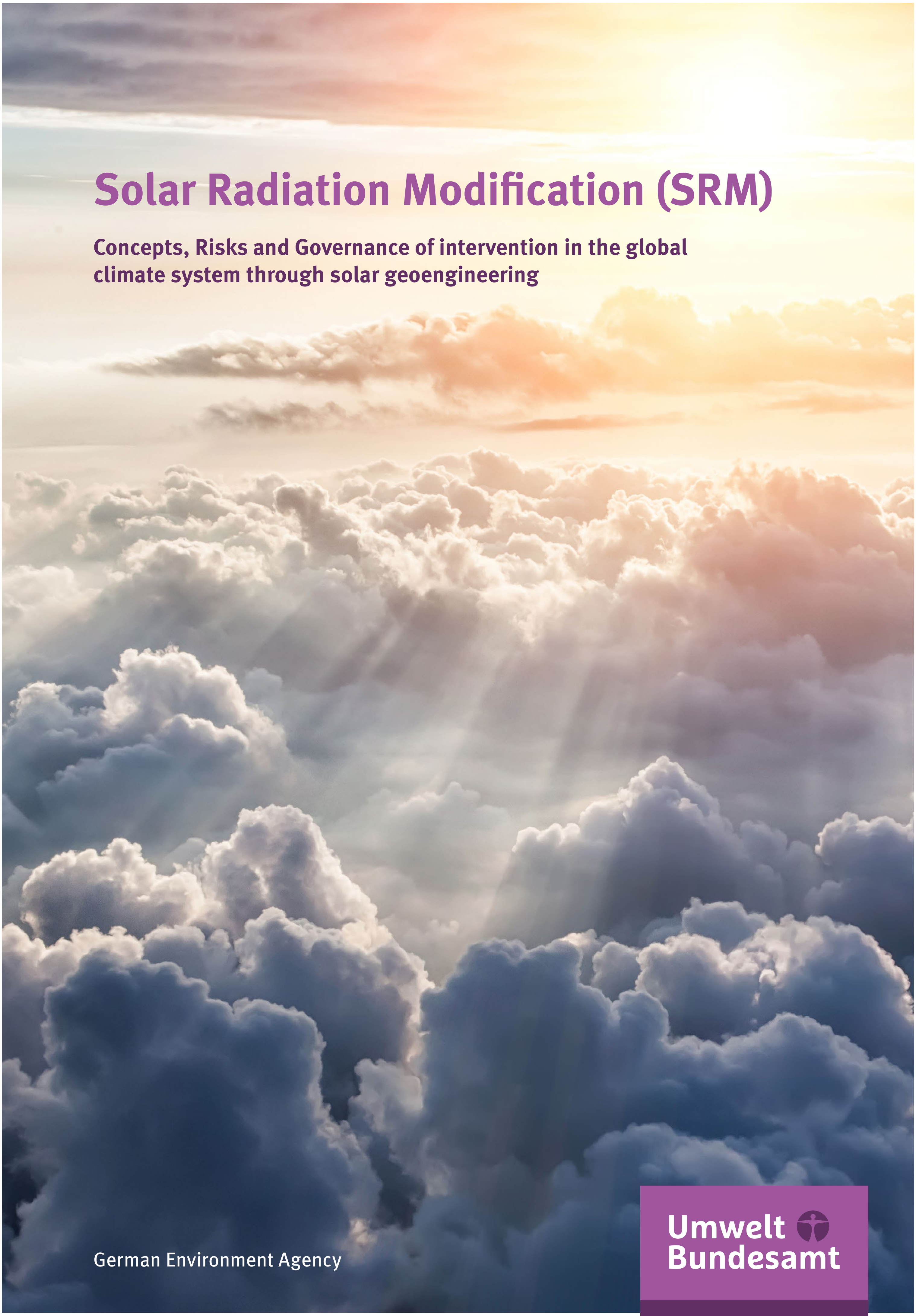

Solar Radiation Modification (SRM)

Concepts, Risks and Governance of intervention in the global climate system through solar geoengineering

German Environment Agency

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Contents

Abbreviations

CBD	Convention on Biological Diversity, Biodiversitätskonvention
CCT	Cirrus Cloud Thinning
CDR	Carbon Dioxide Removal
CMIP	Coupled Model Intercomparison Project
GeoMIP	Geoengineering Model Intercomparison Project
ILM	International Law Materials
IPCC	Intergovernmental Panel on Climate Change
LC/LP	London Convention and London Protocol
MCB	Marine Cloud Brightening
MP	Montreal Protocol
SAI	Stratospheric Aerosol Injection
SCoPEx	Stratospheric Controlled Perturbation Experiment
SO_2	Sulfur dioxide
SRM	Solar Radiation Modification / Solar Radiation Management
SSP	Shared Socioeconomic Pathways
THG	Greenhouse gas
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Program
UNEA	United Nations Environment Assembly
WMO	World Meteorological Organization

Figures

Solar Radiation Modification is not Climate Action

The use and technical deployment of Solar Radiation Modification (SRM) is to be rejected. SRM can neither preserve the current climate nor restore the pre-industrial climate. Instead, it would create an unpredictable new global climate with significant regional impacts.

According to the state of scientific knowledge, sufficient certainty already exists regarding the dangers of SRM to food security, water availability, and the environment. If, after a global rollout, for whatever reason, a global deployment of SRM were to be stopped, it would result in a sharp temperature rise with catastrophic consequences. SRM has the potential to provoke conflicts worldwide and exacerbate injustices.

Based on current knowledge, SRM cannot therefore be considered a future emergency option. It is neither quickly deployable nor cost-effective. It is also not suitable as a transitional technology while reducing emissions and developing technologies for carbon di-oxide removal (CDR).

Beyond the existing governance structures, an international non-use agreement should be aimed for. Based on a prohibition of use, negotiations can take place regarding the regulation of specific and controlled small-scale research projects.

The distinction between research in the context of outdoor experiments and deployment is often blurred in the case of SRM, as it primarily involves the testing of technologies. Therefore, field experiments, whether by research institutions or private companies, must be prohibited in principle. Research using computer models and other theoretical studies can be useful, but must be conducted transparently and inclusively.

SRM research is not climate action research: a weakening of mitigation efforts must also be avoided in research funding. Therefore, a shift of research funds dedicated to the reduction of greenhouse gas emissions and climate adaptation towards funding SRM research should be rejected.

Certificates for cooling effects through SRM, which are intended to compensate for greenhouse gas emissions, are misleading and divert attention from actual climate action and mitigation measures. They should therefore be rejected.

1 The Term Geoengineering

The idea of modifying landscapes and weather through technologies has existed since the 1950s (Oomen, 2021; Oldfield, 2013; Schellnhuber, 2011). In 1977, the term **geoengineering** – meaning large-scale interventions in the Earth's system – was specifically linked to climate change (Marchetti, 1977; Budyko, 1977) and continued to attract attention in the following decades (Caldeira et al., 2017). The idea gained further prominence through publications by Nobel laureate Paul Crutzen (Crutzen, 2006) and the Royal Society, whose widely accepted definition ultimately associated the term geoengineering with climate change (Royal Society, 2009). According to this definition, geoengineering includes **deliberate, large-scale interventions in the climate system with the aim of mitigating anthropogenic global warming**. Since the focus is on modifying the climate, the term **climate engineering** is also frequently used.

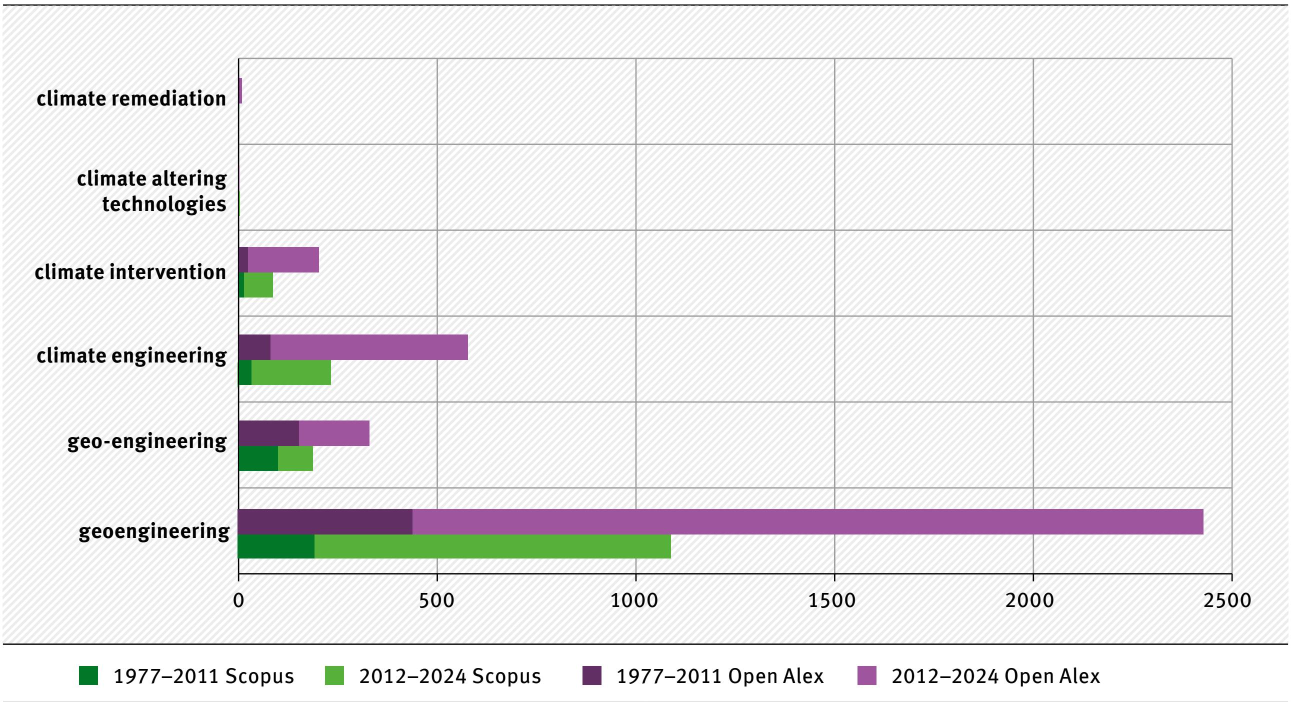
Over time, geoengineering has shifted from being a theoretical and philosophical expression of control and power to becoming a (still "techno-optimistic") potential complementary response to climate change, alongside mitigation and adaptation (Oomen et al., 2021). While the expectations and political relevance of the debate have evolved, the proposed methods and contentious issues have largely remained the same over the past few decades. However, new, more euphemistic terms have emerged, such as **climate intervention**, **climate remediation**, or **climate altering technologies** (the corresponding German translations, such as Klima-Intervention or Klima-Sanierung, are not widely used, as the debate primarily takes place internationally). These terms are sometimes deliberately used to convey neutrality (Preston, 2013), yet they do not change the well-known fact: these approaches carry significant risks for people and the environment. Moreover, the hope for a seemingly simple technological solution – a "techno-fix" for climate change – distracts from the necessary climate action such as greenhouse gas reduction and adaptation, and reduces a societal task of required transformations to what appears to be a purely technical problem (Neuber et al., 2020).

The numerous geoengineering approaches can be divided into two categories. The first category involves approaches aimed at **influencing the Earth's radiation budget**, also referred to as solar geoengineering. The alternative term **Solar Radiation Management** was introduced at a NASA workshop in 2006, with the intent of diverting attention from the controversial discussion surrounding geoengineering (Caldeira et al., 2017). Hence, the less euphemistic and equally common term **Solar Radiation Modification** (SRM) is often used. Some SRM approaches are also found in literature under the topics of 'Ice Sheet Interventions' or 'Glacial Management', aimed at preventing sea-level rise. The second geoengineering category includes a variety of methods for removing carbon dioxide from the atmosphere which are summarized as **Carbon Dioxide Removal (CDR)**. In political contexts, CDR is often referred to as **negative emissions** or **sinks**.

Figure 1

Geoengineering and synonyms in publications

Number of search results in the title



Own research on www.scopus.com and https://openalex.org/. as at 15.10.2024

Due to common traits between SRM and most CDR aproaches as large-scale environmental interventions, and the long-standing history of the geoengineering debate which is reflected in the large number of pulications using the term (see Fig. 1), it is important not to lose the context of the overarching term geoengneering. At the same time, the term “geoengineering” remains relevant, not least because key international decisions are based on this term (Section 9).

In the media and public perception SRM continues to be associated with geoengineering while CDR is often discussed separately and detached from the umbrella term. This separation is sometimes used intentionally to enable more positive communication and public perception of CDR (Müller-Hansen et al., 2023;Heyward, 2013). SRM, on the other hand, is still more often perceived as “megalomania” and viewed negatively in public discourse (Carlisle et al.,2020).

2

Rapid Developments in Politics and Science

Between 2006 and around 2013, geoengineering was a topic of particularly intense discussion. Important political decisions were made during this period, which remain highly significant today. In 2010, the United Nations Convention on Biological Diversity (CBD) adopted a de facto moratorium on geoengineering (UBA, 2019), marking a major **political milestone**. Additionally, the parties to the London Protocol/London Convention (LP/LC) agreed in 2008 that commercial ocean fertilization should not be permitted and that field experiments must be assessed to ensure they have no adverse environmental impacts. Following this, the parties negotiated a legally binding regulatory framework for marine geoengineering, which was adopted in 2013. An international conference on geoengineering was held in 2010 (ASOC, 2010a; ASOC., 2010b). During this period, reports on geoengineering increased in both online and print media (Mercer et al., 2011) This initial phase also prompted the German Environment Agency to take a position on geoengineering and inform the public (UBA, 2011).

After this period, the debate around geoengineering temporarily calmed, but it resurfaced in recent years, driven by the increasingly drastic impacts of climate change, and has progressed as rapidly as global warming itself. A key factor in the **renewed debate** was the scientific recognition that limiting the temperature increase to 1.5°C is necessary to minimize the risk of harmful effects from climate change on people and the environment (IPCC, 2018). This goal was also enshrined in the 2015 Paris Agreement, where member states agreed to limit global warming to well below 2°C and to pursue efforts to cap it at 1.5°C. However, as global annual emissions continue to rise, albeit at a slower rate, rather than fall drastically, many people now view exceeding the 1.5°C limit as inevitable. This concern has led to the idea that, after surpassing the temperature target (referred to as “overshoot”), it may be possible to reverse it or even cool the planet back to pre-industrial levels. For this purpose, the necessity (and feasibility) of Carbon Dioxide Removal (CDR) as well as Solar Radiation Modification (SRM) is increasingly assumed as given. (Section 5). However, essential questions and challenges regarding climate effectiveness, sustainability criteria, scalability, risks, political consequences and market mechanisms remain unresolved, and despite significant research, they mostly reflect the state of knowledge from 2011. SRM in particular covers for the most part merely theoretical approaches that are by no means ready for deployment.

The debate has not only intensified but also evolved in terms of terminology, with a growing distinction between CDR and SRM. CDR is increasingly being discussed separately from geoengineering. Due to the differing political significance of SRM and CDR, the Intergovernmental Panel on Climate Change (IPCC) has ceased using the term geoengineering since its sixth assessment cycle and now addresses the two categories separately (IPCC, 2018; IPCC 2023).

In political discourse, SRM and CDR are also increasingly treated as distinct topics. CDR has already been integrated into the political strategies of several countries, including Germany (Smith et al., 2024; BMWK, 2024; EU Council, 2024), while the global deployment of SRM is currently not being considered. **Germany and the EU** explicitly argue against the use of SRM. The German federal government has positioned itself against SRM in its climate foreign policy strategy “due the existing uncertainties, implications, and risks”, reaffirming the CBD’s de facto moratorium and distancing itself from research aimed at developing and potentially deploying SRM technologies on a large-scale (German Federal Government, 2023). The European Commission reinforced the validity of the CBD’s de facto moratorium in a report on climate and security, emphasizing the enormous risks associated with SRM (EU Commission, 2023). The European Parliament, in a resolution, urged the European Commission and member states to initiate an international agreement prohibiting the use of SRM. (EU Parliament, 2023). The **African Ministerial Conference** on the Environment also passed a resolution calling for an international agreement to ban SRM (AMCEN, 2023).

At the **United Nations (UN**) level, few legally binding regulations currently exist, but the distinction between SRM and CDR is also becoming evident. Acording to Article 4(1) of the Paris Agreement, climate targets are to be achieved through sinks, which can be understood as natural or artificial systems that absorb and store CO_2 from the atmosphere (Paris Agreement, 2015). Increasingly, discussions about negative emissions are taking place at UNFCCC climate negotiations, without directly linking them to geoengineering. Following a draft resolution on geoengineering at the fourth United Nations Environment Assembly (UNEA-4) (Schwitzerland, 2019), a draft resolution specifically on SRM was proposed at UNEA-6 (UNEA, 2024; ENB, 2024), though this second draft was also rejected despite the distinction between terms. Besides these UN negotiations, numerous political reports and governance processes address either geoengineering as a whole or focus exclusively on CDR (Section 8).

Negotiations on SRM at UNEA6 in Nairobi

Non-governmental organizations (NGOs) and other institutions have also taken positions against SRM in recent years (for example, CAN, 2019). National organizations such as the German Federation for the Environment and Nature Conservation (BUND, 2023) and the Heinrich Böll Foundation (HBS, 2018a; HBS, 2018b) have also published position papers. Researchers from various countries, including German Environment Agency President Dirk Messner, launched an initiative calling for an agreement on the non-use of SRM (https://www.solar-geoeng.org/; Biermann et al. 2022). Concurrently, numerous other **initiatives and think tanks** were established, and open letters were written pushing SRM on the agenda. To mention for example „Carnegie Climate Governance Initiative“ (C2G, https://c2g2.net/), „The Alliance for Just Delibaration on Solar Geoengineering“ (DSG, https://sgdeliberation.org/) including a youth network „Climate Intervention Network“ (CIN, https://sgdeliberation.org/activities/youth-engagement-program/climate-intervention-network/), „The Degrees Initiative“ (https://www.degrees.ngo/), „SRM Youth Watch (https://www.srmyouthwatch.org/), „Call for Balance“ (https://www.call-for-balance.com/) and „International Center for Future Generations (ICGF, https://icfg.eu/climate-interventions/).

The increasing attention SRM has garnered within the **scientific community** is reflected in the growing number of scientific studies from various disciplines that explicitly address SRM and its individual approaches (see Figure 2). In addition, there are a growing number of private and statefunded research projects investigating SRM (UBA,2024). The Geoengineering Monitor by the ETC Group and the Böll Foundation provides an up-to-date overview of the numerous global projects: https://map.geoengineeringmonitor.org/. In Germany, there was a project on the risks of SRM by the German Environment Agency (UBA 2024; UBA, 2023), and previously one by the German Research Foundation (DFG, 2019). The EU funded an assessment study called EuTRACE until 2015 (Schäfer et al., 2015). Currently, two EU Horizon-funded projects dealing with SRM are ongoing, with the acronyms GENIE (https://genie.ece.iiasa.ac.at/) and Co-Create (https://co-create-project.eu/). Internationally, notable projects include the “Lighthouse Activity” of the WCRP on geoengineering (https://www.wcrp-climate.org/ci-overview) and the Geoengineering Model Intercomparison

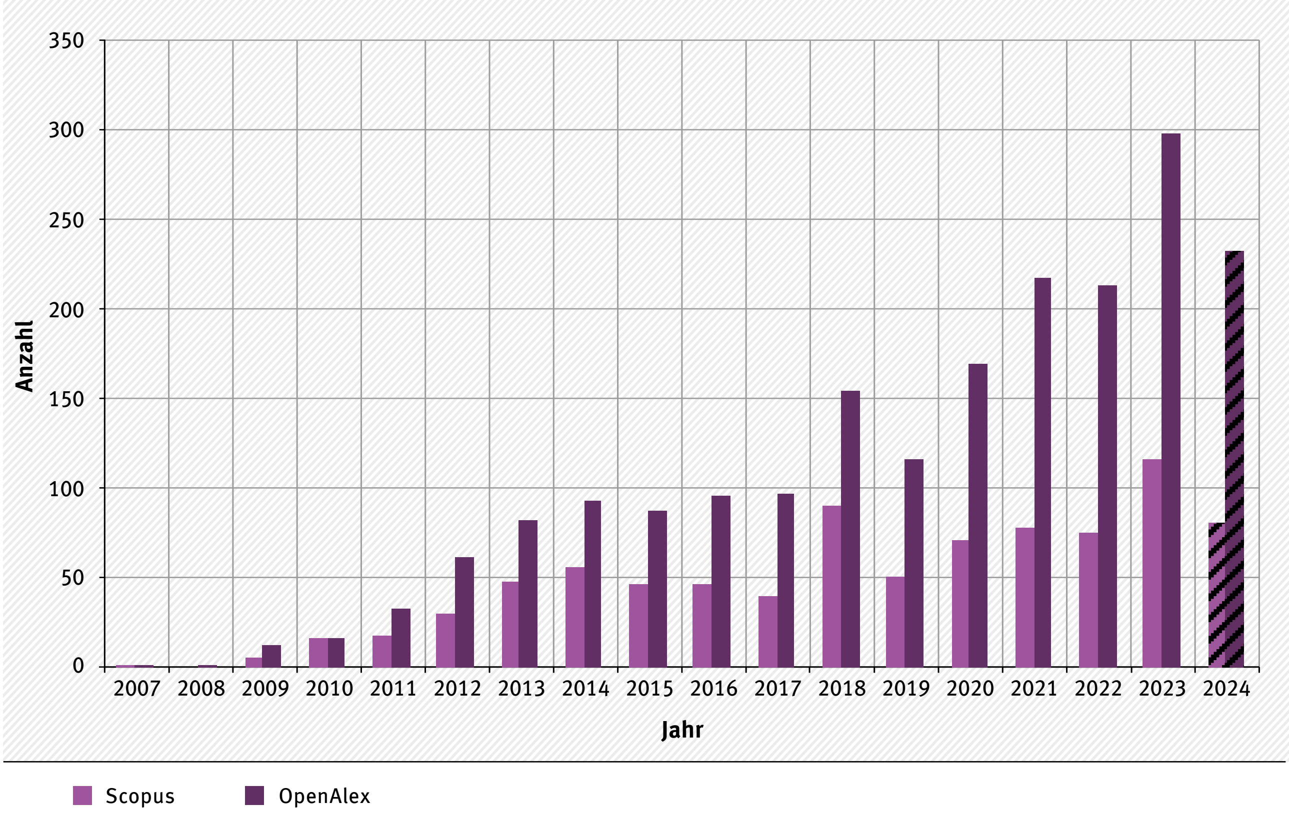
Project (GeoMIP) (https://climate.envsci.rutgers.edu/GeoMIP/). GeoMIP holds regular conferences (GeoMIP, 2024; GRC, 2024; GRC, 2022; GRC, 2017). The program of the 28th General Assembly of the International Union for Geodesy and Geophysics (IUGG) in 2023 included several presentations on SRM and weather modification. Following this, the IUGG published a resolution affirming that SRM is neither a complement nor a substitute for greenhouse gas (GHG) mitigation (IUGG, 2023). Presentations on SRM were also given at conferences of the European Geosciences Union (EGU, https://www.egu24.eu/) and the American Geophysical Union (AGU, https://www.agu.org/annual-meeting).

In 2023, **three institutional reports** generated significant media and public attention. The first was a report on SRM titled “One Atmosphere” (UNEP, 2023), written by 12 external authors and commissioned by the United Nations Environment Programme (UNEP) without an explicit state mandate or involvement. Shortly after, a no less controversial report by the U.S. government followed, which described only a theoretical plan for SRM research and governance and explicitly stated that it would not alter climate policy (Whitehouse, 2023), but it was widely portrayed in the media as a concrete research program. Finally, reports commissioned by the World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) and by the United Nations Human Rights Council (UNHRC) were released (COMEST, 2023; UNGA 2023). While COMEST deals with the theoretical potential of SRM and its development and regulation, the UNHRC report underlines the risk SRM poses to the protection of human rights, and demands prohibiting its use.

Figure 2

Publications on SRM

Number of search results for synonyms for SRM* in title, abstract and key words



*“solar radiation modification“ OR „solar radiation management“ OR „solar geoengineering“ OR „solar climate intervention“ OR „stratospheric aerosol injection“OR „planetary sunshade“OR „marine cloud brightening“ OR „cirrus cloud thinning“

Own research on www.scopus.com und https://openalex.org/. as at 15.10.2024.

3 The Theory Behind the Idea of SRM as a Solution for Climate Change

3.1 Earth's Radiation Budget and the Greenhouse Effect

Sunlight reaches the Earth's atmosphere as shortwave radiation. About one-third of this radiation is reflected back into space. However, most of the shortwave solar radiation reaches the Earth's surface and is absorbed. This absorbed radiation heats the Earth's surface, which then emits longwave thermal radiation (infrared radiation) back into the atmosphere. A small fraction of this thermal radiation escapes the atmosphere through the so-called atmospheric window directly into space. However, the majority is absorbed by greenhouse gases (GHGs), such as water vapor, carbon dioxide (CO_2), methane, ozone, and nitrous oxide. The GHG molecules then re-emit the heat in all directions, including back toward the Earth's surface. This process leads to the warming of the lower layers of the atmosphere compared to an atmosphere without GHGs, similar to the effect of a blanket. This process is known as the greenhouse effect (see Lesch et. al, 2021).

Since the Industrial Revolution, human economic and lifestyle activities have continuously increased the amount of GHG emissions released into the atmosphere. The resulting higher concentration of GHGs ensures that more heat energy remains in the system, causing the atmosphere to warm further. This human-enhanced greenhouse effect is driving anthropogenic (human-caused) climate change (Rahmstorf et al., 2019). Der Zusammenhang zwischen insgesamt The relationship between the total amount of CO_2 emitted by humans and the resulting warming is roughly linear, meaning it is proportional (IPCC, 2021).

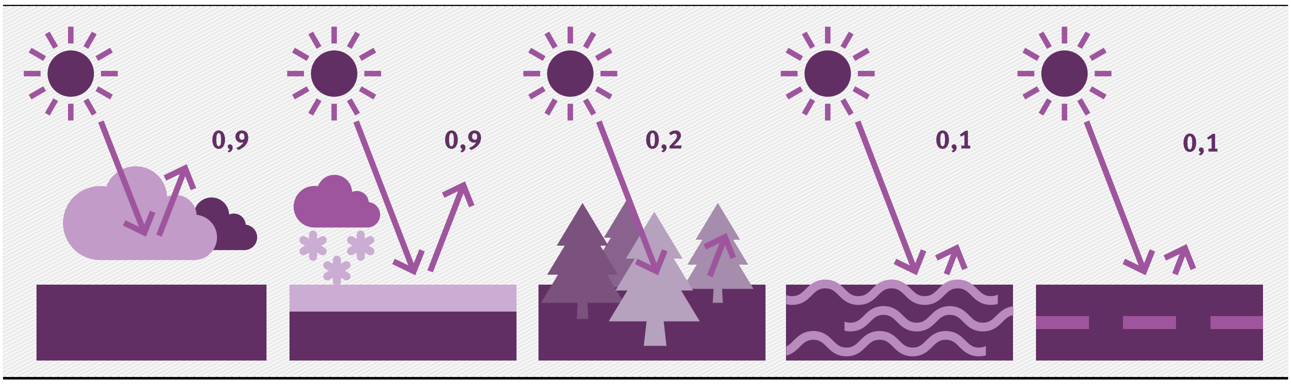
There are four particularly important radiation components: incoming and outgoing shortwave solar radiation, and upward and downward longwave thermal radiation. These four components can be calculated together to obtain a simplified radiation budget for the Earth, also known as the Earth's radiation balance (Foken, 2016). In more detail, the radiation balance can be calculated using highly precise physical models.

3.2 The Albedo

Albedo ("whiteness") refers to the reflectivity of an object's surface or a landscape. In the case of planets like Earth, it is determined by the ratio of reflected solar radiation to incoming shortwave solar radiation. Thus, albedo is a number between 0 and 1. An albedo of 0.9 means that 90% of the sunlight or light is reflected. Such values are typical for snow, and clouds can also have such high values. Asphalt, on the other hand, has a low albedo of 0.1, meaning that most of the sunlight is absorbed, causing the surface to heat up much more than other surfaces. The values for forests and oceans fall somewhere in between (Foken, 2016).

Figure 3

Examples of albedo values for different landscapes



Source: German Environment Agency

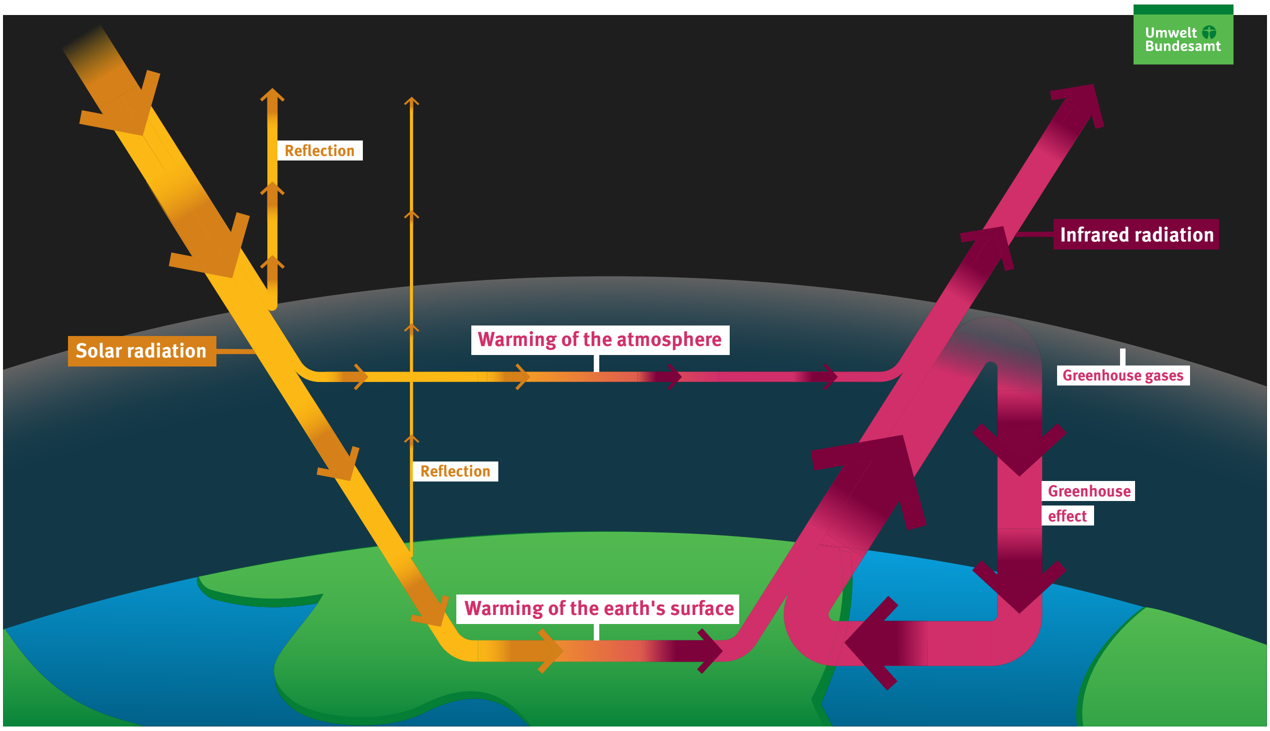
3.3 Modification of the Radiation Budget

In most cases, SRM aims to increase the Earth's albedo. This can occur in the atmosphere, in clouds, or at the Earth's surface (Section 6). In the case of space reflectors, the solar radiation reaching the Earth is reduced from the outset. Depending on the approach, sunlight (or specific wavelength ranges) is either directly reflected or scattered, reaching the Earth's surface as diffuse radiation (Baur et al., 2023a). One speculative approach aims to allow more thermal radiation to escape the atmosphere (Section 6.3 on Cirrus Cloud Thinning, CCT). However, many publications (as well as the statements in this brochure) primarily refer to SRM approaches that reduce incoming solar radiation, particularly stratospheric aerosol injection (Section 6.2 on SAI). SRM (except for CCT) can logically only function on the Earth's daytime side, whereas greenhouse gases (GHGs) are distributed throughout the atmosphere and contribute to global warming, even at night (IPCC, 2014). As a result, SRM cannot cool the Earth uniformly and does not alter the greenhouse effect; it only affects the radiation balance (Section 4).

The idea that SRM could be used to combat global warming is largely based on observations of the global average temperature following major volcanic eruptions. For example, after the eruption of Mount Pinatubo in 1991, the Earth's surface cooled by approximately 0.5°C within a few years (IPCC, 2014). This cooling effect—caused by the shading from ash particles and sulphur compounds released into the atmosphere—is what SRM seeks to mimic. For volcanic eruptions, the location and altitude at which particles are released are crucial for the magnitude of the cooling effect. Therefore, the impact of SRM would depend on where and to what extent it is deployed, for instance, whether it would be used only in the Northern or Southern Hemisphere, over the poles, or near the equator (Bednarz et al., 2023). While the theoretical effects of SRM are often inferred from the relationship between volcanic eruptions and global temperature variations, a direct comparison is only possible to a limited extent. Thus, significant uncertainties remain regarding the exact effects of SRM (DFG; 2014).

Figure 4

Overview of the earth's radiation budget



Source: German Environment Agency

4

The Effects of SRM on the Global Climate

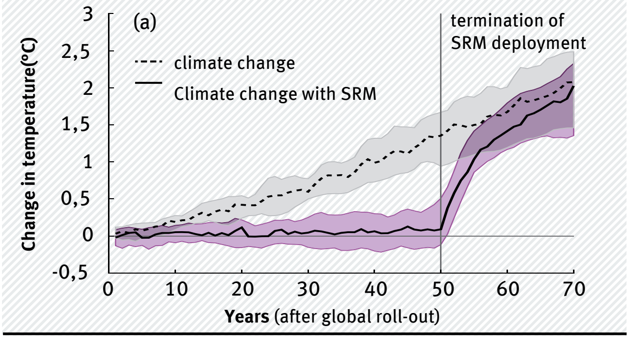
That much is certain: SRM cannot restore pre-industrial climate nor preserve the current one (Kravitz et al., 2013; MacCracken, 2009). By manipulating the Earth's radiation balance, the entire climate system would be fundamentally altered. Moreover, SRM only addresses global warming as a symptom of climate change, not its root cause, which is anthropogenic GHG emissions (Quaas et al., 2017).

This explains the greatest danger posed by SRM: the so-called **termination shock**. If SRM were to be abruptly halted, there would be a sharp rise in global temperatures, leading to sudden climate change within just a few years (Brovkin et al., 2008; Jones et al., 2013). Adapting to such a rapid temperature increase would be extremely difficult, if not impossible, for humans, animals, and plants (IPCC, 2014). This could result in a significant loss of biodiversity, potentially leading to mass extinctions (Trisos et al., 2018). The termination of SRM could be triggered by terrorist attacks, military conflicts, natural disasters, or collisions in space that destroy its infrastructure (Parker, 2018).

Thus, the masking of global warming through SRM would need to be maintained and adjusted until GHG emissions are eliminated. SRM would likely need to be sustained even beyond this point until atmospheric GHG concentrations are reduced to levels where the associated warming is minimal enough for humans and ecosystems to successfully adapt. Some of the emitted CO2 remains in the atmosphere for thousands of years, continuing to contribute to the greenhouse effect. At the time of potential SRM deployment, it would be unclear whether the necessary emission reduction would be realized and whether carbon dioxide removal (CDR) technologies would develop sufficiently to allow for the gradual phasing out of SRM. In any case, the continuous use of SRM would have to be ensured **over multiple generations and centuries** (Baur et al., 2023b; MacMartin et al., 2014).

Figure 5

Schematized termination shock



Source: German Environment Agency based on (IPCC, 2014)

It is also important to consider that SRM's desired effect would be based on the global average temperature, while different regions and climate zones might experience **overcooling or additional warming**. Cooling is generally projected for the tropics, while the polar regions would continue to warm. These temperature differences would, in turn, alter the global distribution and frequency of precipitation, particularly the monsoons (Baur et al., 2024; Roy, 2022; Irvine et al. ,2019; Gabriel et al., 2017; Kravitz et al., 2013; Davies, 2011). This would lead to a weaker hydrological cycle, increased desertification, and negative impacts on human, animal, and plant communities. **Global wind patterns**, such as the jet stream, ocean currents, and the Intertropical Convergence Zone (ITCZ), would also shift as a result of SRM (Tilmes et al., 2013; MacCracken et al., 2013; Davies, 2011).

A central component in this effect chain is the temperature of the stratosphere. Particels deployed there would not only reflect radiation, but also absorb it, leading to stratospheric warming. This temperature increase of up to several degrees Celsius would also change the dynamics of the atmosphere. A warming of the tropical stratosphere could thus slow down the quasi-biennial oscillation or bring it to a complete halt (Laakso et al., 2022). This wind system influences the dynamics of hurricanes and also the Indian monsoon.

5 Narratives and Justifications for SRM

Even among the strongest proponents of SRM, there is consensus that SRM should, due to its dangers and uncertainties, under no circumstances be deployed globally at present (cf. Callies, 2019).Nevertheless, some do not rule out its future use and even claim that its potential use may be inevitable (COC, 2023; MacMartin et al., 2014). Two main justifications are often cited to support this position (Parson et al., 2013).

The first justification assumes that the consequences of climate change could become so catastrophic that SRM, despite all the existing risks, would be used as a **desperate last-resort solution** to stop global warming. In such a scenario, the dangers of SRM could be seen as the **lesser evil** compared to the dangers of unchecked climate change. However, whether SRM could ever actually be considered an appropriate last-resort solution is questionable and is the subject of scientific studies (Neuber et al., 2020; Gardiner, 2013; Gardiner et al., 2010). It is debated not only for ethical reasons, but also due to the fact that the technical development of the infrastructure could take around two decades and likely would not be, as often claimed, available quickly and cheaply (Smith, 2024). Because SRM is therefore not well suited as a mere short-term emergency option, it is argued that its deployment should be prepared in advance.

The second justification is that a moderate and temporary use of SRM could **buy time** to moderately reduce greenhouse gas emissions, rather than enforcing the drastic reductions that are actually needed (buying time argument). This, on the one hand, could lower the costs of economic innovations and, on the other hand, reduce the pressure to adapt to the consequences of climate change. There are numerous simplified depictions of how the curve of global average temperature could be flattened using SRM (peak-shaving). The "peak shaving" assumes that rapid reductions in greenhouse gas emissions would still have to be carried out in parallel to SRM deployment so that SRM would become unnecessary as quickly as possible and would not need to be maintained for centuries, as previously described (Neuber et al., 2020). The need to reduce GHG emissions would probably be neglected all the more (mitigation deterrence, Section 8.3) if SRM could actually be used as safely and flexibly without risks and conflicts, as is assumed for this idea.

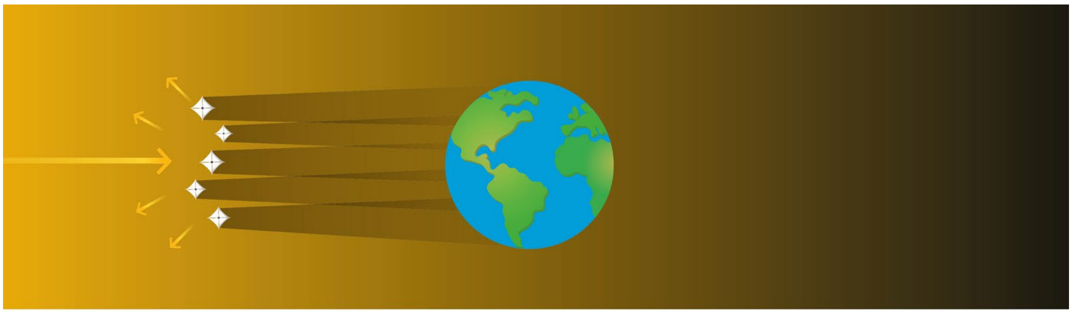
Another, less common argument in favour of SRM is that the release of greenhouse gases, and thus climate change as a whole, is already a far riskier experiment undertaken by humanity. And therefore – so the argument goes – one could justify daring yet another experiment, namely SRM. However, from an ethical perspective, the distinction between intentional and unintentional actions is crucial, and climate change cannot be equated with the deployment of SRM (Schäfer et al., 2015; Owen,2014). The argument also suggests that the "follow-up experiment" involves the same mechanisms as global warming. In reality, however, it interferes with new subsystems of the climate system (Section 3.1).

Against the backdrop of unpredictable climate changes and the incomparable interference with the environment (and possibly space) through SRM, the ethical question arises about humanity's role in nature. In this context, the accusation is examined that SRM has no justification at all and is instead an expression of human hubris (Owen, 2014).

6

SRM Approaches

6.1



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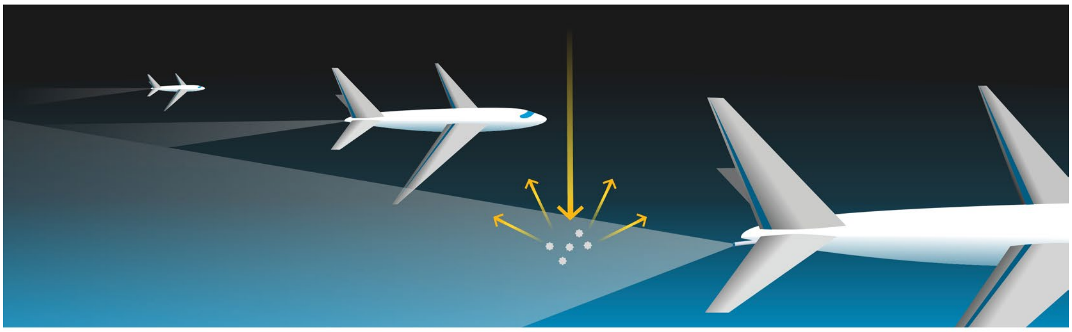

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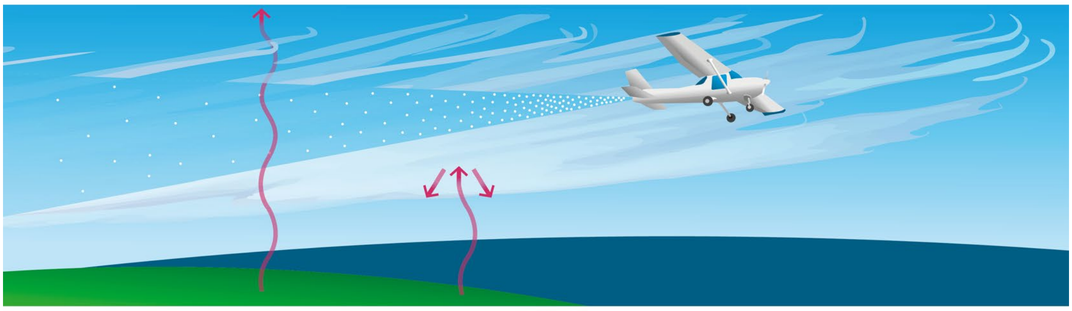

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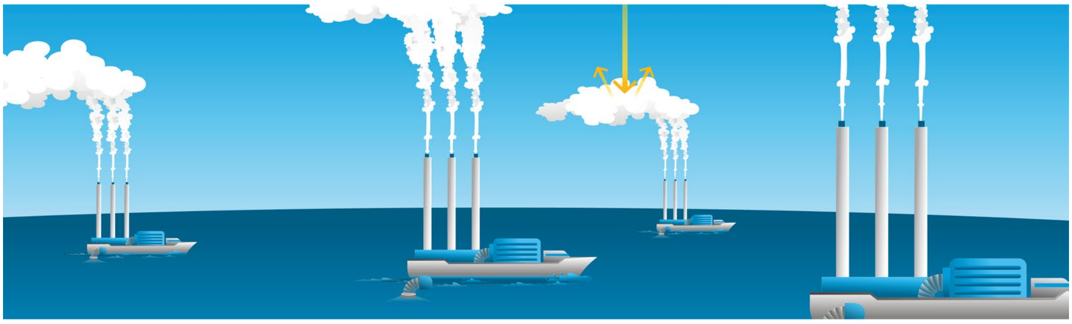

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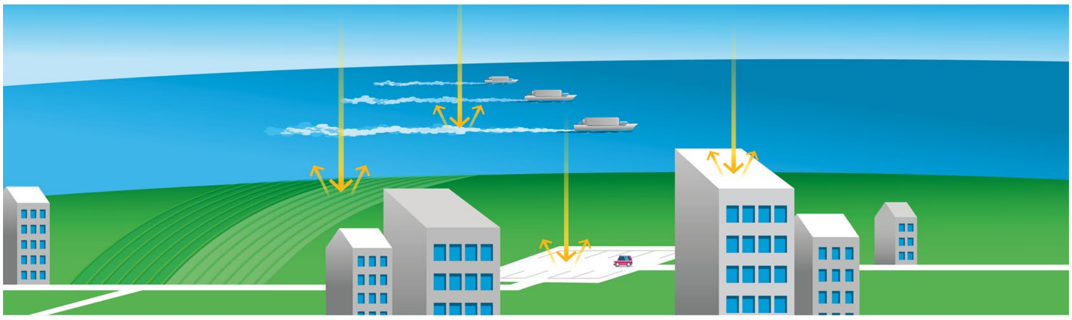


6.1 Planetary Sunshade and Other Space-Based Megastructures

Gigantic space mirrors that prevent part of the sunlight from reaching Earth: What may sound like science fiction is, at least for some researchers, a serious option. The most well-known concept is the proposal of a **planetary sunshade** (or: **planetary sunshield**). This megastructure would need to be installed behind the so-called inner Lagrange point between the Sun and Earth (L1), as it could be held in a stable position there by the balanced gravitational forces of the Sun and Earth. At this point, the structure would be about 2.4 million kilometres away from Earth, approximately six times the distance from the Earth to the Moon. Due to this distance, a sunshield would no longer cast a direct core shadow on Earth but rather a diffuse partial shadow that would spread evenly over the entire globe. To create such a large shadow, the sunshield would need to be between one and two million square kilometres in size and ideally composed of many large solar sails (PSF, 2023).

In recent years, there have been several space missions where solar sails have been tested as fuel-free propulsion systems for satellites. A solar sail from NASA's 2022 “NEA Scout” mission measured 86 square meters (Locket et al., 2020). Recently, NASA successfully built a 1,700 square meter solar sail for the “Solar Cruiser” mission. This sail was intended to be placed at the L1 point and demonstrate that such an installation could be held in position for an extended period. The rocket launch was initially planned for 2025 but has been postponed to 2028 due to time and budget issues (Johnson et al., 2023). Although these solar sail tests are not directly related to SRM, the research results would be essential for further development of an SRM sunshade. For this reason, the Planetary Sunshade Foundation (PSF) urges the U.S. government to fully fund and carry out this mission (PSF, 2023).

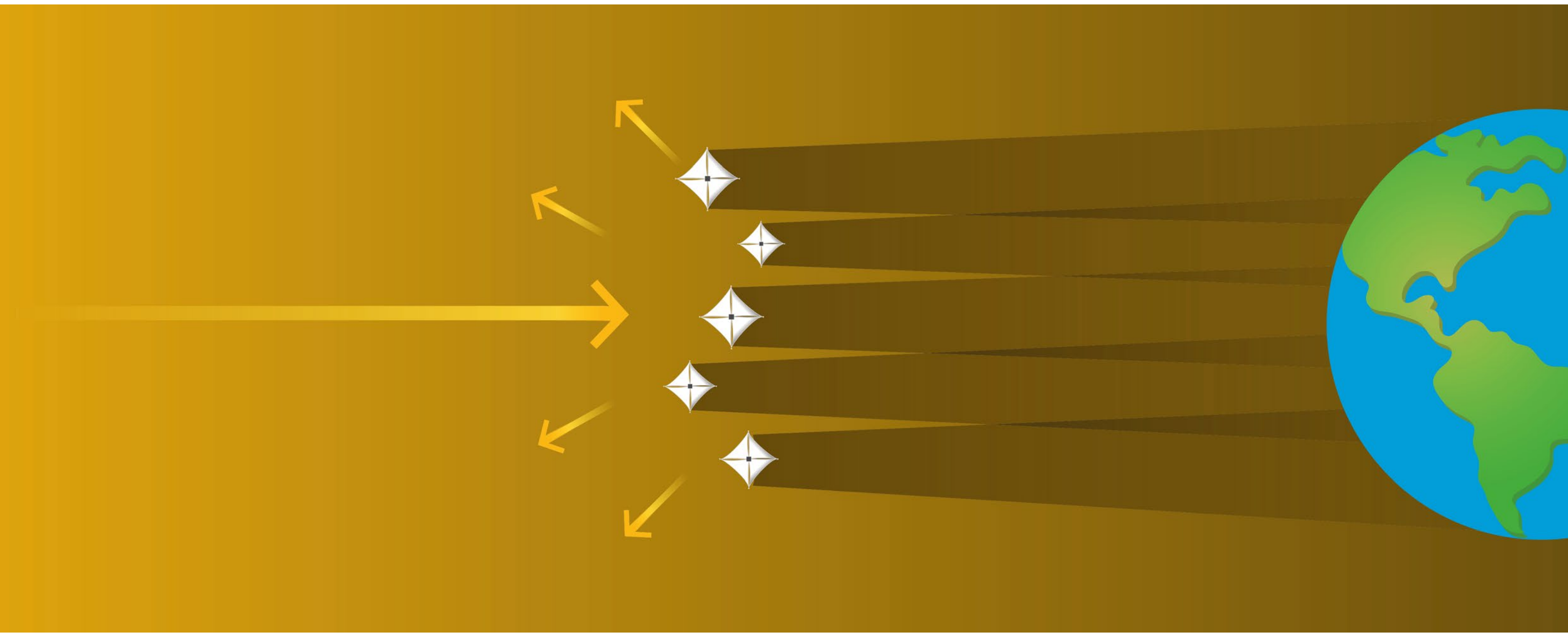
The material used for solar sails, developed more than twenty years ago, consists of an extremely thin plastic film coated with aluminium. This reflective membrane could also be used for sails larger than 10,000 square meters (NASA, 2024) making it suitable for SRM purposes. A sunshield capable of lowering Earth's temperature by 1°C would require an estimated seventy to hundreds of millions of tons of material (PSF, 2023). Thousands of rocket launches over several decades would be necessary to transport these masses into space. Therefore, there are considerations to construct only the basic structure on Earth and transport it into space by rocket. The raw materials could be mined directly from the Moon or asteroids and processed in space, as rocket launches from the Moon would require less fuel (Scott et al., 2022; Bewick et al., 2011). However, even if materials were mined on the Moon, a significant number of rocket launches from Earth would still be needed, releasing substantial amounts of water vapor, potentially CO2, and nitrogen oxides, which would accelerate global warming and stratospheric ozone depletion (Roy, 2022).

To accelerate and reduce the cost of this industry, investments would be necessary in space logistics, such as refuelling stations and fuel production (NSTC, 2022). To reduce material costs and stabilize the position of the shield, a tether could be envisioned, with a counterweight on the Sun-facing side. If equipped with solar panels, the tether's length could be flexibly adjusted to accommodate specific situations, such as solar winds. Additionally, this tether would serve as a safety measure, ensuring that a malfunctioning sunshield would be pulled toward the Sun instead of crashing down to Earth, which could have disastrous consequences. However, such robust, long tethers do not yet exist (Szapudi, 2023).

Since the construction of such a megastructure would take many decades, it is not a short-term measure against climate change. Instead, a sunshield could eventually replace temporary, non-permanent methods such as Stratospheric Aerosol Injection (SAI, Section 6.2). A sunshield is portrayed as a sustainable, permanent solution (PSF, 2023). At the same time, the structures are considered reversible, as they could simply be allowed to drift off into space, thus reversing the cooling effect (Baum et al, 2022). However, the sudden removal of a sunshield, whether intentional or accidental, would lead to a Termination Shock (Section 4) (PSF, 2023). Furthermore, it is both ethically and technically problematic to dispose of such a megastructure in space. Space debris is already a serious and rapidly growing problem (ESA, 2023).

The Planetary Sunshade Foundation places the further development of this method in the context of an arms race for space. It is promoting the project with the claim that the pioneering countries of lunar mining and space logistics could claim the entire economic advantage for themselves (PSF, 2023). This way of thinking promotes neo-colonialist structures and power imbalances, which would also be perpetuated and even exacerbated beyond Earth, because the financial advantage would lie not only with the industrialized countries, but also with individual space powers. Climate action appears to be merely a pretext here.

In addition to the solar shield, there are other proposals for space-based SRM, such as rings made of lunar or asteroid dust, glass shields, mirrors and other reflectors that would be installed both in low-Earth orbit and at other Lagrange points (Baum et al, 2022; Beweick et al, 2013). Dust clouds, for example, would be less costly to produce but difficult to regulate. Depending on the orbit in which they circle, they would only be positioned in front of the sun two times, but they would block much more radiation than desired. Installations close to earth harbour the risk of collision with satellites and space debris. In addition, their changing shadows would be clearly perceptible and would affect plant growth and life on Earth (Bewick et al., 2011). Some of the ideas are based on very few, individual observations. Once, for example, Venus briefly moved between the Sun and Earth, but too briefly to have a measurable temperature effect (PSF, 2023). And during the Little Ice Age a couple of centuries ago, reduced sunspot activity led to colder winters (Baum et al, 2022).



6.2 Stratospheric Aerosol Injection

When SRM is discussed, it often refers to the injection of aerosols into the stratosphere, i.e. at an altitude of around 20 km, known as stratospheric aerosol injection (SAI) (HBS, 2021a). SAI is the most popular approach, as the desired cooling effect was derived from that of volcanic eruptions (Section 3.3). So far, research has been based in particular on these analogies and computer models (Section 7.1); field experiments have been stopped (Section 7.2).

Aerosols can have cooling or warming properties depending on their chemical composition and altitude. In SAI, chemicals that reflect more sunlight into space are released into the stratosphere, thereby increasing the planet's albedo. From the point of release, they would spread globally through worldwide wind systems, altering the climate system (Section 4) (Baur et al., 2024).

The best-understood substance is sulphur dioxide (SO_2), which reacts with atmospheric water molecules to form sulphate aerosols. However, due to the well-known negative effects of sulphate aerosols, other substances like calcite, soot, titanium dioxide, zirconium dioxide, aluminium oxide, and diamond dust are being discussed and studied in laboratories (Vukajlovic, 2021; Smith, 2020). The effects of these artificially produced **chemicals** could be more controllable than SO_2 and sulfuric acid (Lawrence et al., 2018). However, like sulphate aerosols, they also carry the risk of warming the stratosphere by several degrees Celsius (Lawrence et al., 2018; Jones et al., 2016). Currently, most predictions still rely on the assumption of using sulphate aerosols (Brody et al., 2024).

In the case of sulphate aerosols, the resulting **depletion of the ozone layer** is well-researched. These aerosols interfere with the chemical processes that form ozone, thus reducing the concentration of stratospheric ozone (Drdla und Müller, 2012). Additionally, the absorption properties of sulphate aerosols lead to warming of the stratosphere, which alters atmospheric currents such as the Brewer-Dobson circulation and the quasi-biennial oscillation, disrupting the global distribution of ozone (UBA, 2016). Changes in stratospheric chemistry also affect methane, nitrogen oxides, water vapor, and cloud dynamics (IPCC, 2018). The damage to the ozone layer, which protects against harmful UV radiation, and the resulting expansion of the ozone hole, particularly over Antarctica, poses a threat to the biosphere in general and human health specifically.

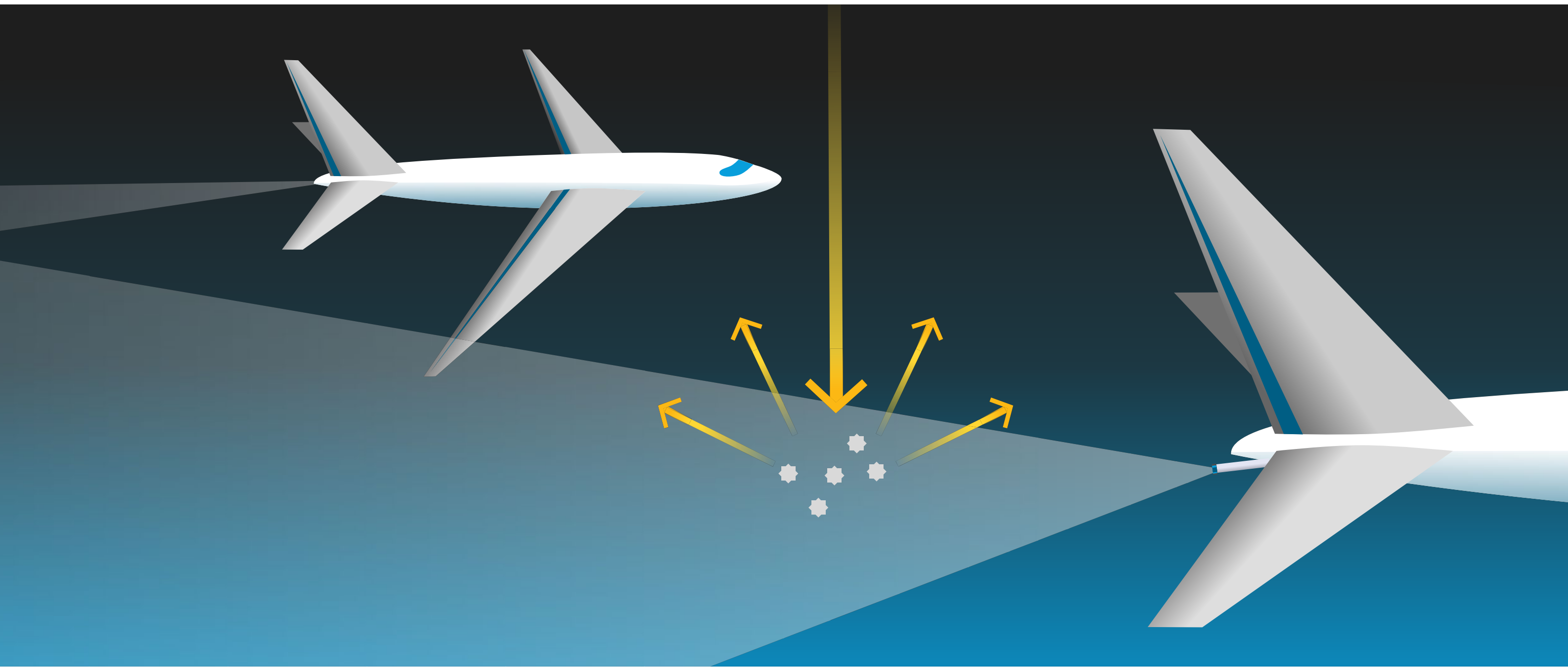
Another environmental and **health risk**, previously considered resolved, would be the return of acid rain if the sulphate aerosols are washed out of the atmosphere. Any additional acid deposition is a burden on ecosystems (Schäfer et al., 2015; Robock, 2008).

SAI would also result in less visible light reaching the Earth's surface than at present. This effect would be similar to "shadowing" and would make the sky appear permanently milky white, which would have a non-negligible impact on human mental health (PSF, 2023; Robock, 2008).

Aerosols only remain in the stratosphere for a few years or months. As they sink, the aerosols influence the composition of cirrus clouds and thus possibly have an unexpected additional cooling or warming effect (Section 6.3) (Robock, 2008; Kuebbeler et al., 2012).

Due to the only temporary effect, aerosols would have to be continuously produced and spread over centuries (Neuber et al., 2020). Balloons or rockets could also be considered, but above all **aeroplanes**. Normal commercial aircraft or jets cannot fly at an altitude of 20 kilometres and would not be suitable for SAI due to their shape. It would require hundreds of custom-built aircrafts (Smith, 2024; Smith et al., 2018). In addition, an infrastructure would be needed so that this fleet could continuously land, refuel and take off again. The design of SAI aircrafts is described in detail in studies (Bingaman et al., 2020; Janssens, 2020).

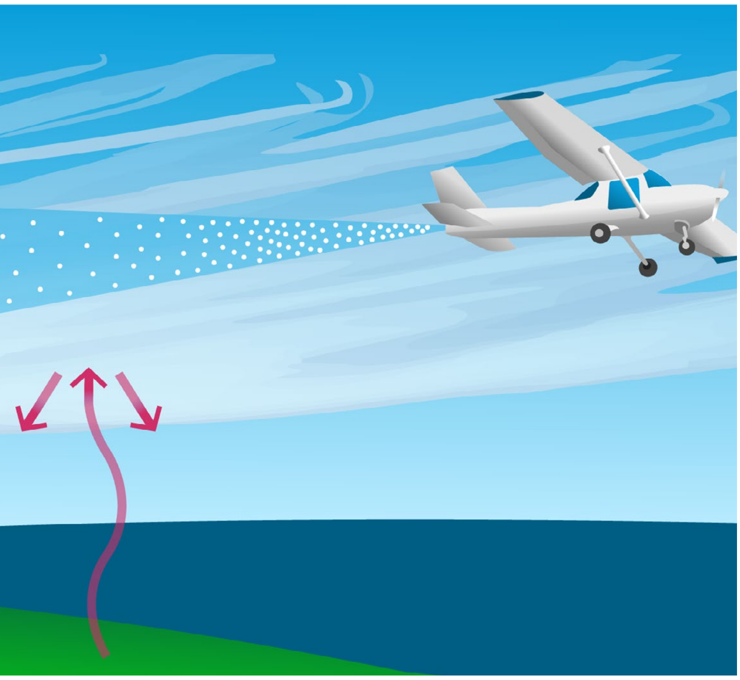
To reduce global average temperatures by 1 °C, around 8 to 16 million tonnes of SO2 would have to be emitted annually (WMO, 2022). If aerial refuelling aircrafts were used for this purpose, a conservative estimate of around 137,000 **flights per year** would be necessary for 8 million tonnes of SO2. One study assumes that 4,000 flights will take place in the first year and 60,000 flights per year 15 years later (Smith et al., 2018). As there is currently no alternative to fossil fuel-based paraffin available in sufficient quantities, these flights would end up causing a lot of emissions and cancelling out the theoretical cooling effect of the aerosols emitted. In addition, the ozone layer would be damaged to the same extent as it was during the greatest expansion of the ozone hole in the mid-1990s (WMO, 2022). Additionally, the question arises about sourcing SO_2, as natural deposits are limited. Artificial production is based on the **petroleum industry** (Muraca et al., 2018; Brovkin et al., 2008). The production of SO_2 itself would therefore cause greenhouse gas emissions, which would also have to be offset.



6.3 Cirrus Cloud Thinning

Cirrus clouds (also called ice or feather clouds) are located higher than other types of clouds, usually in the upper troposphere, at altitudes of about 5 to 13 km. Due to the cold temperatures at these altitudes, they are composed of ice crystals rather than water droplets. The properties of cirrus clouds generally prevent long-wave heat radiation from escaping into space (Section 3.1), meaning they mostly have a warming effect. The SRM approach known as **Cirrus Cloud Thinning (CCT)** aims to thin cirrus clouds so that more heat radiation can escape into space, resulting in a cooling effect (Tully et al., 2021). Unlike other SRM methods that focus on altering solar radiation, this approach is sometimes classified under "Radiation Modification."

The idea behind CCT is to increase the formation of larger ice crystals instead of numerous smaller ones, as larger crystals would retain less heat radiation. To achieve this, additional particles, such as sulphate, aircraft soot, or mineral dust, would need to be released into the atmosphere to serve as condensation nuclei at those altitudes (Tully et al., 2021). Cirrus clouds, being located at 8-13 km altitude, are reachable by commercial airplanes. If the required amount of condensation nuclei is not too large, specialized planes for CCT may not be necessary. The amount of particles to be released is estimated to be only a few kilograms per flight (DFG, Website).



In science, there are still major uncertainties regarding the formation, dynamics and composition of clouds. Statements about the manipulation of clouds are therefore subject to even greater uncertainty. Research on CCT is currently mainly based on models (Section 7.1) which show similar effects to SRM in general with regard to CCT modification, for example a changed water cycle (Tully et al., 2021; Storelvmo et al., 2013). There are also laboratory experiments in so-called *cloud chambers* (Steinke et al., 2024).

It is difficult to predict when and where cirrus clouds will form, meaning that CCT is not suitable for continuous and global use (Caldeira et al., 2017). Implementation at the poles in particular is being discussed because the air there naturally contains fewer particles (Gruber et al., 2019). The polar regions are particularly vulnerable to climate change, and the melting ice in Antarctica and the Arctic reduces the albedo, further driving warming. During the polar night, the warming effect of cirrus clouds is especially pronounced, as the cooling effect of reflecting sunlight is absent (DFG, Website). However, it is important to note that the polar regions are part of the complex global climate system, and wind circulations and the water cycle ensure that the effects of CCT would also be felt outside the poles. If the particles enter cloud-free, highly humid air masses, additional cirrus clouds could form, having a warming effect instead (HBS, 2021b).

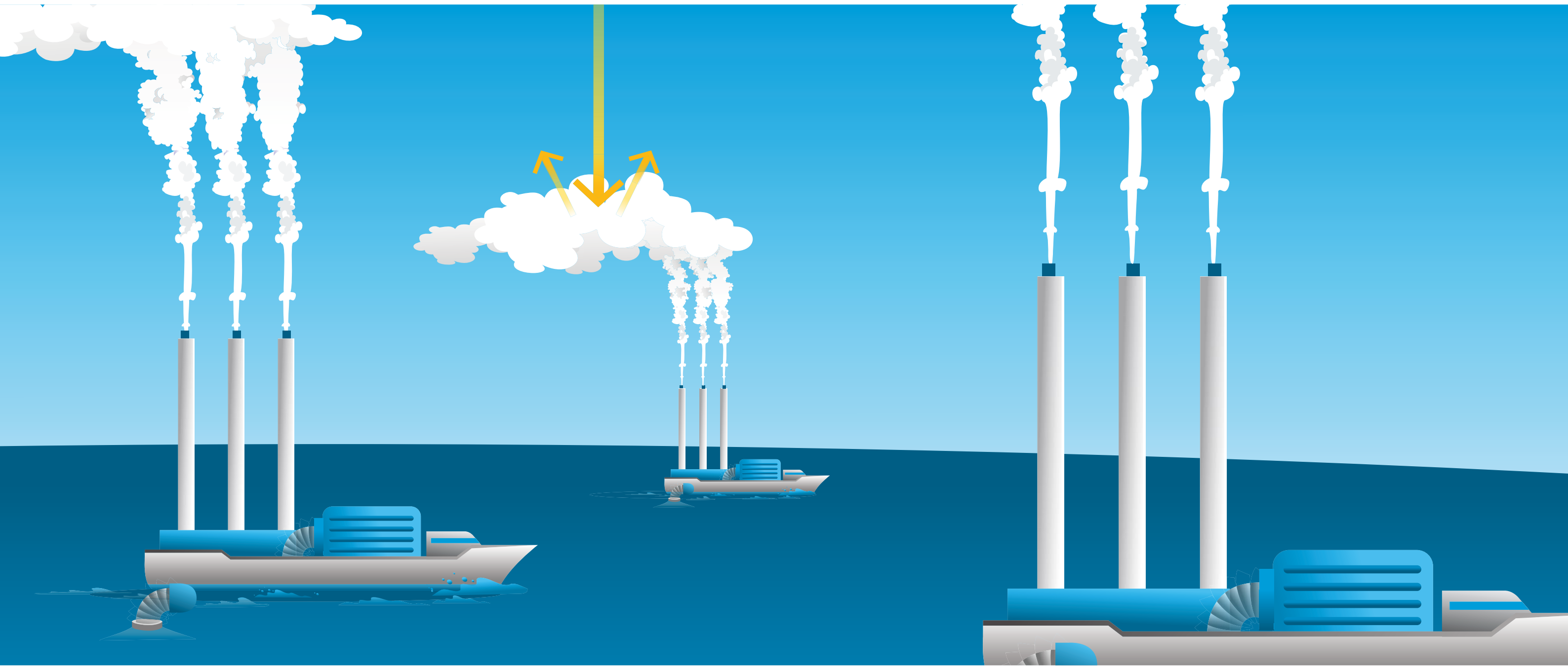
If too many condensation nuclei are introduced, an excessive number of ice crystals could form, leading to the opposite effect: the cirrus clouds would trap even more heat than before. This unintended warming effect could be deliberately used to melt sea ice in the Arctic, potentially opening up new shipping routes. However, the threshold for the amount of particles required to trigger this effect is not yet known (HBS, 2021b).

6.4 Marine Cloud Brightening

Clouds consist of millions of tiny water droplets. In addition to temperature and humidity, tiny particles such as grains of sand, salt crystals or dust (so-called condensation nuclei), on which water can condense and form droplets, play a key role in their formation. The content of water droplets determines the reflective properties of clouds and therefore their albedo. In marine cloud brightening (MCB), existing stratocumulus clouds in the lower troposphere are brightened so that more solar radiation is reflected on their white surface (Possner et al., 2023; HBS, 2021c; Latham 1990). The marine atmosphere tends to be cleaner and dust-free. Artificial enrichment of the maritime atmosphere with condensation nuclei could therefore significantly increase cloud albedo, because considerably more and smaller droplets would then form, which would scatter and reflect the sunlight more strongly (Latham et al. 2012). Suitable particles that act as condensation nuclei could be deployed by ships. The salt content of the seawater would be sufficient for this, so that no additional chemicals would be necessary (although the properties of other substances are nevertheless being investigated, e.g. paraffin-like oils, Russel et. al 2013).

Since clouds are spatially irregular and have limited lifespans, the release of particles would need to occur in large quantities, be distributed over wide areas, and be repeated frequently. Because the clouds formed would dissipate after only a few hours or days, studies estimate that between 10,000 and 100,000 ships would be needed to continuously spray salt particles in order to achieve a significant effect (Claudel et al., 2024; DFG, XXXX). To lower the global average temperature by 1°C, studies calculate that 70 million tons of dry sea salt would be required per year (IPCC, 2018). Since ships are equipped with relatively short "chimneys," natural updrafts would have to be used to lift the seawater to heights of several hundred meters to two kilometres (DFG). This massive fleet of autonomous ships would require enormous amounts of ship fuel, which is currently derived from fossil fuels, thereby generating additional emissions that would further contribute to global warming and need to be offset by MCB. Thus, the development of autonomous, renewable-energy-powered specialised ships would be required first. Due to these challenges with MCB, drones are also being considered as an alternative to transport optimized synthetic salts instead of sea salt to save on both quantity and energy (Claudel et al., 2024).

One of the most important effects is the change in light intensity and temperature in the vicinity of the deployment site, which can have a negative impact on several processes in the atmosphere and the ocean. For example, the growth of phytoplankton in the ocean may decrease because of shading. In addition, the mixing of the upper ocean is increased by strong local cooling, which in turn changes the nutrient supply and has an impact on biodiversity and ecosystems. Far-reaching changes in the water



column, food webs and biogeochemical cycles are to be expected, which could also affect the ocean's ability to sequester carbon (GESAMP 2019).

The regional change in the radiation budget and water cycle has transboundary, global consequences for the atmosphere and the oceans due to the indirect and complex connections with ocean and wind circulation (Lockyer et al., 2019, Possner et al. 2023). For example, MCB has an impact on sea level rise, which could decline on one side of the Earth but be all the more drastic on the other (Haywood et al., 2023). The same applies to MCB as to SRM as a whole: Just because the global average temperature can be reduced mathematically, the temperature is not evenly distributed, and the regional effects can vary. This is a problem with MCB because although GHGs have a global and round-the-clock effect, MCB would only have a regional effect and only during the day. The resulting uncertainty in the study results is exacerbated by uncertain correlations, for example with ocean circulation (Ricke et al., 2023). Overall, the principle of MCB is based on theoretical considerations and computer modelling (Possner et al. 2023).

It is being discussed and trialled whether the small-scale use of MCBs can be useful to mitigate hurricanes locally, for example, or to protect coral reefs from excessive warming (Wanser 2017). MCB is already being researched for this purpose on the Great Barrier Reef in Australia (Tollefson, 2021). The current field experiment in Australia is taking place on a ship on which an atomiser is installed. It has many small spray heads that break the seawater into tiny particles and spray them extremely quickly. These specially designed spray heads are similar to those used in weather modification (see text box). For chemicals other than sea salt, appropriately adapted spray heads would be required, which represents an engineering challenge (Wanser 2017).

Precision is also important. If the particles are too small or too large, evaporation or rain can occur, which could dissolve the cloud and thus have the opposite effect (Feingold et al., 2024). Accordingly, the location and timing of the injection and the presence of stratocumulus clouds are also crucial (Possner et al. 2023).

Excursus: Weather modification

Weather modification methods, also known as cloud seeding or rain enhancement, are very similar to CCT and MCB. While CCT and MCB as SRM measures are intended to change the global climate in the long term, weather modification is only intended to have a localized and short-term effect. For example, weather modification is intended to promote rain or snowfall or prevent severe thunderstorms. For example, silver iodide, lead iodide or copper sulphide is burnt or salt water is sprayed to create small particles (Gekkieva et al., 2021). Depending on whether a (thunder) cloud or clear sky was already present, this can prevent the formation of large hailstones, stimulate the formation of raindrops or promote the formation of a new cloud. The effect is not yet completely certain, as it is difficult to judge whether the weather event would have occurred without the addition.

The environmental impact of the chemicals applied and the effect in neighbouring countries also need to be investigated. Nevertheless, weather modification is being further developed and used. China, for example, has had a centre specifically for weather modification since 2021 (Simon et al., 2023) and the United Arab Emirates has had an extensive funding programme for outdoor experiments on rain enhancement since 2015 (www.uaerep.ae; Hosari et al., 2021). In Germany and Europe, aircraft have been used for hail defence for several decades (Svabik, 1989). The World Meteorological Organization (WMO) has assembled a team of experts in the field of weather modification that has published a report on the state of development (Flossmann et al., 2019; WMO, 2018). Due to the similarities between weather modification and SRM, the question arises as to whether the research results and infrastructure could ultimately also be used for SRM (Bluemling et al.,2020).

6.5 Increasing the Surface Albedo

There is a whole range of approaches that aim to increase the albedo (see section 3.2 of certain surfaces. White colours or reflective materials can be applied on land, in water, in cities, in deserts or on ice. The systematic, large-scale use of these small-scale methods would have an impact on the global climate.

White cities and bright fields

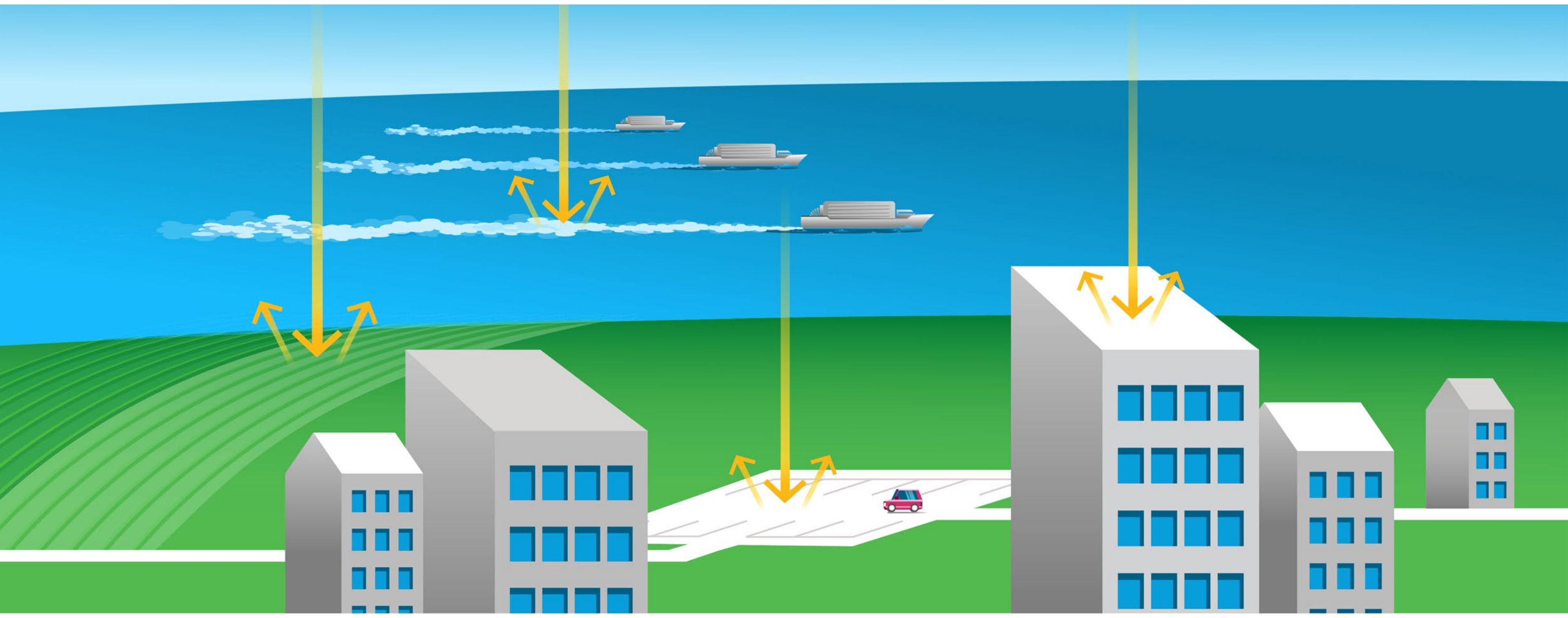
In urban areas, there is a prevalence of dark, warm surfaces. Most surfaces are comprised of roofs and roads. Thus, it sounds promising to colour all asphalt and roof surfaces white. The sheer amount of urban surface area should be able to offset the climate change effect of total global CO2 emissions (Akbari et al., 2008). However, it is important to note that this would not be a sustainable measure. The easily soiled surfaces would have to be repainted repeatedly. The paints used for this could pollute the soil and groundwater if they are applied directly to the road in large quantities. Whitewashing roofs is not efficient in areas where it is dark for long periods in the winter and where surfaces are often covered by snow anyway. On the other hand, it is advantageous in warm regions because the cooled buildings require less energy for air conditioning (Tzempelikos et al., 2021; Oleson et al., 2010). Overall, the white buildings cool the ambient temperature. This is why New York has already painted numerous roofs white and Los Angeles has painted some streets white in pilot projects. However, these measures are not SRM experiments that aim to change the global climate, but rather efforts to counteract the heat island effect of cities (see text box) (Frie et al. ,2022).

Forestry and agricultural areas could also be not completely white, but at least lighter in colour. Various methods of soil cultivation, but especially the selection of lighter-coloured plants, are being discussed. Some varieties contain less chlorophyll, have more reflective wax layers on their leaves, or have favourable canopy growth forms. These traits can be enhanced through breeding or genetic modification (Genesio et al.,2020; Morton, 2009; Ridgewell et al., 2009).

Theoretically, the whitening approach could be applied to any surface. For example, there are ideas to cover the desert with white foil, which could destroy the entire ecosystem (HBS, 2021d). One company offers to distribute aluminium-coated sandbags in the desert (https://lumobag.com/). Deposited sandbags or foils can sink into the sand due to sandstorms and would require extensive maintenance.

Ship wake brightening and microbubble foam

Since the ocean is a large, dark surface with low albedo, there is the idea of covering it with white foam made of microbubbles. Machines would be required specifically to continuously produce microbubbles. The foam in the wake of large ships could also be treated with chemicals (e.g. surfactants) to make it last for weeks or months. If implemented on a large-scale, a vast portion of the world's largest interconnected ecosystem would be deprived of light. A continuous foam layer would not only block light but also reduce the oxygen supply, threatening the entire marine food web. Additionally, the surfactants



used could be toxic. The entire marine ecosystem would be endangered by such changes. The oceans play a crucial role in the Earth's carbon cycle, as they absorb and store carbon dioxide from the atmosphere. The large-scale deployment of this method could severely disrupt many of the ocean's functions, including its ability to store carbon dioxide (Robock, 2011). This method could therefore worsen climate change. Moreover, the ships and machines required for this process would produce additional greenhouse gas emissions, as emission-free fuel sources for ships are not currently available on a large-scale. It is also unclear whether the approach would work at all, as ocean bacteria could damage the microbubble layer (Minunno et al., 2023; HBS, 2021e; Zhao et al., 2020; Ortega et al., 2018; Gabriel et al., 2017; Crook et al., 2016).

Spreading reflective particles on the sea and on ice surfaces

In a similar approach, reflective materials, such as tiny glass beads, are to be spread on the ice and in the ocean (Johnson et al., 2022). The mass production of artificial snow using huge machines and the spread of large white plastic films or the stimulation of algal blooms (e.g. coccolithophores) are also being discussed (Farkas et al., 2023; Feldmann et al., 2019; GESAMP 2019; Field et al., 2018). Negative environmental impacts are to be expected due to the properties of the materials being deployed (GESAMP 2019). Plastic waste in the ocean is one of the most obvious problems. The materials released and their degradation products could also be toxic and accumulate in the food chain. The idea of dispersing reflective particles on the ocean surface stands in stark contrast to environmental policies aimed at reducing the input of nutrients, pollutants, and waste into the oceans. Additionally, there is a practical issue: to fully ensure the effect on albedo, the reflective surfaces would need to remain free from contamination and biofouling. The necessary cleaning would involve additional costs and chemical inputs and would require significant technical effort. Further environmental impacts would result from the required transportation, installation, maintenance, and disposal efforts, all of which would produce additional greenhouse gas emissions. Conflicts with other uses of the oceans are also to be expected. There are also concerns regarding ethical and security aspects (Bennett et al., 2022), and initial protests by affected Indigenous populations, such as against the Arctic Ice Project (https://www.arcticiceproject.org). Research on the use of reflective particles to increase the surface albedo of the oceans is still in its infancy, and numerous uncertainties remain regarding the types of materials, their environmental impacts in different locations and at different scales, their effectiveness as climate action techniques, and the economic and social feasibility of such large-scale activities.

Some of these geoengineering approaches are not aimed at lowering the global average temperature, but rather at slowing the flow rate of glaciers or the melting rate of ice shelves and sea ice to preserve ice sheets in Greenland, the Arctic, and Antarctica. The primary goal is to slow sea level rise. (Minunno et al., 2023; Lockley et al., 2020). As the melting of the ice would only be prevented, but no new white area with an additional cooling effect would be created, these approaches are sometimes differentiated from SRM. In studies, they are also treated as a separate geoengineering category called "**ice management**" or "**Arctic intervention**". However, even if they are specifically intended for Greenland, for example, the large-scale approaches have similar effects on the climate as a global SRM deployment, interfere with the water cycle and consume enormous amounts of resources (Argüello et al., 2023; Bodansky et al., 2020).

Excursus: albedo enhancement and climate adaptation

Not every measure to increase surface albedo necessarily qualifies as a geoengineering measure. By definition, geoengineering involves large-scale and profound interventions in the climate system. This is because such measures are intended to influence the climate globally. SRM approaches aimed at increasing surface albedo, in themselves, initially only have a localized effect, but they would need to be applied systematically and over a large area. When scaled up, they could have a significant impact on the climate and potentially create an entirely new climate.

Adaptation, on the other hand, aims to increase the resilience of systems to the impacts of climate change, rather than fundamentally changing the climate itself. Some adaptation measures also make use of the cooling effect of white surfaces, but only to achieve a local cooling effect. The distinction between SRM and adaptation is important, as adaptation, along with reducing greenhouse gas emissions, is one of the two key pillars of climate action.

To the extent that measures aim to deeply intervene in the climate system, they do not fall under the category of climate change adaptation. However, if the measures are intended and feasible to be applied only locally, they are considered adaptation measures (for further distinction, Section 9.1).

7

SRM Research

7.1 Uncertainties of SRM models

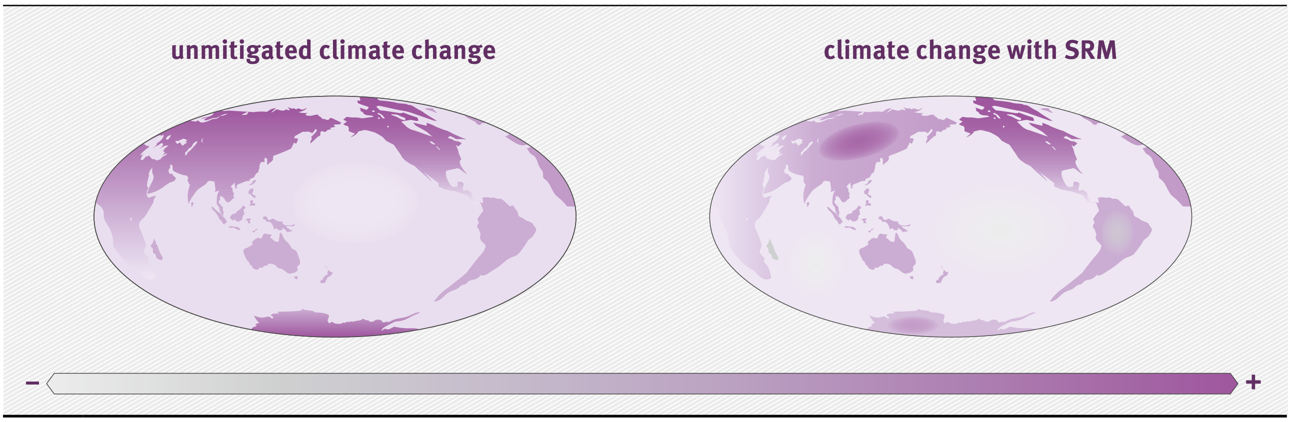
Models are generally an important tool in climate science, as they allow experiments to be carried out in a complex global system without actually intervening in the environment. In this way, the influences of different parameters can be compared with each other and projections for future developments can be made. Different models can be used as a basis, depending on the region and the issue to be covered. There are Earth system models, which in turn include individual models for the oceans and atmosphere, economic scenarios and combinations of both (DFG; 2014). The more detailed the resolution needs to be, the more computing capacity is required. Climate models have been developed and continuously improved for decades to describe and project the ongoing climate change. Nevertheless, there are considerable uncertainties, because fundamental processes and elements of the climate system are not yet fully understood, such as the dynamics of clouds or the dynamics of aerosols (Gettelmann et al., 2016). Even if they are the most suitable tool we have for predicting climate change, it must be borne in mind that modelling is always only an approximation of reality and cannot fully capture it (Alizadeh, 2022; DFG; 2014). This becomes particularly relevant, when political decisions with serious consequences, such as the use of SRM, are to be derived from this.

Geoengineering models have been developed based on climate models. The aim is to predict whether different SRM implementations could have a cooling effect and how these affect precipitation patterns, sea levels, temperature distribution and droughts. Determining the additional influence of SRM based on interactions whose true magnitude is more or less unknown is a major modelling challenge. (Caldeira et al., 2017). Even small deviations in the assumptions, parameterizations and simplifications can produce a wide variety of results and error ranges, so that either the potential or the risks of SRM predominate (ART GS EU Council, 2023; IPCC, 2022). This includes not only parameters of the climate system, but also socio-political and economic assumptions, which also determine the plausibility of the results (IPCC, 2022). SRM deployment would have to last one or more centuries, meaning that statements about its consequences would also have to be reliably projected over such long periods of time (Baur et al., 2023b). However, the uncertainty of scenarios grows exponentially over time and becomes a decisive factor after just a few decades (Alizadeh, 2022) The assumed timing of deployment, especially in combination with the assumptions on the course of climate change, can also significantly influence the results and limit the projected effectiveness of SRM or reverse the effect (Wieners et al., 2023; Ricke et al., 2023).

To better compare the results of different studies and make more reliable statements, standardised models from the coordinating Geoengineering Model Intercomparison Project (GeoMIP) have been used since 2010, based on the Coupled Model Intercomparison Project (CMIP), which provides the central scenarios for the IPCC reports. Within GeoMIP, there are standards for modelling SRM interventions called, for example, “G6solar” or “G6sulfur” (Visioni et al., 2023; Kravitz et. Al, 2011). In principle, these models greatly simplify the use of SRM. With “G6solar”, for example, only the parameter of the incident solar radiation is reduced. And in the other models, the injection of aerosols is also simplified and assumed to be centralized at one or a fewpoints, e.g. at the equator. The models are based on the CMIP6 scenarios SSP5_8.5, which projects unabated climate change with very high emissions, and SSP2_4.5, which assumes moderate climate action policies. The SRM input is often mathematically adjusted so that it is sufficient to reduce global warming from SSP5_8.5 to the level of SSP2_4.5 (Lozán et al., 2023; Yuo et al., 2023). The future effects of the idealized SRM deployment are then compared with those of unabated climate change. However, the current state of scientific knowledge is that the SSP5_8.5 scenario is now an unlikely worst-case scenario because it would require reversing climate action that has already been initiated (Fotso-Nguemo et al., 2024; Hausfather et al., 2020). Accordingly, almost all previous SRM studies are based on dubious assumptions. The results of the comparison of the risks of SRM and climate change depend largely on which comparison scenario is

Figure 6

Risk vs. risk modeling scheme



Source: https://acp.copernicus.org/articles/23/15305/2023/

chosen, so that the evaluation should always be carried out with an awareness of the uncertainties (Fasullo et al., 2023; Visioni et al., 2021).With the revision of the scenarios in the IPCC's 7th reporting cycle up to around 2028, the assumptions behind the geoengineering models will also be updated and SSP2_4.5 will be increasingly used. For the fast track of the CMIP7 process, an SRM simulation was selected that assumes SO2 injection (Visioni et al., 2024). While it is widely acknowledged that SO2 is actually unsuitable due to its negative side effects (Section 6.2), the modelling for both calcite and diamond dust as aerosols is not yet advanced enough.

The results of the modelling are often presented as world maps. As observational data does not exist for all regions, the available information must be interpolated to the entire world. There is less data available in the Global South in particular, while data is concentrated in industrialized countries. In the interest of transparency, the regions on the world map for which not enough data was available to calculate the values should be labelled. Regional peculiarities in particular are of enormous importance for risk assessment and are easily lost when comparing two world maps (Meyer et al., 2022; Ludwig et al., 2022). Short-term, local weather changes also have a long-term impact on society and ecosystems but are not depicted in the coarse temporal and spatial resolution of the models.

Nevertheless, it is important to model the effects of SRM deployment only in a "simulated world", as deployment in the real world is associated with serious risks (Sections 4 and 8) (DFG; 2014). However, although simulations and models generate indispensable knowledge about climate change and the fundamentals of the complex climate system, and increasingly meaningful results are obtained by comparing different simulations with each other, generalized statements that transfer the simulated effects to the real impact of SRM should be viewed with caution (Caldeira et al., 2017). There are no empirical values from the real world that could be used to validate the results of SRM. Data from actual observations are generally important building blocks of such climate system simulations (ART GS EU Council, 2023; Caldeira et al., 2017).

7.2 Laboratory and Field Experiments

According to some authors, the next step in the modelling process should be supported by field experiments conducted directly in the ocean, atmosphere, or space. These experiments should be small enough to avoid environmental impacts but still help to shed light on certain aspects more effectively (UNEP, 2023; ART GS EU Council, 2023).The exact behaviour of aerosols in the stratosphere, for example, cannot be predicted accurately enough using computer simulations or analogies to volcanic eruptions alone (Jinnah et al., 2023; Caldeira et al., 2017). This is why, for example, the UK and US projects abbreviated as SPICE and SCoPEx were planned, in each of which a test balloon was to ascend. However, these field trials on SAI failed due to protests by local residents and NGOs (Jinnah et al., 2024; Baker et al., 2024). The sulphate releases by balloon by a private company from the USA over Mexican territory also caused conflicts (SEMARNAT Mexiko, 2023). Field experiments were carried out to increase surface albedo (see section 6.5) and MCB (see section 6.4).

Small-scale outdoor experiments can contribute to verifying individual atmospheric physical interactions. However, it should be emphasized that **small-scale experiments are not suitable for providing sufficient knowledge about the risks of an actual SRM deployment**. In order to investigate the already known risks on a regional or global scale in more detail and to be able to assess them with sufficient reliability, field activities on a larger scale, i.e. on a regional or global scale, would actually be necessary (Parson et al., 2013). **Meaningful experiments would therefore have to be "global experiments" and would no longer differ from a deployment**. The same risks for the environment and the affected population groups, which may already be irreversible, would exist. (DFG; 2014).

One problem with field experiments would be to clearly attribute the consequences and possible damage, e.g. from floods and droughts, to the experiment and to rule out the possibility that these were not caused by other dynamics of our complex climate system (Terry et al., 2024; DFG; 2014). One problem with field experiments would be to clearly attribute the consequences and possible damage, e.g. from floods and droughts, to the experiment and to rule out the possibility that these were not caused by other dynamics of our complex climate system.[1]

In addition to field experiments, **laboratory experiments** are also carried out. These can involve testing the chemical properties of aerosols, foam and other materials or using cloud chambers to create artificial clouds (Steinke et al., 2024). In contrast to field experiments, laboratory experiments tend not to have any direct environmental impact

In principle, scientific experiments should serve to increase knowledge about the mode of action and risks of SRM. This is to **be distinguished from the development of technical infrastructure**, in which, for example, spray heads and balloons as well as space installations are designed, built and finally tested (Tollefson, 2021).

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[1] See the protests of Hungarian farmers in connection with hail protection: https://haszon.hu/haszonagrar/innovacio/jegkar-halalos-fenyegetes.

7.3 Does Research lead to Deployment?

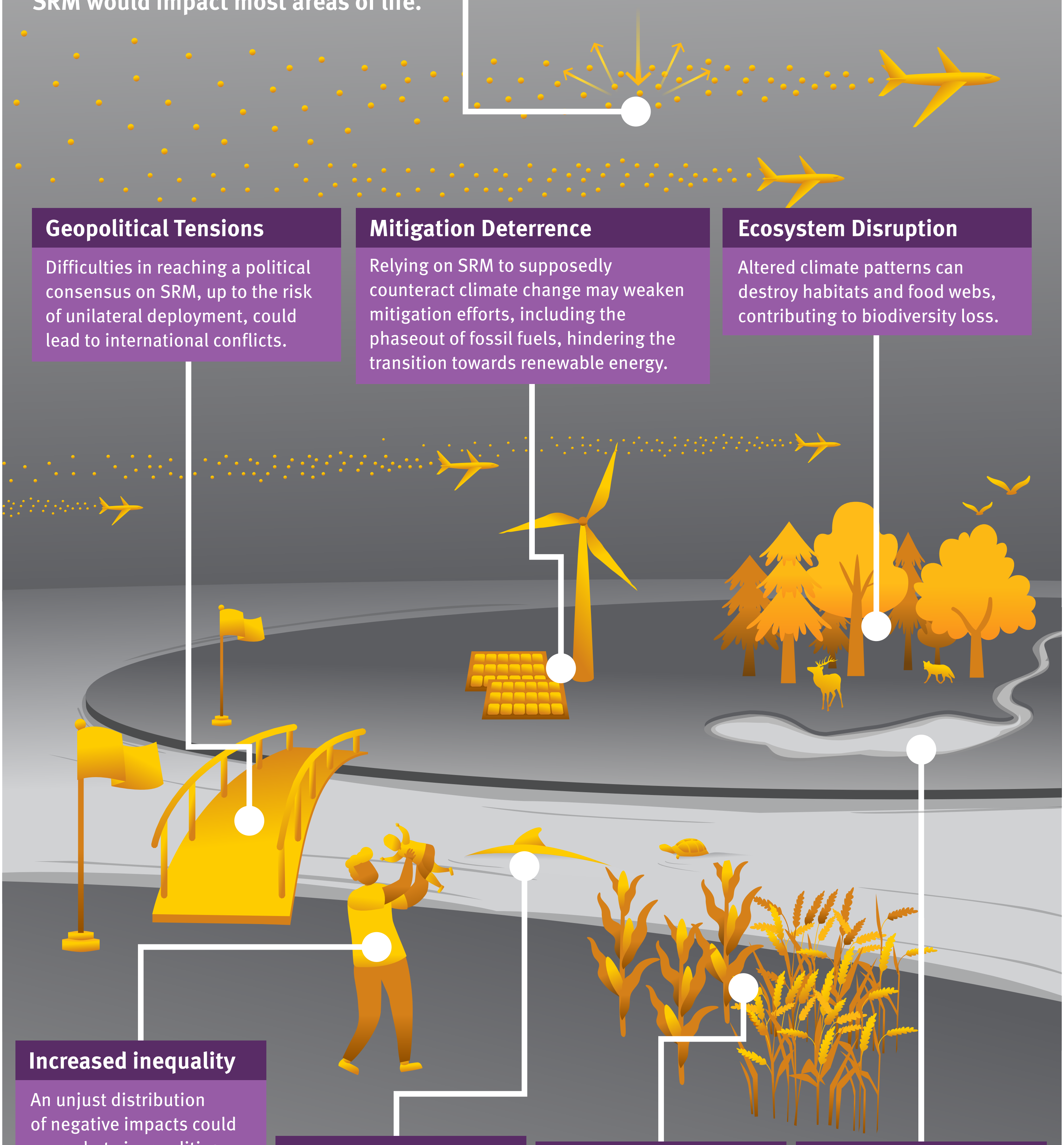
There is a lively debate as to whether more research, and in particular field experiments, will contribute to SRM ultimately being used. Figuratively speaking, one is standing on a **slippery slope** and gradually sliding from research into deployment (Callies, 2019). The conclusion drawn from this is to limit research on certain methods or scales, as it could lead to a point where the deployment is theoretically prepared, and this could then result in actual implementation (Andow, 2023; Quaas et al., 2017). In addition to technical feasibility, the political acceptance of small-scale SRM experiments is also helping to reduce the hurdles to larger-scale SRM deployment (Lockyer et al., 2019).Moreover, the scientific community itself or the institutions founded for this purpose act as a lobby for further research (Lin, 2016; Jamieson, 1996).On the other hand, project initiators want the high investment costs to be worthwhile (Gardiner et al., 2010). If the risks are found to be too high during the initial trials, it might therefore not be considered necessary to announce the cancellation of all efforts, but the conditions could also be scaled down so that the experiments do not have to be abandoned (Neuber et al.,2020). In addition, funding and infrastructure for other non-SRM projects are blocked and, as this means they can achieve less knowledge and progress, it is easier for the SRM experiments already underway to receive further funding. People also get used to new situations quite quickly, so that future generations may not even question SRM experiments. All of these points result in a positive feedback loop (McKinnon, 2019). Although it is also questioned whether suitable regulation could mitigate this effect (Callies, 2019), the risk that a research project could develop its own momentum towards deployment cannot simply be brushed aside and, in view of a precautionary policy, is considered a valid counter-argument (Andow, 2023). Research on SRM also has a great deal in common with general climate and atmospheric research, albeit with different emphases. It therefore makes more sense to invest effort and resources in understanding the climate system, as this will definitely help future generations, rather than in costly SRM experiments, the effects of which are unpredictable and potentially dangerous (Gardiner et al., 2010).

Extensive publicly funded research projects could also have an impact on markets and political processes. The normalization of SRM associated with extensive research projects may lead international investors and venture capital financial instruments to view future market opportunities for SRM approaches more favourably, thereby strengthening interest in the deployment of SRM (Surprise et al., 2022). SRM could solidify as a promising future business model (see the critical description of the attempt to commercialize SRM in (CSSN 2021)).Consequently, there are calls for SRM research not to be financed by public funds at all (Biermann et al., 2022).

Risks of Solar Radiation Modification (SRM)

SRM is supposed to mask global warming by enhancing the earth's albedo, for example by stratospheric aerosol injection. Thus altering the whole climate system, SRM would impact most areas of life.

Umwelt
Bundesamt



Geopolitical Tensions

Difficulties in reaching a political consensus on SRM, up to the risk of unilateral deployment, could lead to international conflicts.

Mitigation Deterrence

Relying on SRM to supposedly counteract climate change may weaken mitigation efforts, including the phaseout of fossil fuels, hindering the transition towards renewable energy.

Ecosystem Disruption

Altered climate patterns can destroy habitats and food webs, contributing to biodiversity loss.

Increased inequality

An unjust distribution of negative impacts could exacerbate inequalities between and within nations, while the risk of a termination shock and technological dependency might impose burdens on future generations.

Threatened Marine Ecosystems

Undiminished ocean acidification could adversely impact marine biodiversity and fisheries.

Food Security Threats

Changes in precipitation and monsoon patterns could disrupt agricultural production, threatening food supply stability.

Water Cycle Alteration

Unpredictable changes could affect the availability and quality of freshwater and compromise water security.

8

SRM Harbours Many Risks

Based on the modelling and due to the mode of action of SRM (Section 4), some risks of SRM are already clear, even if considerable uncertainties remain. Despite research, not all negative effects can be ruled out. If SRM were to be used globally, unexpected consequences would emerge (Young, 2023; Davies, 2011).

8.1 Risks to water availability and food security

Modelling (Section 7.1) is used to predict the influence of SRM on precipitation distribution and also on plant photosynthesis and thus on **(drinking) water availability** and crop yields, i.e. **food security** (Davies, 2011). If one were to assume that SRM could easily reverse climate change, one could conclude that all negative effects of climate change could be averted. However, contrary to some claims, SRM will not simply prevent the negative impacts of climate change on food security (Proctor et al.,2018). Even if positive effects of SRM on water availability in certain regions can be modelled compared to unmitigated climate change, the results are uncertain and do not take into account the effects of changing precipitation or local effects (Fotso-Nguemo et al., 2024). In addition to droughts and flooding on agricultural land, the change in the photosynthetic performance of arable and forest plants is a threat to the livelihoods of the people who depend on them (Xia et al., 2014; Robock, 2008). The mere decrease in temperature would of course counteract heat stress and could therefore increase crop yields, yet individual crop failures would always occur (Pongratz et al., 2012).These local effects are not modelled in detail in global computer models. On a global scale and accepting known uncertainties, it can be stated that SRM would generally lead to an increase in crop yields (Fan et al., 2021). However, this differs for individual arable crops and is made under the assumption of constant cultivation (Xia et al., 2014). For other crops, the calculation results in a massive decline of yields. Overall, there is still considerable uncertainty, meaning that no final statement can be made (Yang et al., 2016). In addition, for some communities, particularly indigenous populations or those from developing countries, even a local, short-term crop failure of individual varieties can be life-threatening. The food security of population groups that live from fishing is also not considered in the studies. These would be massively threatened by the acidification of the ocean (Kortetmäki et al., 2023). In addition, the studies primarily focus on the ongoing fertilising effect of CO2 as the growth-increasing factor (Xia et al., 2014; Pongratz et al., 2012). However, this contradicts the argument that the CO2 concentration would have to be reduced during SRM use anyway (Section 5).

8.2 Risks of international political conflicts

The effects on the global climate described above (Section 4) can make violent, cross-border and internal conflicts more likely (Global Risk Report, 2024; Sovacool et al., 2023). The changes caused by SRM could be favourable for one region, while another state could see its livelihood threatened, for example by changes in the monsoon (ART GS EU Council, 2023; Michaelowa, 2021; Schellnhuber 2011). Unpredictable climatic changes caused by SRM would create winning and losing countries (ART GS EU Council, 2023; Global Risk Report, 2022).Those who would suffer the most are the same populations already most affected by climate change, as they would be unable to adapt quickly to the changing conditions (Rickels et al., 2020; Schäfer et al., 2015). Since the capacities for potential deployment are more likely to be found in industrialized countries, neo-colonialist structures may emerge (Sovacool, 2021; Bellamy et al., 2018) and the power imbalance between industrialized and developing countries would be reinforced by SRM.

SRM as an emergency solution could be misused for militarization and securitization (Neuber et al.,2020). Even if a targeted attack may be too risky due to the lack of precision of the regional effects of SRM, it could at least be perceived or used as a military threat (ART GS EU Council, 2023). Additionally, the termination of an SRM deployment through military intervention and thus the riggering of the termination shock could be used as a threat (Lockyer et al., 2019). Especially as populists and authoritarian governments are on the rise worldwide, the military misuse of SRM cannot be ruled out (Global Risk Report, 2023).

Beyond the intentional military use of SRM, there is a significant risk for international political processes. Many states tend to not take climate change seriously and fail to invest sufficiently in sustainable GHG reduction. However, with increasing extreme weather events, pressure on such governments to adopt climate action may grow. Instead of implementing genuine climate action, they might resort to SRM, presenting it as a seemingly cheap and quick “solution” to gain public approval. The cross-border and long-term risks would not be a deterrent for nationalist and populist governments. On the contrary, there tends to be a dismissive attitude toward multilateral organizations. Due to these contexts and because an agreement of the global community on a consensual SRM deployment and its “optimal” intensity, duration and location appears unrealistic (Muraca et al., 2018), a deployment by individual states is more likely than a jointly coordinated implementation of SRM (Michaelowa, 2021; Young, 2023).

The question arises as to how countries that do not agree with the use of SRM might respond. Possible countermeasures could involve influencing the climate in the opposite direction **(counter-SRM)**, such as the targeted release of GHGs or carbon (Heyen et al., 2019; Horton et al., 2011; Millard-Ball, 2012). It seems unlikely that a government would intentionally drive climate change, which is why economic sanctions, such as those imposed today, are more obvious. However, as these do not always work, the countermeasure could be to stop the SRM deployment through military attacks - be it cyberattacks or the destruction of infrastructure (Lockyer et al., 2019). In the case of space installations in particular, only a few states would be able to do this.

8.3 Risk of mitigation deterrence and for climate adaptation

The reinterpretation of the societal task of reducing greenhouse gases and adapting to climate change as a seemingly purely technical problem obscures the need for behavioural changes and a socio-ecological transformation. The research and deployment of SRM must be designed in such a way that they do not lead to dependencies on existing structures (lock-in effect). However, considering that the resources needed for SRM are closely tied to the fossil fuel industry, this condition does not seem to be met (Neuber et al.,2020; Muraca et al., 2018; Owen, 2014). Even beyond the direct links between fossil fuels for the operation of SRM infrastructure, SRM and the fossil fuel industry are linked. Numerous publications discuss the so-called moral hazard or mitigation deterrence effect (ART GS EU Council, 2023; Neuber et al.,2020; Schäfer et al., 2015; Hamilton, 2013; Preston, 2013; Gardiner et al., 2010).

While no one can definitively predict whether relying on SRM as a techno-fix will actually lead to reduced attention to GHG mitigation and delay the transition away from fossil fuels, it is plausible that the mere focus on and research into SRM diverts political engagement, media attention, and limited financial resources that could otherwise have been invested in climate action. The counterargument that is discussed controversially suggests that the fear of the threat posed by the use of SRM could actually prompt other states to drastically reduce their GHG emissions rather than rely on SRM. However, nuanced analyses on mitigation deterrence and specific substitution effects between climate policy and SRM have been carried out (McLaren, 2016)

The transition away from fossil fuels could be hindered if the potential of **renewable energy** sources is negatively affected by SRM. The performance of photovoltaic systems could be reduced, as they operate most efficiently with certain components of direct sunlight. However, it is precisely this direct sunlight that would be reduced by an SRM approach. (Smith et al., 2017; Robock, 2008). Initial findings indicate that the influence on wind power is of little significance globally and in the long term but shows large local fluctuations (Baur et al., 2024). Renewable energies could therefore become less cost-effective and competitive with fossil fuels as a result of SRM, which would delay GHG reduction and extend the duration of SRM deployment (Baur et al., 2023a). However, these results should be regarded as provisional overall and are subject to considerable uncertainty (Kumler et al., 2025).

Individual companies offer certificates for sale via small-scale SRM activities that are intended to offset the CO2 emissions of companies. However, these supposed ‘cooling certificates’ cannot contribute to GHG neutrality and tend to have **a greenwashing quality** (Diamond et al., 2023).

SRM can in no way replace immediate and comprehensive **adaptation** to climate change. The climate and ecosystems react in a complex and in some cases irreversible way to the increase in CO2 concentrations in the atmosphere, which cannot be completely reversed by masking warming after the fact. Climate adaptation, on the other hand, is aimed at resilience to climate change impacts and is therefore indispensable. By delaying the implementation of adaptation measures, the research and development of SRM increases the damage caused by climate change. At the same time, SRM can reduce our adaptive capacity – the ability of populations, ecosystems and economies to adapt to the impacts of climate change and changing environmental conditions (UBA, 2021) – through the associated risks to water availability, food security and ecosystems (see sections 8.5 and 8.6).

8.4 Risiks for future generations

Delaying GHG mitigation and climate adaptation would have long-term consequences for future generations. The moral question of **intergenerational equity** is an important aspect. This is because intergenerational inequality can be exacerbated by the fact that SRM would have to be sustained over several centuries and generations. It can be argued that successful implementation of SRM would mitigate the consequences of climate change for future generations, but it also shifts the negative long-term impacts, risks and costs of SRM deployment into the future. In particular, the threat of a sudden rise in temperature due to the cessation of SRM deployment is tantamount to blackmail, with future generations being forced to reduce greenhouse gas concentrations in the atmosphere and to continue the transformation of society, that current generations have resisted, at all costs (Davies, 2020). Furthermore, today's reliance on an unsafe technology also restricts the room for manoeuvre and self-determination of future generations (Schäfer et al., 2015). In addition, the argument is put forward that future generations should be provided with SRM as part of the toolbox against climate change (arm the future argument). This is questionable insofar as there are sufficient options for avoiding the climate crisis that are associated with lower risks (Gardiner, et al., 2010).

8.5 Risk of one-sided and non-transparent funding

Most of the funding for SRM research comes from private investors and (philanthropic) foundations from the Global North (SGNUA, 2023). There are also government research programmes. Alongside "SilverLining" and individual billionaires, "Open Philanthropy" has been the largest donor to date (ART GS EU Council, 2023; Surprise et al.,2023). Bill Gates' Fund for Innovative Climate and Energy Research (FICER), which finances the research programme on solar geoengineering at Harvard University (Harvard's SGRP) (The Keith Group), as well as the Degrees Initiative (formerly the SRM Governance Initiative, SRMGI), are also worth mentioning. The latter supports researchers from the Global South with financial resources and technical support from SRM experts, mainly from the Global North (DEGREES Initiative). Possibly, entire research careers are conditioned by these funding streams and the interests of the Global South could be used to further normalize the SRM debate (Chalmin, 2024).

Many and similar institutions often work together and have close links to policy makers, scientific associations and government agencies (Surprise et al.,2023). In this context, there is concern that private actors from the Global North could actually own SRM technologies through their knowledge advantage as well as financial and technological capacities and patents, which also increases the power imbalance between industrialised and developing countries (UNEP, 2023; Robock, 2008).

8.6 Risky cost calculations

Low costs are repeatedly cited as an advantage in the discussion about SRM. From this, the possibility of **unilateral deployment** by wealthy individuals or individual states is inferred. However, it is questionable whether private actors have the logistical and military capacities to maintain an SRM deployment, especially against international will. Only a few states would actually be in a position to do so (Parson et al., 2013).

Another risk is the **underestimation** of the actual costs. The costs of SRM are higher than often assumed (Aaheim et al., 2015). Relatively, compared to other geoengineering approaches, SAI in particular may be favourable, but in absolute terms the costs exceed what individual states or individuals can afford (Smith, 2020). (Smith, 2020). Whilst the annual costs may be low, the long period of time over which SRM would need to be applied should not be overlooked. In addition to the production of the required machinery and infrastructure, the costs of fuel, personnel, limited resources, etc. must also be considered. In addition to these direct operating costs, the incalculable costs of damage to the environment, biodiversity and human life or political **compensation payments** are particularly important, but are not sufficiently taken into account when claiming that SRM is favourable (Rickels et al., 2020; Schäfer et al., 2015; Klepper et al.,2012; Davies, 2011). Uncertainty about the social and economic consequences of environmental changes is a cost factor in itself (Gramstad et al., 2010). This can result in sums that could also be used to combat global hunger, develop medicine or promote education (Davies, 2011). There is currently no plan for monitoring the impact and effectiveness of SRM, which would be very expensive and time-consuming (Michaelowa, 2021). Standardized monitoring would also be the basis for any claims for compensation. However, there is also no system for compensation payments and setting one up is already proving difficult in the case of the consequences of climate change. In addition, it would hardly be possible to determine whether a severe weather event is still a consequence of climate change or was triggered by SRM and, if several countries use different methods, by which and when exactly. The only possibility of comparison is offered by computer models, but it is questionable whether a simulation would be recognized as a justifiable basis (Schäfer et al., 2015).

8.7 Risks for environmental and marine protection

Even if SRM were to be maintained at a constant level and no termination shock were to occur (Section 4), further risks would arise from the masking of global warming. As the concentration of CO2 in the atmosphere would remain the same or continue to rise and therefore more CO2 would be dissolved in the ocean water, **ocean acidification** would persist and sometimes worsen (Wagner, 2023; Robock, 2008). Coral reefs in particular suffer from ocean acidification. A decreasing ocean surface temperature may reduce the stress factor of coral bleaching, but ocean acidification has negative consequences for reproduction and calcification that would not be remedied by SRM. On the contrary, overcooling of tropical latitudes by SRM is predicted, which could even increase the impact of ocean acidification on corals (Kwiatkowski et al., 2015; Couce et al., 2013). SRM is expected to cause far-reaching changes in the water column, food webs and biogeochemical cycles in the oceans, which could also impair the ocean's ability to sequester carbon (GESAMP 2019).

The environmental and health risks posed by the particles and materials used vary depending on the approach, whereby different chemicals could also be used within one approach (Section 6). Measures in the stratosphere or in space could severely damage the ozone layer. The chemicals and substances used for this purpose (such as NO2), which are produced by the combustion of fuels or re-entry into the atmosphere, promote ozone depletion and delay the closing of the ozone hole (Roy, 2022; UBA, 2016; Tilmes et al., 2009).

SRM could lead to further loss of biodiversity (IPCC, 2018). In order to determine the exact impact on the environment, detailed knowledge of the processes in the ecosystems and the climate system and the interactions between the atmosphere, biosphere and hydrosphere would be needed, but this is not available to a sufficient extent (Matthews et al., 2009). Similar to other large-scale interventions, the environmental damage caused by the new infrastructure required for SRM, the propulsion systems, the production of materials, and their transportation must also be taken into account (Robock, 2008). This could result in habitat and biodiversity loss, soil and water pollution. SRM deployment in response to the climate crisis must not counteract efforts to address the **biodiversity** and **pollution crises.**

9

An International Regime for the Comprehensive Governance of SRM?

The debates surrounding SRM are often heated and polarized. It is important to remember that SRM, as a large-scale response to the climate crisis, remains a purely theoretical option at present. There is no reasonable prospect of SRM deployment, with outcomes that could be predicted with sufficient certainty, anytime soon. Therefore, this Section aims to take a sober look at the existing legal framework and regulatory options. In this Section 9, we will first examine the concept of SRM in international law, followed by a discussion of the regimes and treaties that could govern SRM as such and which could serve as key forums for future decision-making. Section 10 will then address existing regimes and regulations that already limit certain impacts of some SRM techniques.

The debate on SRM regulation and governance – a brief overview

The number of publications and proposals on the regulation and governance of SRM has risen sharply in recent years. In some cases, the actors, political processes and the effects of scientific assessment reports by international institutions are described. It is noted (Gupta/Möller, 2019), that there is already an informal “de facto governance” that characterizes the perception of existing options and international policy processes on SRM. Other studies focus on the future regulation of SRM. Some focus on “enabling governance”, i.e. the facilitation of SRM research and deployment (e.g Buck et al. 2023; Honegger et al., 2013), while others focus on the limitation and regulation of SRM in the sense of “restrictive governance” (e.g Gupta et al., 2024).Several studies examine the suitability of existing international institutions and treaties and largely conclude that no treaty regime would be suitable per se as a central forum for the governance of SRM (e.g: Bodle/Oberthür 2014; Krüger 2020; Reynolds 2019). A large proportion conclude from this that there is a problematic fragmentation of international law and significant governance gaps (Honegger et al. 2013, p. 134, Reynolds et al. 2022). The assessment of this question is largely determined by the initial premises of the respective authors. If one assumes that an internationally regulated facilitation of SRM activities is to be promoted, the gaps in international law are regularly assessed to be particularly serious. Other authors emphasize that it may be impossible to agree and regulate the deployment of SRM and the modalities of global implementation multilaterally (Corry 2017; Hulme 2014). In this context, calls for a non-use agreement have been formulated (Biermann et al., 2022; Gupta et al., 2024) formuliert.

9.1 The concept of SRM and geoengineering in international law

Few international legal texts explicitly mention geoengineering or SRM. A definition of SRM under international law was provided under the Convention on Biological Diversity (CBD). Decision CBD X/33 defines SRM as a sub-form of geoengineering as follows: *"any technologies that deliberately reduce solar insolation"*.

However, these and the usual SRM definitions do not easily help to differentiate between SRM measures for climate adaptation (see box in section 6.5) and for weather modification (see box in section 6.4). Does the whitening of roofs count as SRM? And would the creation of clouds on particularly hot days over a limited area, for example to protect a coral reef or as part of the Olympic Games, also be categorized as SRM? To decide whether these or similar cases constitute SRM or not, the characteristics of the overarching concept of geoengineering (Section 1) must be considered. The central feature of the geoengineering concept is the objective of deliberately intervening in the climate system through large-scale measures. Roof whitening, for example, does not involve the targeted and large-scale influencing of the climate. The aim of whitening roofs is usually to improve living conditions on this limited area.[2] Also, a temporary **measure to influence the (current) weather cannot be equated with a (long-term) change in the climate**. Insofar as overlaps with weather impact and climate adaptation remain in marginal areas of the SRM concept, a normative definition and regulation of SRM is nevertheless possible. The fact that in individual cases it is not always possible to make a clear distinction in advance is typical of normative and political terms. These do not have the same degree of selectivity as definitions in natural sciences. The decisive factor here is that criteria are available that can be used to weigh up and decide on individual cases in the procedures provided for this purpose. The legislator or other decision-makers can use these criteria to determine further categorizations if necessary.

9.2 Biodiversity Convention and the de facto geoengineering moratorium

Of particular importance for the control and regulation of SRM is the **decision under the** Convention on Biodiversity (CBD) from 2010, CBD X/33 ((CBD, 2010); (UBA, 2019)). It is one of the few international legal texts that explicitly mention SRM. The decision applies the precautionary principle to SRM and specifies the criteria that must be ensured in advance regarding research and deployment. The decision stipulates that SRM may not take place as long as these criteria are not met. The decision is therefore also referred to as a **"de facto moratorium"**.

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[2] However, a different assessment could be made if small-scale changes in surface albedo are integrated into a comprehensive incentive mechanism for so-called "climate action" and therefore need to be considered in aggregate.

Wording of the CBD X/33 de facto moratorium

Article 8(w) calls on the international community to "ensure, in the absence of science based, global, transparent and effective control and regulatory mechanisms for geo-engineering, and in accordance with the precautionary approach and Article 14 of the Convention, that no climate-related geo-engineering activities that may affect biodiversity take place until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts, with the exception of small scale scientific research studies that would be conducted in a controlled setting in accordance with Article 3 of the Convention, and only 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."

In implementing the precautionary principle, the decision establishes a **general** ban on the use of SRM ("to ensure that...no geoengineering activities...take place"), which can only be lifted if certain conditions are met. The de facto geoengineering moratorium therefore does not impose an unconditional and absolute ban on SRM but formulates conditions for the implementation of SRM activities.

It is therefore only possible to deviate from the ban set out in the decision if several conditions are met. In particular, a **sufficient scientific consensus** is required on the mode of action and effects of SRM. The "associated risks to the environment and biodiversity as well as the associated social, economic and cultural impacts" must also be considered. Only if the use of SRM could be fairly assessed on this scientific basis would the use of SRM even be considered. According to the current state of knowledge, the effects of the proposed SRM techniques cannot be determined with sufficient certainty. However, some negative effects of SRM, such as changes in precipitation patterns, can already be assumed with a high degree of certainty (see sections 8.5 and 8.6).

A further condition is the existence of "scientific, global, transparent and effective **control and regulatory** mechanisms". This means that SRM may only be implemented if appropriate international mechanisms have been created to control SRM. This prohibits individual states from going it alone. The text of the decision excludes "small-scale research experiments" in a "controlled environment" from this prohibition under strict conditions. To date, there is no consensus as to whether only activities in laboratories and cloud chambers or other precautions for field activities fulfil this requirement (Rabitz et al., 2022, S. 142). A sector-specific development of the criteria was undertaken under the London Protocol (Section 10.2).

Excursus: Status of the de facto geoengineering moratorium (Dec. X/33)

The binding nature of the decision under international law must be assessed in a differentiated manner, since this decision is a matter of so-called secondary international law. This law is negotiated and adopted by state representatives based on and in accordance with the provisions of the binding treaty. The question of the binding nature of secondary law arises particularly in international environmental law, where there are no independent actors (legal subjects) and a lower degree of institutionalization exists compared to other areas of international policy (see, for example, the World Health Organization or the International Monetary Fund).

It should be noted that the decision was taken unanimously by all Parties at the 10th Conference of the Parties to the Convention on Biological Diversity in 2010. It assesses the interpretation and application of the binding Biodiversity Convention based on Art. 23 para. 4 CBD. An undifferentiated mere denial of the binding nature of the decision does not do justice to this. In particular, the formal status of the decision cannot be altered or invalidated by the substantive limitations in the formulation of the obligations. For example, it follows from the introductory wording ("Invites Parties and other Governments, according to national circumstances and priorities") of the decision that the individual substantive requirements are to be interpreted considering the circumstances. This does not affect the formal status of bindingness of the decision.

* The report of the Royal Society makes a similar distinction and characterises the decision as a "normative precedent" Royal Society 2011, p. 32. On the gradations of binding force under international law, see also Brunnée 2022.

The validity of the de facto geoengineering moratorium was reconfirmed in December 2016 and in November 2024 (Decision of the Conference of the Parties XIII/14 and XVI/17).

Building on the CBD's existing decisions on geoengineering, there is ongoing discussion about whether the CBD would be a suitable central regulatory forum for geoengineering or SRM. One argument in favour of this is that the scope of the Biodiversity Convention is sufficiently broad to cover the impacts of the various technologies. In addition, it is the only quasi-universal forum that explicitly addresses SRM. The CBD also includes a series of obligations for cooperation and exchange in the fields of research and technology (Art. 17, 18 CBD), which could be suitable for coordinating and evaluating further research efforts on SRM (Krüger 2020, p. 331).

However, some authors consider the CBD to have too little political weight, especially as the USA has not ratified the CBD (Sugiyama/Sugiyama 2010, p. 13; Wirth 2013, (p. 413 (433)).Considering the advantages and disadvantages, the CBD appears to be the most suitable central regulatory forum for SRM (Bodle/Oberthür 2014, p. 74; Hubbard 2016, p. 618).

9.3 ENMOD as a treaty for the fundamental regulation of SRM?

The ‘Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques’ (ENMOD) of 1978 prohibits hostile weather modification and distinguishes it from weather modification for peaceful purposes. The convention has been signed by 58 states, including the USA. As the large-scale implementation of SRM would necessarily also result in weather modification, the applicability of the convention to SRM is frequently discussed. However, the question of the conditions under which a “hostile” deployment of SRM would occur is problematic. Some authors argue that any SRM deployment that has adverse effects such as droughts would be a violation of the ENMOD Convention (Robock 2008).Other authors argue that the use of SRM should be considered “peaceful” in the sense of this convention and therefore cannot fall under the obligations of this treaty (Parson 2014, p. 96).

As a result, the ENMOD Convention contains numerous broad legal terms (“hostile”, “serious effects”), the concrete application of which to SRM is difficult (Gupta et al., 2024,p. 14; Honegger et al. 2013, p. 130). At the same time, the convention does not provide for any mechanisms that could help to clarify these issues. **In its current form, the ENMOD Convention can at best reaffirm a prohibition of SRM**. In contrast, the criteria of CBD Decision X/33 appear to be more detailed and nuanced. They are to be considered more suitable as a basis and starting point for any international efforts to further develop the regulation of SRM.

9.4 Climate law

Whether SRM can and should be part of international climate law is the subject of much debate. The starting point for answering this question must be Article 2 (1) of the Framework Convention on Climate Change. This article defines the objective of international climate law, namely “the **stabilization of greenhouse gas concentrations** in the atmosphere”. SRM does not change the concentration of greenhouse gases, but the Earth’s radiation budget. SRM is therefore **not covered by the objective of international climate law**.

Nevertheless, SRM is sometimes categorized as an option for achieving the “temperature goal” set out in Article 2 of the Paris Agreement and, building on this, it is proposed as a suitable treaty regime for the international governance of SRM (Honegger et al. 2013, p. 134.). It should be noted that the introduction to Article 2 explicitly places the “temperature goal” in the context of achieving the objectives of the Framework Convention on Climate Change (“This Convention aims to achieve the objectives of the Framework Convention on Climate Change, including its objective, by improving its implementation…”). The “temperature goal” therefore is rather a target than a goal and has the function of determining whether the measures to stabilize greenhouse gas concentrations are sufficient. In the legal sense, the **1.5 degree target is therefore not an independent goal, but merely an indicator of whether the objectives and goals of international climate law are being sufficiently pursued**. Under no circumstances is the setting of the 1.5 degree limit intended to cause a departure from the climate action hierarchy (Krüger 2020, p. 452; more open, however: Stoll et al. 2022, p. 432). The Paris temperature target can certainly not be used to derive and justify an obligation to use SRM (Krüger 2020, p. 455). **SRM is therefore not a means of climate action.**

From a functional perspective, there are also significant reasons against using the international climate action regime as the central regulatory forum for SRM. In both science and practice, it is often argued that the highly complex international climate diplomacy should not be burdened with an additional responsibility (cf. Kukonnen/Yamineva 2013, 161(165); Bodle/Oberthür 2014, p. 161.) Additionally, a weakening of efforts to reduce greenhouse gas concentrations is said to be expected, as the focus on SRM could shift political attention toward perceived alternative options (Section 8.3 on mitigation deterrence). Finally, it should be considered that the climate action regime, with its focus on climate action and climate science, would not be capable of adequately assessing potential impacts on biodiversity or other environmental aspects (non-climate issues) (Bodle/Oberthür 2014, p. 174). The international **climate action regime is therefore neither legally nor functionally suitable for the governance and regulation of SRM**.

10

Rules that limit Individual SRM Approaches

10.1 Rules that limit SAI activities

Stratospheric aerosol injections would typically need to be carried out at an altitude of around 20 km, meaning that space law would not apply. Instead, regulations for the protection of the atmosphere would be relevant. Since stratospheric aerosol injections can vary significantly in individual case, only generalized statements can be made.

International rules for the protection of the ozone layer and air pollution control

The framework convention for the protection of the ozone layer is the **Vienna Convention for the Protection of the Ozone Layer**, which has been in force since 1988 and has now been universally ratified. In Article 2 (2) of this convention, states commit to undertaking, among other things, measures to prevent human activities from endangering the ozone layer. The "Scientific Assessment of Ozone Depletion" published in 2022 summarizes the complex interaction effects between the ozone layer and numerous variants of aerosol injections (WMO 2022, p. 21 ff).According to the current state of knowledge, the implementation of aerosol injections in the variants discussed to date therefore poses a **threat to the ozone layer** and would **run counter to the fundamental protection objective of the Vienna Convention for the Protection of the Ozone Layer** (Krüger 2020, p. 127; Rickels 2011,p. 101); states have a duty to adequately prevent changes to the ozone layer.[3]

The **Montreal Protocol** for the Protection of the Ozone Layer specifies the Vienna Convention and lists individual substances that are to be gradually reduced ("phase down") or eliminated. Depending on the aerosols used, the regulations of the Montreal Protocol can therefore also limit the use of SRM. However, the aerosols most frequently discussed in connection with SAI, sulphate aerosols, have not yet been listed under the Montreal Protocol.

The **Geneva Convention** on Long Range Transboundary Air Pollution (CLRTAP) and its protocols are intended to reduce transboundary air pollution. The convention was developed in response to the phenomenon of acid rain. It was signed and ratified as a regional convention by 51 European and North American countries. Three of the protocols (Helsinki, Oslo, Gothenburg) contain commitments to limit sulphate emissions. For stratospheric aerosol injections using SO2 this means that there is effectively no room for manoeuvre for the contracting states to release additional sulphate emissions. The CLRTAP therefore contains significant restrictions for some forms of stratospheric aerosol injections. The convention does not provide for a mechanism to weigh up any conflicting interests.

International aviation law

The regulations for international aviation law are laid down by the Civil Aviation Organization (ICAO) based on the "Convention on the International Civil Aviation". They cannot regulate state operations, but they can regulate the activities of private project organizers and research institutions. Annex 2 of the Convention ("Rules of the Air") stipulates in Art. 3.1.4: *"Nothing shall be dropped or sprayed from an aircraft in flight except under conditions prescribed by the appropriate authority and as indicated by relevant information, advice and/ or clearance from the appropriate air traffic services unit"*. The deliberate release (dropping) of aerosols is only permitted if expressly authorized by the relevant authorities and applicable regulations. In the development of such a regulatory framework, existing international regulations must be taken into account. This is particularly true for CBD Decision X/33. Accordingly, a general and explicit prohibition of SRM would first have to be laid down, before considering exceptions for research activities under strict conditions (see also Section 11.2).

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[3] Insofar as authors discuss a "climate emergency" ((Krüger 2020, p. 135) that could limit the obligation to protect the Ozone Layer, this cannot be based on the text of the Vienna Convention. Moreover, the consideration of objectives or measures external to a given regime presupposes their legality and legitimacy within the context of the international legal order, but cannot justify the legality and legitimacy of aerosol injections intended to pursue these extraneous objectives.

German and European law: Special permits for experiments?

Even if no conclusive legal assessment can be made in view of the large number of theoretically conceivable case constellations, it should be noted that SAI activities in particular do not **operate in a legal vacuum**, but that relevant prohibitions and possibilities for limitation already exist. In exercising their discretionary powers, authorities should not decide on (exceptional) permits for research experiments without considering the international agreements on SRM. It should be emphasized that no SRM (research) activities are currently planned in Germany. The comments are intended to contribute to a discussion taking place in the literature as to whether there is an urgent need for regulatory action regarding the creation of a legal framework for SRM experiments.

Depending on the individual case, different regulations can lead to the activity being generally prohibited and subject to a permit or authorization requirement. Air traffic law and pollution (immission) control law in particular impose restrictions on the release of aerosols or particles into the atmosphere. **Air traffic law**, for example, regulates the use of airspace by aircraft. As aerosols can only be released into the stratosphere with the aid of aircraft such as balloons or airplanes, it can be assumed that air traffic law applies to SAI. According to Section 13 (1) of the German Air Traffic Regulations (LuftVO), the dropping or releasing of objects or other substances from aircraft is generally prohibited. The targeted release of substances as part of an SAI activity is therefore prohibited in principle. According to Section 13 (2) of the regulation, the locally competent aviation authority may allow exceptions if there is no danger to persons or property. The wording of the paragraph (“may”) shows that the authority is obliged to make a so-called discretionary decision. This means that all relevant aspects must be considered; the immediate “danger to persons or property” is therefore not the only decisive factor. In the case of micro and small scale experiments, the indirect risks posed by SRM activities as a whole must also be taken into account (see section 8 above). Next, the provisions of international law standards must also be considered.

According to the “principle of international law-friendliness” *(Völkerrechtsfreundlichlichkeit)* enshrined in the German Constitution, international law standards must be considered when interpreting the German laws and exercising discretionary powers. This obligation to take into account even applies to intergovernmental norms that are not formally binding under international law (Deutscher Bundestag WD 2018, p. 23). **Decision CBD X/33 would therefore have to be considered when the competent authority decides whether to grant a derogation for research experiments.** This decision under international law (see section 9.3 above) was also confirmed in the Federal Government’s external climate strategy (Federal Government, 2023, p. 58) and the EU Commission’s communication (EU Commission, 2023) Furthermore, the CBD decision operationalizes the precautionary principle in the context of SRM. The precautionary principle is enshrined in the Primary Treaty Law of the European Union (Art. 191 TFEU).

When interpreting the national provisions based on the criteria of the CBD X/33 decision, it can be assumed that these are opposed to the granting of an **exemption authorization**. This applies at least to the current factual and legal situation. Relevant criteria here are the legitimate scientific interest, no mere development of the technical infrastructure, a thorough prior assessment of possible environmental risks and the need to conduct the experiment in a “controlled environment”. In particular, it should be borne in mind that small-scale experiments have so far no ascertainable scientific value for assessing the effects of a large-scale SRM deplyment on weather and climate (Section 7.3 and DFG; 2014).

Conducting tests with special missiles or balloons can also lead to the development of infrastructure for SAI measures and the promotion of the market maturity of these measures. However, the technical preparation and development of infrastructures should be rejected as preparation for deployment (see Federal Government, 2023, p. 58).

Furthermore, the German **Federal Immission Control Act** (BImSchG) can limit SAI activities. The targeted application of aerosols falls under the “air pollutants” defined in Section (4) BImSchG and causes immissions within the meaning of Section 3 (2) BImSchG because it acts as an air pollutant on the atmosphere by changing the natural composition of the air. According to the implementing provisions in the “TA Luft” and the “43. BImSchV”, sulphur oxides are also capable of causing harmful effects on the environment. According to the 43.

BImSchV, aggregate emission limits apply in particular to SO2 and particulate matter PM 2.5, even if they do not originate from installations (Section 1 (1): Point sources and diffuse sources). The reduction obligations with regard to total emission quantities that apply in accordance with Section 2 (1) of the 43. BImSchV are also binding for SAI activities.

10.2 Regulations for marine geoengineering

The London Protocol (LP) to the London Convention (LC) on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter of 1972 contains regulations on marine geoengineering. The applicability of the LP depends on whether the activities involve the introduction of substances into the sea. Therefore, only those SRM activities that involve the release of “waste or other materials,” such as the dispersal of reflective particles or the solidification of foam on the ocean surface through the addition of chemicals, are covered (Sections 6.4 and 6.5). The 2013 Amendment introduced the term “marine geoengineering,” although the term “SRM” is not used in the LP text. The 2013 Amendment includes a prohibition on the application of the CDR method of ocean fertilization, allowing only activities that are classified as **legitimate scientific research**. The Amendment sets criteria to distinguish between research and (commercial) application, which is a novelty in international law. It requires proof that the project contributes to the “advancement of knowledge,” uses a recognized scientific method, and has undergone peer review. Furthermore, the design and execution of the project must not be influenced by economic interests. Direct financial benefits from research projects, such as the sale of certificates, are prohibited, and such projects cannot be classified as “legitimate scientific research.” The Amendment secondly also requires a **structured environmental assessment** to minimize negative impacts asmuch as possible. Thirdly, it outlines requirements for **consultation** with potentially affected states, regional organizations, and the involvement of independent international experts.

The Amendment is structured in such a way that it could be applied to other marine geoengineering techniques. However, it is problematic that only about 50 states have signed the LP, and the Amendment has not yet entered into force. Nevertheless, many states, including the USA, apply the LP regulations domestically, even without having ratified or signed the LP.

Marine geoengineering regulations also arise from the **United Nations Convention on the Law of the Sea** (UNCLOS), which binds 169 states, as recently confirmed by the International Tribunal for the Law of the Sea in its advisory opinion on May 21, 2024. In its opinion, accepted by all state parties as the correct interpretation of the law of the sea, the Tribunal ruled that marine geoengineering measures must not cause a transfer of burdens from one medium to another.[4]

In two unanimous statements from 2022 and 2023, the LP state parties noted that, in addition to some CDR techniques, Marine Cloud Brightening (MCB) and microbubbles could pose significant risks to the marine environment, and thus a general prohibition is desirable, with only “legitimate scientific research” being permitted. It remains unclear whether these activities qualify as large-scale, climate-effective SRM measures, or if their goal, for instance, is the protection of local coral reefs.

Additionally, there is ongoing discussion about the extent to which the regulatory framework of the LP could be applied to Stratospheric Aerosol Injection (SAI) activities. The LP’s regulatory framework for marine geoengineering is based on two pillars: first, the prohibition of application, aligning with the concept of a non-use agreement. The second pillar is the general permissibility of field trials under strict conditions and prior control. The requirements for “legitimate scientific research” exclude the commercialisation of research results. It is doubtful whether this model for regulating field trials would be sufficient for SAI activities. Furthermore, based on current knowledge, a legitimate research interest would generally be denied, as there is no reliable data on the effects of weather dynamics and precipitation patterns. The LP concepts were originally created primarily for CDR measures and cannot easily be transferred to SAI. In particular, transferring the regulations and concepts of the London Protocol to SAI would first require a **comprehensive and binding commitment to a general prohibition of SAI** (also Section 11.1 on research regulation).

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[4] ITLOS Advisory opinion No. 31, 21.05.2024, para. 231.

10.3 Legal Situation in Outer Space

The implementation of SRM measures in outer space is also being discussed (Section 6.1). International space law provides an important framework for SRM, which already forms a basis for regulating and limiting possible SRM activities in space (Baum et al., 2022, p. 6; Krüger 2020, p. 99). It is true that international space law does not contain any regulations that explicitly prohibit or regulate SRM activities. Nevertheless, some basic rules and procedural requirements are relevant for SRM activities in outer space. For example, the Outer Space Treaty contains a “common benefit clause”, according to which all activities in outer space should be carried out for the benefit of all states (Art. I). From this it can be deduced that a unilateral SRM activity that is potentially harmful to other states should not be carried out (Rickels 2011, p. 143).The Earth’s environment is also mentioned as a relevant protected good (Art. IX). Art. XI contains provisions on consultation obligations and requires comprehensive transparency on all activities. Compliance with these obligations must also be ensured by national laws in the case of private missions. For example, the future German Space Act will stipulate an authorization requirement for private activities (BMWK 2024).

10.4 Further restricting regulations

Other international regulations also do not directly address SRM or specific technologies as such, but rather are related to the goods to be protected and can limit individual SRM activities depending on the specific impacts they are likely to have. For example, the **prohibition of significant transboundary harm**, which is a recognized principle in general international law provides that activities that cause harm be avoided. Secondly, **human rights conventions** can also limit SRM. According to the Human Rights Council, the extent of the potential socio-economic impacts of a global SRM application is not compatible with human rights based on current knowledge (UNGA 2023, para. 46, 61) Based on current knowledge, a global SRM deployment would therefore also run counter to the realization of the **Sustainable Development Goals**.[5] Numerous regional environmental and nature conservation agreements could also be affected and violated by SRM deployment.

10.5 Interim conclusion

In conclusion, it can be stated that the discussed SRM activities **are not operating in a legal vacuum. Even today, they are subject to numerous significant restrictions** (see also UNGA 2023, para. 31). States, as well as national and international authorities and institutions, have several **options for regulatory intervention**. However, the existing regulations leave considerable room for interpretation. Decision CBD X/33 should be applied to fill this margin.

At present, no major regulatory gaps can be identified. However, the existing regulations do not answer the question of how SRM could be concretely implemented despite the existing restrictions. Some authors view this as a significant regulatory gap, especially when more optimistic assumptions and speculations about the potential future benefits and risks of SRM are considered. Such assumptions about SRM, however, cannot be justified based on the current state of scientific knowledge.

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[5] More open, however, and assuming the possibility of successful SRM (Honegger et al. 2020, p. 15 ff.).

11

Recommendations for the Governance and Regulation of SRM

11.1 Advancing an international non-use agreement

- **An international non-use agreement must be driven forward.**

To prevent unilateral national actions and limit future SRM activities, a non-use agreement must be driven forward. This agreement must further develop the content and criteria of the decision under the Convention on Biological Diversity (CBD X/33 “De Facto Geoengineering Moratorium”), which must not be weakened. Such a non-use agreement has been called for by the African Ministerial Conference on Environment and the German Government declared to be open for discussions on a non-use agreement or binding moratorium (see section 2 above).To bridge conflicting positions and improve the chances of success for a non-use agreement, it should be made clear that a **general prohibition** is a **prerequisite for precautionary** regulation of SRM and that only on this basis could any future field experiments be regulated and made possible in a controlled manner (see 11.2 Research regulation).

- **A binding confirmation of the geoengineering de facto moratorium X/33 and plurilateral agreements should be promoted.**

Particularly if an international consensus on the further development of the criteria is not yet possible, a binding confirmation of the CBD X/33 decision is also a goal-oriented step. A plurilateral agreement could also be a first step. This would initially be limited to a group of like-minded states that are in favour of precautionary regulation.

- **The coordination and mutual consideration of international legal institutions must be improved.**

If an international non-use agreement is achieved, the international governance and regulation of SRM will continue to be characterized by many individual regimes, as is already the case. The fragmentation that already characterizes international law in many areas has the advantage that the various risks and perspectives can be adequately taken into account, particularly in the case of SRM. Therefore, the coordination and mutual consideration of the individual treaty regimes relevant to SRM must also be improved. In particular, no specific regime should promote SRM activities or lift existing restrictions without considering the assessments and obligations of other treaty regimes.

11.2 Research regulation requires a ban on use

- **Should national, regional or international regulations for the controlled performance of SRM experiments be considered in the future, this would require the establishment of a general prohibition on SRM. This also applies to the mere modification of existing regulations.**

Enabling the control of field experiments is only possible on the basis of a comprehensive limitation of all SRM activities, including research as well as deployment. This also applies when only small-scale activities are in question. This is necessary in view of the **fluid boundaries between research and deployment**. Without a binding general prohibition of deployment, a continuous expansion of field experiments could easily take place and field experiments could become larger and larger and ultimately lead to large-scale application (Section 7.3). Above all, “research regulation” can only be legally justified with the help of a general prohibition on use. Taking into account the freedom of research, which is enshrined in many constitutions, such as Article 5 of the German Basic Law, a restriction of research activities is only permissible if sufficient risks to other legally protected constitutional interests are present. For the assessment of SRM activities and their effects, it is not significant whether the activity is (also) carried out for research purposes or is labelled as an application. Only the actual activity can be prohibited, not the research itself. The term “research regulation” can be misleading in this respect. **Research regulation signifies that limited exceptions to the general prohibition of an activity can be provided for the purpose of research under qualified conditions.**

A binding general prohibition on SRM activities should therefore be established at national and international level **prior to the creation of regulations for SRM experiments**. Nor should existing regulations simply be adapted in favour of SRM experiments without first establishing a fundamental and explicit ban on SRM activities.

11.3 Currently national regulations for SAI field experiments are not necessary

- **The introduction of a statutory procedure for the comprehensive evaluation of SAI research projects and their scientific interest does not currently appear to be expedient or necessary.**

According to the existing legal situation in Germany and other EU states, SAI field experiments should not be possible in principle, but an exemption license could be requested (see Section 10.1.3). A key aspect of the authorities' decision would be whether a legitimate scientific interest can be demonstrated. The exact standards and criteria according to which such a legitimate scientific interest in a SAI activity would have to be demonstrated are not specifically formulated in either German or EU law. Currently, the decision of the Convention on Biological Diversity under international law should be used (see section 10.1.3). However, the relevance of small-scale experiments for assessing the regional and global impacts of large-scale SAI activities is scientifically questionable (see Section 7.2); a legitimate scientific interest is therefore doubtful.

A legal formulation and further development of these criteria therefore appear neither necessary nor appropriate at present. There is also currently no need to install such a procedure in Germany, as no SAI experiments are planned. Compared to conducting small-scale field experiments, there are also the alternatives of conducting experiments in laboratories, e.g. in cloud chambers, or observing naturally occurring phenomena such as volcanic eruptions. Finally, the **political signalling effect** and questions of public acceptance should also be considered in the event of the creation of a European or German research framework for SRM field activities. In fact, SRM is still a purely theoretical option and will not be a viable option by any reasonable standards soon. In any case, before creating a legal framework for conducting small-scale SAI field experiments, a general ban on SAI ban be enshrined in law (Section 11.2).

- **The criteria for permissible SAI research must be internationally harmonized and agreed upon.**

Instead of defining national or regional catalogues of criteria for SAI research that could allow field experiments, such criteria should be agreed internationally. If field experiments are to be permitted in a controlled manner, the international community must therefore press ahead with further concretisation of the criteria of the Biodiversity Convention X/33 decision based on a general prohibition of SAI. For example, there should be an international agreement on what exactly is meant by a "controlled environment". Whether field experiments can fulfil this requirement at all in the case of SAI should continue to be discussed and agreed upon internationally.

- **Current developments must be monitored.**

As the existing law, which limits the possible future implementation of SRM activities, is fragmented and can be assessed differently depending on the individual case, the existing law should be scrutinized more closely for regulatory gaps and coherence. This involves observing and evaluating current developments.

11.4 Ensuring responsible funding and governance for desk research

- **The funding of research into climate action instruments must not be weakened.**

To not weaken efforts to stabilize greenhouse gas concentrations, public funding for SRM research must not come at the expense of funding for research on climate action instruments.

- **Public funding for SRM research must be limited in both scope and focus.**

The **"slippery slope"** argument strongly supports a cautious approach to SRM research, as extensive engagement with SRM contributes to its normalisation and the perception of SRM as a viable climate policy option (Section 7.3). Nevertheless, developing independent, interdisciplinary, and critical assessment capabilities for SRM, as objectively as possible, is important. Only in this way can proposals or activities by other actors be evaluated in a well-founded and convincing manner. In balancing these considerations, a **moderate** level of public funding for desk-based research aimed at determining the risks of SRM seems appropriate. The primary objective of any SRM research **must be focused on exploring the risks**. Under no circumstances should the technological development of infrastructures necessary for SRM activities be advanced.

- **The balance and objectivity of research projects must be ensured and made transparent.**

To avoid path dependencies and misjudgements driven by self-interest, research activities must be planned and funded in a way that incorporates a **broad and interdisciplinary range of expertise**, and special attention must be given to conducting a **thorough examination of potential conflicts of interest**. In particular, commercial self-interests must be excluded. Additionally, the sources of research funding must be disclosed by the researchers. Furthermore, when selecting researchers for an SRM project, it is important to bear in mind that an objective and sufficiently critical scientific evaluation of SRM can hardly succeed if the relevant expertise is primarily limited to the SRM research field itself. The decision-making process for selecting research projects must be documented according to the aforementioned criteria and made publicly available.

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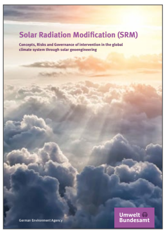
List of international treaties

Short title	Official Title	Source
CBD	Convention on Biological Diversity, 5 June 1992, entered into force on 29 December 1993	United Nations Treaty Series, vol. 1760, p. 79
ENMOD Konvention	Convention on the Prohibition of Military Use of Environmental Modification Techniques, 10 December 1976, entered into force on 5 October 1978	United Nations Treaty Series, vol. 1108, p. 151
Geneva Clean Air Convention/CLRTAP	Convention on Long-range Transboundary Air Pollution, 13 November 1979, entered into force on 16 March 1983	United Nations Treaty Series, vol. 1302, p. 217.
Gothenburg Protocol	Protocol to the 1979 Convention on Long-range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-level Ozone, 30 November1999, entered into force on 17 May 2005	Document of the Economic and Social Council EB.AIR/1999/1
Helsinki Protocol	Protocol to the 1979 Convention on Long-Range Transboundary Air pollution on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30 per cent, 14 June 1985, entered into force on 2 September 1987	United Nations Treaty Series, vol. 1480, p. 215
LC/ London Convention	Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 29 December 1972, in force on 30 August 1975	United Nations Treaty Series, vol. 1046, p. 120
LP/ London Protocol	Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 07 November 1996, entered into force on 24 March 2006	36 ILM (1997)
Outer Space Treaty	Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 19 December 1966, entered into force on 10 October 1967	United Nations Treaty Series, vol. 610, p. 205
Paris Agreement on Climate Change	Paris Agreement to the United Nations Framework Convention on Climate Change	United Nations Treaty Series, vol. 3156, p. 79
UNFCCC/Framework Convention on Climate Change	United Nations Framework Convention on Climate Change, 9 May 1992, entered into force 21 March 1994	United Nations Treaty Series, vol. 1771, p. 107
Vienna Convention	Vienna Convention for the Protection of the Ozone Layer, 22 March 1985, entered into force 22 September 1988	United Nations Treaty Series, vol. 1513, p. 293



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