based on the same moral values and principles of international law valid for the stratospheric aerosol injection regime. Many adjustments have been made over time needed also, if stratospheric aerosol injections are deployed. There are also many advantages to the fund structure. E.g., the up-front levy ensures the payout of potential victims. It also mitigates the potential for interstate conflict because states do not have to sue each other directly in the event of damage, but can turn to a neutral international organization. Under the Solar Radiation Management, e.g., oil companies and other large fossil fuel companies can be required to provide funds for collective liability insurance. Third, it is difficult to prove causality from consequences and causation. This is likely the most difficult problem in the quest for a workable liability regime. Traditionally, establishing legal liability has required proof of a direct cause-and-effect law between the act of an alleged perpetrator and the harm suffered by the victim. Because the negative consequences of stratospheric aerosol injection use are highly dependent on the high complexity of the climate system, this relationship cannot be established. As a result, liability mechanisms can be exploited by claiming damages without being able to prove that they were caused by stratospheric aerosol injection. Although the possibilities of searching for explanations with the help of computer modeling are increasing, it remains questionable to what extent a liability judgment can be based on an assessment that is not 100 percent accurate. A probability limit calculated by the simulations has to be defined which is considered legally reliable. These and other questions need to be answered in order to implement a liability system based on statistical models (Horton et al., 2015).

There is an alternative solution to these difficulties in forming a liability regime, i.e. a multilateral parametric climate risk insurance to facilitate agreement on the use of Solar Radiation Management measures. States that favor the use of these measures can purchase reduced-rate climate insurances to demonstrate their positive position toward Solar Radiation Management by ensuring compensation without assigning blame and assuming risk transfer (Horton and Keith, 2019). Averse states can be more likely persuaded to reduce their opposition. Parametric insurances recently have emerged as a new form of climate risk management. These are based on objective environmental indices, above which a payout is made, and offer several advantages, e.g., a design to protect against future damage and to cover severe losses without the need to find a responsible state for the damage (Linnerooth-Bayer and Hochrainer-Stigler, 2015).

5.3 Technical Regulatory Mechanism

A regulatory mechanism is necessary to prevent or mitigate risk. Thus, it can counteract a “slipery slope” scenario (Parker, 2014) and reduce negative impacts on the environment. From the lack of these regulatory and control mechanisms, the CBD rejects the use of Climate Engineering measures, see “Treaties and Conventions”. The following section will explore technical options to influence stratospheric aerosol injection impacts or how risk can be minimized. Before Solar Radiation Management measures, especially stratospheric aerosol injection, are implemented, maintenance and shutdown options must be addressed. Maintenance is about the continuous adjustment of control variables that exist for the stratospheric aerosol injection technique (Battisti et al., 2009). The need for adjustment depends on what undesirable effects are observed during the deployment. It is also important to carefully consider options that can be used up front to minimize future risk. These are based almost exclusively on climate simulations, which is why their results, as well as their informative value and validity, are discussed.

Risk reduction methods

One method to optimize stratospheric aerosol injection deployment and reduce risk is to target aerosol injection across latitudes. Idealized simulations showed that certain injection patterns can reduce the hazards of the Solar Radiation Management technique. It was observed that pre-industrial precipitation conditions can be reproduced and Arctic sea ice can be restored. The extent to which this targeted injection is technically feasible is as yet unclear (Ban-Weiss and Caldeira, 2010). A variety of deployment patterns exist to discuss in more detail once further knowledge has been gained through field experiments. The ideas are based on simulations, which have an idealized character and are not based on observations of reality. The simulation of Solar Radiation Management in climate models is based on the translation of a technological statement into computable analogs. These technologies make assumptions about the physical impacts of using, e.g., stratospheric aerosol injection. Scientists can use the results to anticipate consequences for climate and the environment (Kravitz et al., 2020). Climate models can describe the effects of different emission and solar irradiance scenarios on climate. Thus, they are an indispensable tool in predicting risk associated with Solar Radiation Management deployment. Especially with the background that so far hardly any field experiments have been performed for the input of particles into the stratosphere, with which it is possible to better understand atmospheric chemistry and aerosol physics. This is likely to change in the near future, as there is already an elaboration of an experiment that will be used to improve the understanding of stratospheric aerosols. The "Stratospheric Controlled Pertubation Experiment" (SCoPEx) plans to release a small amount of Calcium Carbonate at an altitude of 20 km with the help of a balloon equipped with propellers and to take measurements. The implementation of the experiment still lacks approvals from the advisory board and regulatory agencies and platform tests on the transport system must be performed (Keutsch Group at Harvard). Until the assumptions of the simulations can be verified with data from experiments, other means must be used to show validity of the models as far as possible. What simulations exist for the Solar Radiation Management measures, what they study and what uncertainties exist will be discussed below. The international Geoengineering Model Intercomparison Project (GeoMIP) is investigating various model experiments and possible scenarios of emission trajectories. They are labeled G1 to G7 and address the possible impacts of

Solar Radiation Management. The project is a continuation of the Coupled Model Intercomparison Project (CMIP), which is used to make relatively accurate predictions of climate trajectories through large agreements. This project is an important component of the IPCC Assessment Reports, as it includes different concentration pathways of greenhouse gases. The goal of both GeoMIP and CMIP is to improve the comparability of model results. E.g., G1 discusses the effects of the unrealistic but revealing scenario in which the sun is "turned down". At the same time, the CO_2 concentration instantly quadruples. A variety of models simulated these circumstances and analyzed the consequences for global mean temperature. They arrived at consistent results. Although precipitation decreases with the reduction in solar radiation, without the reduction, temperature increases sharply within the fifty years and precipitation increases. So the first GeoMIP scenario represents a better approximation of pre-industrial climate than without a change in radiative forcing. E.g., G2 describes counteracting the 1% CO_2 increase per year over pre-industrial levels by gradually reducing solar radiation. Simulating the scenario, the modeling groups sometimes arrive at different results, showing a scatter in their estimates of the 1 °C cooling. The evolution of the amount of carbon exchanged varies between the natural carbon reservoirs (Jones et al., 2013). Visioni et al. (2021) also found uncertainties in the context of several G6 simulations. The goal of $G6_{sulfur}$, e.g., is to reduce radiation with the help of SO_4 injection. Observations included scatter in the amount of sulfate needed at the end of the century, differences in the latitudinal distribution, and uncertainties in how much the temperature is reduced. These observations suggest the need to look more closely at the causes of the uncertainties to better plan the use of stratospheric aerosol injection (Visioni et al., 2021). The uncertainties are present in several areas. One is in the conversion of SO_2 to aerosols and the subsequent distribution of these by circulation. But also the chemical reaction of stratospheric components, such as Ozone and Methane, the dynamics and the extent of local warming produced are effects in the stratosphere that are difficult to scale. At the Earth's surface, the consequences for precipitation, weather extremes, or ultimate cooling per Mt SO_2 are not changes that can be estimated with certainty. The uncertainties are variably related. E.g., stratospheric dynamics affect the lifetime and distribution of aerosols. Their size is determined by chemical and microphysical processes and the totality of all properties affects radiative forcing. To the extent of this, stratospheric warming behaves, which in turn affects stratospheric chemistry and dynamics (Kravitz et al., 2017). These uncertainties need to be reduced in the future in order to better assess the magnitude of the consequences of Solar Radiation Management and to adequately inform decision makers, if deployment of the technologies is applied. Aside from conducting field experiments, there are other ways to improve simulation accuracy. E.g., modeling approaches can be used that do not examine climate specifically, but instead highlight individual processes on a physical basis. Climate models can be used and some processes constrained, e.g., by specifying a uniform injection distributions.

Influence of SO_2 lifetime

In advance the removal of SO_4 aerosols, the crucial influencing variables and processes that affect the lifetime of aerosols are discussed. In exploring the influence of volcanic ash particles on the lifetime of SO_2 in the stratosphere and on aerosol optical properties, Zhu et al. (2020) describe the interactions of aerosols in the stratosphere and offer new perspectives on the role of volcanic ash in climate change. Using simulations, they found that S can be removed more rapidly from the gas phase by volcanic ash due to the heterogeneous reactions of SO_2 on ash. SO_2 reacts on ash and leads to a shortened lifetime of SO_2 (Zhu et al., 2020). The surface of ash particles brings high reactivity and provides a basis for heterogeneous nucleation of H_2SO_4 gas, in which the gas condenses on the surface of the particles. The SO_2 aerosols coagulate with the ash particles, i.e., the particles agglomerate (Hamill et al., 1977). The oxidation rate of SO_2 is increased when H_2O is injected because this increases the OH concentration. Other influencing factors are the height and width of the injection (Yang et al., 2007). To achieve an SO_2-reducing effect by H_2O injection, a large amount of H_2O is required. Zhu et al. estimate that injecting 26 Tg of H_2O into the stratosphere, the SO_2 lifetime reduces the reference value of 26 days by eight days. An alternative way to increase OH concentration is to mimic the effect of aerosol scattered light. This causes photolysis, the splitting of a chemical bond by electromagnetic radiation. It turns out to be unrealistic to expect a dramatic OH increase to be achieved naturally by enhancing this effect. The simulation deviations from the satellite reference values are caused by the underestimation of the SO_2 response to mineral dust and volcanic ash. Ultimately, simulations that account for heterogeneous SO_2 chemistry on ash particles remove about 43% more S from the stratosphere than without (Usher et al., 2002). To the coagulation and sedimentation rates, the stratosphere-troposphere exchange rate also plays a role in calculating the residence time of SO_2 particles in the stratosphere. The size and density of the particles are decisive factors (Niemeier et al., 2011).

Counter geoengineering for subsequent adaptation

The term counter geoengineering covers all countermeasures that counteract climate interventions. It is used primarily in the discussion of whether unilateral deployment of Solar Radiation Management measures is appropriate or possible as a weapon. Any measures that fall under it can have the same effect as stopping deployment or can also reduce the effect (Battisti et al., 2009). Parker et al. (2018) divided them into two types. The first way they call equalization, in which the radiative forcing caused by stratospheric aerosol injection is to be offset with the help of warming agents, such as specially designed particles or greenhouse gases. The second is defined as neutralization, which is characterized by stopping the effectiveness of the aerosols.

This can be done by injecting a base, or by techniques to accelerate coagulation and thus atmospheric deposition of S particles. One option of compensation is the injection of carbon, or black particles, into the lower atmosphere. This warms as a result and there is a multiplier effect as the particles increase sunlight absorption on the Earth's surface as they fall. The idea is easy to implement, so particle filters can be removed from coal-fired power plants and the desired effect can be achieved. While the method seems unrealistic because of the health effects of soot emissions to avoid, it can be used as a threat, e.g., if a country wants to oppose Solar Radiation Management measures. This is not a far-fetched option for Russia, which benefits most from global warming (Lane, 2010). Much closer is the warming of the stratosphere through the introduction of greenhouse gases that offset the cooling shortwave radiative forcing by increasing the warming longwave radiative forcing (Horton, 2011). Relevant greenhouse gases include Chlorofluorocarbons and Sulfur Hexafluoride. The fluorinated greenhouse gases are characterized by a long lifetime and a strong absorption of thermal radiation emitted by the Earth, thus they cause a high radiative forcing. Ultimately, only a few greenhouse gases can be discussed because their lifetime optimally must be between a decade and a century. Their effect on Ozone must also be discussed: Difluoromethane, e.g., has a limited effect on it and thus is a possible candidate for use (Parker and Irvine, 2018). Teller et al. (1997) introduced particles of solids, which, unlike fluorinated gases, have a shorter lifetime and high radiation efficiency. The particles can be coated with a thin metal layer that reflects almost only infrared radiation and thus absorb long-wavelength radiation well. Neutralization methods, unlike counterbalancing methods, must be designed more specifically for the Climate Engineering technique they are intended to counteract (Parker and Irvine, 2018). Looking for a substance that will neutralize sulfate aerosols, it is important to discuss how it will specifically affect their lifetime. The higher the coagulation rate, the faster the aerosols sediment and the shorter their residence time in the stratosphere is, i.e. the faster the particles coalesce and form larger particles, the faster they sink to the ground (Hamill et al., 1977). This can be achieved by using particles that have a coagulation-promoting surface. Alternatively, aerosol lifetimes can be shortened by certain processes, such as ultraviolet photoionization, which enables charging of particles in the sub-50 nm size range (Nishida et al., 2017), or electrical charging of particles (Parker and Irvine, 2018). The implementation of counter geoengineering is difficult and so far it remains a theoretical proposal (Weitzman, 2015). A technique must be developed that is efficient against Solar Radiation Management impacts and financially affordable, or does not exceed Solar Radiation Management damages cost. Side effects on health and environment have to be low enough to be acceptable. Even if the technical requirements can be met, it remains unclear whether counter geoengineering is politically feasible because the consequences of both Solar Radiation Management and counter geoengineering measures are difficult to predict. Counter geoengineering loses its relevance as a threat tool in a free-driver scenario if Solar Radiation Management deployment is multilaterally and diplomatically negotiated (Parker and Irvine, 2018).

Risk stopping the measures

A frequently discussed problem of Solar Radiation Management deployment among scientists is the termination problem. This describes the effect that if the Solar Radiation Management measures are stopped, the mean temperature will rise to a level that is reached even without the measures. This increase starts much faster because the radiative forcing is so high. Thus, one also speaks of the "termination shocks" or "abort shocks". Especially in the context of counter geoengineering, addressing this risk is inevitable. The effect depends on the amount of Sulfur, the characteristics of the termination, and the period of exposure. The most important problem with this precipitous rise in temperature is that many ecosystems and species are not able to adapt so quickly to this rapid climate change. As a result, termination shocks have been cited in a variety of publications as a reason that once Solar Radiation Management measures are implemented, the measures must be maintained for centuries (Parker and Irvine, 2018). Injecting as few aerosols as necessary or considering stratospheric aerosol injection only as a stopgap measure are other conclusions made in terms of avoiding shocks. Parker and Irvine's (2018) study examined possible policy responses that mitigate the risk of termination shocks. They emphasize the need to build a resilient and robust Solar Radiation Management system. Jones et al. (2013) conducted simulations as part of the GeoMIP experiment and found that termination of climate manipulative policies lead to abrupt climate change. Precipitation, temperature, and sea ice occurrence change much faster than without Climate Engineering under the influence of increasing greenhouse gas emissions. Depending on how long the deployment takes, how high the greenhouse gas emissions are and how much the Earth cools, the rate of change is significantly different (Jones et al., 2013).

6 Limitations and Further Research

The most present challenge of Solar Radiation Management in literature on potential governance is uncertainty. Today, risk and impacts can only be assessed using computer simulations and are not based realistic field experiments. Further research is needed that examines impacts, how deployment can be regulated, to what extent connections can be made between deployed technologies and observed impacts and how deployment interventions can be monitored (Parson and Ernst, 2013). The efficiency of Solar Radiation Management governance depends on the evolution of climate change, but also on research and development of Solar Radiation Management measures and technologies. Thus, three scenarios occur in which different types of governance are required. Mankind finds itself at a point where urgent action is needed. It is the emergency scenario, in which decisions must be made about whether to implement Solar Radiation Management, how to allocate cost and how to deal with potential risk. Other scenarios gain in importance, if there is no global acute need for action, but there are regional disasters, e.g., the Indian monsoon fails affecting Southeast Asia and Western China. Then, in addition to the tasks in the emergency scenario, the focus is on the mediation of international conflicts, because the winner-loser problem is particularly evident. The third scenario involves unilateral action by a state which acts within a governance framework of its own design and without international cost-sharing or oversight. This state has to convince other states of its plan to avoid conflicts (Victor, 2019). In the case of the multilateral parametric insurance proposal, a binary categorization is made into states that are in favor of Solar Radiation Management measures and those that are against. This simplistic assumption is unrealistic because the positioning will more likely correspond to a spectrum in which some states will also take no position (Horton and Keith, 2019). Most of the literature on the design of Climate Engineering governance elaborates on moral values to guide policy decisions, but the specific operational implementation remains unclear. Guidance for requiring a bottom-up structure to form these moral values is also lacking. Also unclear remains the implementation of flexibility in relation to a simultaneously robust governance framework (Parson and Ernst, 2013).

7 Conclusions and Outlook

The governance of Climate Engineering, in particular Solar Radiation Management, represents an upcoming challenge for global climate protection policies characterized by large uncertainties. Today, potential impacts of climate interventions can only be assessed on the basis of simulations with deficiencies in the microphysics of the stratosphere in particular. Plans to conduct larger field experiments, e.g., SCoPEx, raise hope that scientific results and findings today can be complemented with real data. Today's lack of valid insights currently hinders the development of needed governance. Ethical and political challenges make a Solar Radiation Management implementation unlikely in this decade. We discuss opportunities, challenges, and limitations of international regime structures. Combining flexibility, robustness, and efficiency with several moral values and principles, such as equity and transparency, currently is not possible in any of the existing political structures. Raising awareness of this issue is necessary as a first step, followed by the initiation of a global discussion on Climate Engineering involving the global public, scientists from all affected sectors and countries and global, national and local policy makers.

It is exciting to see how progressive climate change and advanced research results and findings will lead to a change so that policy makers understand the need for global and efficient climate measures, e.g., Solar Radiation Management. Stratospheric aerosol injection in particular – with its large potential – can be a stopgap measure: optimally, it is applied complementing more and more greenhouse gas mitigation. Needed regulatory mechanisms have been already widely discussed in literature from a policy perspective. Technical implementations to control effects of aerosols after stratospheric aerosol injection are only discussed in few publications. Approaches are provided by counter geoengineering, which is used to argue against the misuse of Solar Radiation Management measures as a weapon ("climate war"). Technical implementations to neutralize or control effects of injected aerosols have emerged in this context. Further research must better review the proposed synthesis of counter geoengineering for a regulatory mechanism and must determine a precise approach. But, the risk of termination shocks seems to be an insurmountable obstacle, today.

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