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Abstract: Solar Radiation Modification (SRM): Intractable Governance and Uncertain Science

This discussion paper provides an examination of proposed solar radiation modification (SRM) technologies and their multifaceted implications, based on insights gained from two expert workshops convened by the German Environment Agency and the Copernicus Institute of Sustainable Development, blended with an overview of the academic literature as well as personal assessments and opinions from the authors. SRM encompasses diverse methods proposed to moderate the effects of climate change by reducing solar insolation into the earth climate system, with prominent options including stratospheric aerosol injection (SAI) and marine cloud brightening (MCB). While some advocate for SRM research as imperative given the urgency of the climate crisis, others emphasize the need for caution due to potential technological, ecological, and geopolitical of SRM. The governance of SRM research poses significant challenges, with disagreements often rooted in divergent worldviews and values. We underscore the importance of nuanced approaches, advocating for a multilateral moratorium on the *use* of SRM while also supporting a stringent framework regulating research activities. Our analysis highlights the necessity of an informed and inclusive dialogue on SRM governance, balancing scientific inquiry with ethical and societal considerations.

Kurzbeschreibung: Solar Radiation Modification (SRM):

Dieses Diskussionspapier untersucht Technologie-Ansätze zur Beeinflussung der Sonneneinstrahlung (Solar Radiation Modification, SRM) und ihre vielfältigen Auswirkungen. Es basiert auf den Erkenntnissen aus zwei Expert*innen-Gesprächen, die vom Umweltbundesamt und dem Copernicus Institute of Sustainable Development abgehalten wurden, und kombiniert diese mit einem Überblick über die wissenschaftliche Literatur sowie persönlichen Einschätzungen der Autor*innen. SRM umfasst verschiedene technologische Ansätze zur Abmilderung der Auswirkungen des Klimawandels durch eine Verringerung der Sonneneinstrahlung in das Klimasystem der Erde. Zu den bekanntesten Optionen gehören Stratospheric Aerosol Injection (SAI) und Marine Cloud Brightening (MCB). Während einige die SRM-Forschung angesichts der Dringlichkeit der Klimakrise als zwingend notwendig erachten, betonen andere, dass aufgrund der potenziellen technologischen, ökologischen und geopolitischen Auswirkungen von SRM Vorsicht geboten ist. Die Steuerung der SRM-Forschung stellt eine große Herausforderung dar, wobei die Meinungsverschiedenheiten oft in unterschiedlichen Weltanschauungen und Werten begründet sind. Wir unterstreichen die Bedeutung nuancierter Ansätze und plädieren für ein multilaterales Moratorium für den Einsatz von SRM, unterstützen aber auch einen strengen Rahmen zur Regulierung von Forschungsaktivitäten. Unsere Analyse unterstreicht die Notwendigkeit eines sachkundigen und umfassenden Dialogs über die Governance von SRM, bei dem wissenschaftliche Untersuchungen mit ethischen und gesellschaftlichen Erwägungen in Einklang gebracht werden.

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List of abbreviations

Abbreviation	Explanation
CBD	Convention on Biological Diversity
CCT	Cirrus cloud thinning
CDR	Carbon dioxide removal
CERF	Civil Engineering Research Foundation
CO_2	Carbon dioxide
DAC	Direct air capture
GHG	Greenhouse gas
MCB	Marine cloud brightening
NAS	U.S. National Academic of Sciences, Engineering, and Medicine
RRI	Responsible Research and Innovation
SAI	Stratospheric aerosol injection
SDGs	Sustainable Development Goals
SRM	Solar radiation modification, solar radiation management, solar geoengineering
UNFCCC	United Nations Framework Convention on Climate Change
UV	Ultraviolet

Zusammenfassung

In diesem Diskussionspapier werden der Wissensstand zu den Technologie-Ansätzen der Solar Radiation Modification (SRM), die damit verbundenen Risiken und ihre politischen Auswirkungen untersucht. Es stützt sich auf Erkenntnisse aus zwei Expert*innengesprächen, die das UBA und das Copernicus Institute of Sustainable Development am 15. September und 19. Oktober 2022 abgehalten haben, kombiniert mit einem Überblick über die wissenschaftliche Literatur sowie persönlichen Einschätzungen der Autor*innen.

SRM (auch Solar Radiation Management, Climate Intervention und Solar Geoengineering genannt) beschreibt eine Reihe von Technologie-Ansätzen, die dem anthropogenen Klimawandel durch eine Verringerung der Sonneneinstrahlung in das Klimasystem der Erde entgegenwirken sollen. Indem sie die Albedo der Erde erhöhen, könnten sie die Energiemenge im Klimasystem begrenzen und so zu einer geringeren Erwärmung führen. Die Debatten über SRM-Technologien sind vielfältig und kontrovers, wobei die Meinungen über ihre Umsetzbarkeit, Risiken und ethischen Auswirkungen auseinandergehen. Während die einen für die weitere Erforschung von SRM als potenzielle klimapolitische Strategie plädieren, warnen andere aufgrund der ungewissen und potenziell schädlichen Folgen eingehend vor ihrer Entwicklung. Diese Meinungsverschiedenheiten verdeutlichen die Notwendigkeit, die mit SRM verbundenen komplexen Herausforderungen mit Bedacht zu behandeln und robuste regulatorische Rahmenbedingungen zu schaffen. In der wissenschaftlichen Literatur werden verschiedene Technologien als potenzielle SRM-Methoden behandelt, wobei die Stratospheric Aerosol Injection (SAI) und das Marine Cloud Brightening (MCB) zu den bekanntesten Optionen gehören. Trotz ihrer bereits langen Erforschung und des dadurch hervorgehenden Potenzials werden sie jedoch auch stark kritisiert, u. a. im Hinblick auf ihre Wirksamkeit, die ökologischen Risiken und die geopolitischen Auswirkungen. Mögliche Wechselwirkungen zwischen SRM und den Zielen für nachhaltige Entwicklung der Vereinten Nationen (SDGs) bringen zusätzliche Komplexität mit sich. Während Befürworter*innen argumentieren, dass der Einsatz von SRM die negativen Auswirkungen des Klimawandels auf verschiedene SDGs abmildern könnte, bestehen Bedenken hinsichtlich der möglichen negativen Auswirkungen auf die Ernährungssicherheit, die Verfügbarkeit von Wasser, die Ökosysteme und die demokratischen Entscheidungsprozesse. Dies verdeutlicht die Notwendigkeit umfassender Forschungs- und Governance-Mechanismen zur Steuerung jener komplexen Beziehungen zwischen SRM und den SDGs.

Als der Klimawandel auf die politische Tagesordnung trat, gehörten Geoengineering-Technologien, zu denen SRM traditionell gezählt wird, zu den ersten Lösungsvorschlägen. Sie wurden jedoch zunehmend umstritten, da sie von den notwendigen Klimaschutzmaßnahmen abzulenken drohten. Mitte der 2000er Jahre lebte das Interesse wieder auf, als die Royal Society 2009 ihren Bericht zu Geoengineering veröffentlichte. Es folgten verschiedene wissenschaftliche und politische Bewertungen von Geoengineering, unter anderem durch das Umweltbundesamt (2011). Die politische und wissenschaftliche Debatte über Klimawandel und Geoengineering hat sich seitdem weiterentwickelt und unterscheidet zunehmend zwischen der Kohlendioxid-Entnahme aus der Atmosphäre (Carbon Dioxide Removal, CDR) und SRM.

SRM ist umstritten und unsicher. Es bestehen Fragen zur Wirksamkeit, zu möglichen unerwünschten Auswirkungen und zu den spezifischen Risiken, die mit den verschiedenen Technologien verbunden sind. Die *stratosphärische Aerosolinjektion (SAI)* zielt darauf ab, das einfallende Sonnenlicht zu streuen, indem eine große Menge an Aerosolpartikeln (etwa Schwefeldioxid) in die Stratosphäre (oberhalb von etwa 20 km) eingebracht werden. Die hauptsächlich modellgestützte Forschung zu SAI lässt Zweifel an der Zuverlässigkeit der Prognosen aufkommen, insbesondere was die Auswirkungen auf globaler und regionaler Ebene

betrifft. Es gilt zwar als gesichert, dass SAI zu einer Verringerung der globalen Temperaturen führen würde, doch verbleiben weiterhin Unsicherheiten hinsichtlich des Ausmaßes dieser Abkühlung und der weiterreichenden Auswirkungen auf verschiedene Klimasysteme. Potenzielle negative klimatologische Auswirkungen bieten einen zentrale Anlass zur Sorge, einschließlich Veränderungen der Niederschlags- und Sturmmuster sowie der Kohlenstoffaufnahme, die regionale Schwankungen und vorübergehende, auf die Tageslichtseite des Planeten begrenzte Auswirkungen aufweisen könnten. Eine weitere kritische Ungewissheit betrifft den potenziellen Abbau des stratosphärischen Ozons aufgrund erhöhter Aerosolwerte, was zu einer erhöhten UV-Strahlung an der Erdoberfläche führen könnte. Weitere Unwägbarkeiten betreffen die möglichen Auswirkungen von SAI auf die landwirtschaftliche Produktivität und ökologische Systeme. Nach wie vor gibt es Fragen zu den sicheren und wirksamen technische Umsetzung von SAI, einschließlich Überlegungen zu Aerosoltypen und der Methode des Eintrags in die Stratosphäre. Diese Ungewissheiten stellen nicht nur eine wissenschaftliche Herausforderung dar, sondern haben auch erhebliche politische Auswirkungen, die zu geopolitischen Spannungen führen können.

Marine Cloud Brightening (MCB) zielt darauf ab, die Erde zu kühlen, indem das Reflexionsvermögen tief hängender Wolken über Teilen des Ozeans erhöht wird. Dazu werden mehr Partikel in die Wolken eingebracht, um mehr Kerne zu erzeugen, um die sich Tröpfchen bilden können, wodurch ihr Reflexionsvermögen erhöht wird. Es bestehen jedoch erhebliche Unsicherheiten in Bezug auf die Wirkung von MCB, einschließlich des Abkühlungspotenzials und der Wechselwirkung mit Wolken, Aerosolen und Niederschlagsmustern. Die Forschungsarbeit zu MCB ist meist modellbasiert, jedoch bestehen Unstimmigkeiten zwischen den Modellen und mit Beobachtungsdaten hinsichtlich der Wechselwirkungen zwischen Aerosolen und Wolken. Dies lässt Zweifel an der Zuverlässigkeit der Modellprojektionen für die Wirksamkeit und die Risiken von MCB aufkommen. Darüber hinaus ist die technische Umsetzung von MCB noch unzureichend, und seine potenziellen Auswirkungen auf marine Ökosysteme sind ungewiss. Es stellt sich die Frage, wie MCB-Forschungsprojekte einzurichten und zu überwachen sind und wann sie im Falle negativer Auswirkungen zu stoppen sind.

Die meisten anderen vorgeschlagenen Technologien werden aufgrund der wirtschaftlichen Kosten, der technischen Unsicherheiten, der prognostizierten Wirksamkeit und der potenziellen Risiken als unrentabel für eine erfolgreiche Abkühlung des Klimas angesehen. Dazu gehören Weltraumspiegel, die Aufhellung von Infrastrukturen, die gentechnische Veränderung von Pflanzen zur Verbesserung der Albedo und die Verwendung von Mondstaub zur Abschirmung der Erde vor Sonnenlicht. Eine Alternative mit Potenzial, wenn auch nur regional, ist das Cirrus Cloud Thinning (CCT). Bei CCT werden die Zirruswolken in der oberen Troposphäre ausgedünnt, damit mehr langwellige Strahlung entweichen kann, was zu einer Abkühlung des Klimas führen könnte. CCT ist jedoch kaum bekannt, und seine Wirksamkeit und Durchführbarkeit sind ungewiss. Sie bietet zwar Vorteile gegenüber MCB und SAI, da sie mehr langwellige Strahlung entweichen lässt, birgt aber auch Risiken und Unsicherheiten in Bezug auf die Auswirkungen auf regionale Niederschläge, das genaue Kühlungspotenzial und die Durchführbarkeit. Die Forscher vermuten, dass die CCT, wenn sie erfolgreich ist, möglicherweise nur zur Kühlung der antarktischen Regionen beiträgt und keine globale Kühlung bewirkt. Insgesamt bestehen nach wie vor erhebliche Unsicherheiten in Bezug auf die Wirksamkeit, die Durchführbarkeit und die potenziellen Auswirkungen von CCT.

Die Governance, Erforschung und potenzielle Umsetzung von SRM stellen komplexe Herausforderungen dar, die mit geopolitischen sowie Aspekten der Gerechtigkeit verwoben sind. Grundlegende Meinungsverschiedenheiten bestehen weiterhin hinsichtlich der Rolle von SRM in der Klimapolitik, wobei sich in einigen Punkten ein Konsens abzeichnet: SRM kann die

Bemühungen um eine rasche Dekarbonisierung nicht ersetzen, es kann die Erwärmung vorübergehend verschleiern, ohne jedoch die Ursache zu bekämpfen, und SRM-Technologien für die globale Kühlung sind höchst unsicher und riskant. Zu den Bedenken hinsichtlich der Governance gehören die potenzielle Ablenkung von Treibhausgasminderung, die Festlegung auf SRM-Technologien im Sinne eines Lock-in-Effekts, militärische und sicherheitsrelevante Effekte, Herausforderungen für die demokratische Entscheidungsfindung und die globale Gerechtigkeit bei der Umsetzung und Wissensproduktion. Als Reaktion darauf plädieren viele Wissenschaftler*innen und Governance-Forscher*innen für ein internationales Abkommen über die Nichtnutzung von SRM, um deren Entwicklung, Freilandversuche und Einsatz zu verbieten. Viele sind sich über die Dringlichkeit eines Moratoriums für den *Einsatz* von SRM einig. Uneinigkeit herrscht jedoch über die in dem Abkommen vorgeschlagenen strengen Vorschriften und die teilweise Streichung von Mitteln für die Forschung und Entwicklung von SRM. Dies spiegelte sich auch in den beiden vom UBA einberufenen SRM-Expertenworkshops wider, in denen Wissenschaftler*innen auf den erheblichen Wissensmangel hinwiesen, der zu eklatanten Unsicherheiten über die Wirksamkeit, Risiken und Kosten von SRM führt. Einige der Wissenschaftler*innen sahen darin einen wichtigen Grund für mehr (auch staatlich finanzierte) Forschung und äußerten auch die Hoffnung, dass dadurch SRM als einfache Lösung für den Klimawandel entkräftet werden könnte. Die meisten Expert*innen waren sich einig, dass ein Abkommen über die Nichtnutzung und eine strengere Kontrolle der Forschung erforderlich sind. Die öffentliche Finanzierung wurde als entscheidend für die Transparenz erachtet, auch wenn weiterhin Bedenken hinsichtlich der Normalisierung und Entwicklung von SRM bestehen. Insgesamt unterstrichen die beiden SRM-Workshops die Notwendigkeit einer soliden Governance, Transparenz und demokratischer Prozesse in der SRM-Forschung und der potenziellen Umsetzung.

Die heute getroffenen Entscheidungen in der SRM-Governance werden diese in den kommenden Jahren prägen, was die Verflechtung von Forschung, Governance und gegenwärtigen politischen Dynamiken verdeutlicht. Insgesamt besteht Konsens darüber, dass internationale Zusammenarbeit und Steuerungsmechanismen erforderlich sind, um die mit SRM verbundenen geophysikalischen, ökologischen und politischen Risiken zu bewältigen. Es ist weithin anerkannt, dass SRM niemals ein Allheilmittel für den Klimawandel sein kann und die Bemühungen zur Treibhausgasreduktion nicht ersetzen sollte und kann.

Die Frage, ob SRM als Schutzmaßnahme gegen die schwerwiegendsten Auswirkungen des Klimawandels dienen kann, ist nach wie vor umstritten. Daher schlagen wir vor:

- Verfolgung eines multilateralen Moratoriums für den Einsatz von SRM oder alternativ Bildung einer Koalition von Parteien, die bereit sind, auf den Einsatz von SRM zu verzichten.
- Schaffung eines strengen Rahmens für die SRM-Forschung, der von Forscher*innen mit unterschiedlichem disziplinärem Hintergrund gemeinsam entwickelt wird. Dieser Rahmen sollte sich mit dem Zweck, dem Umfang, der Finanzierung, der Transparenz und den partizipativen Prozessen der SRM-Forschung befassen, wobei der Schwerpunkt auf politischen und gesellschaftlichen Risiken liegen sollte. Der Selbstverwaltung innerhalb der Forschungsgemeinschaft sollte entgegengewirkt werden.
- Verweigerung der Unterstützung für die Entwicklung von SRM-Technologien, wenn die Forschung nicht strenger kontrolliert wird, insbesondere im Hinblick auf öffentliche Konsultationen und die Vielfalt der Perspektiven und Wissensformen.
- Anreize und Ressourcen für Forscher*innen bereitstellen, damit sie sich in Partnerschaft mit Fördereinrichtungen an der Entwicklung umfassender Governance-Rahmenwerke

beteiligen. Im Wesentlichen plädieren wir dringend für die Verabschiedung eines Nichtnutzungs-Abkommens zu SRM, das sich an den im CBD-Beschluss X/33 dargelegten Grundsätzen orientiert. Die Vorzüge und Grenzen der bestehenden Vorschläge für ein solches Abkommen müssen sowohl in der Politik als auch in der Wissenschaft weiter diskutiert werden.

Summary

This discussion paper explores the level of knowledge on proposed solar radiation modification (SRM) technologies, their associated risks as well as their governance implications. It draws upon insights from two expert workshops convened by the UBA and the Copernicus Institute of Sustainable Development on 15 September and 19 October 2022, blended with an overview of the academic literature as well as personal assessments from the authors.

SRM (also referred to as solar radiation management, climate intervention, and solar geoengineering) describes a set of proposed technologies that aim to counteract anthropogenic climate change through reducing solar insolation into the earth climate system. Aiming to enhance the earth's albedo, they could limit the amount of energy in the climate system, hence leading to less warming. Debates surrounding SRM technologies are multifaceted and contentious, with divergent viewpoints on their feasibility, risks, and ethical implications. While some advocate for further research into SRM as a potential climate intervention strategy, others caution against its development due to the uncertain and potentially harmful consequences. These disagreements underscore the need for cautious consideration and robust governance frameworks to address the complex challenges associated with SRM. Within the academic literature, various technologies appear as potential SRM methods, with stratospheric aerosol injection (SAI) and marine cloud brightening (MCB) among the most prominent options. These technologies have been extensively studied, reflecting their perceived scientific promise. However, they also face significant criticism, including concerns about their effectiveness, ecological risks, and geopolitical implications. Possible interactions between SRM and the United Nations Sustainable Development Goals (SDGs) introduce additional complexities. While proponents argue that SRM deployment could mitigate the adverse effects of climate change on various SDGs, concerns persist regarding its potential negative impacts on food security, water availability, ecosystems, and democratic governance. These complexities underscore the necessity of comprehensive research and governance mechanisms to navigate the intricate relationships between SRM and the SDGs.

Geoengineering technologies, under which SRM has traditionally been grouped, were among the first proposals when climate change entered the political agenda. However, they became controversial as potential distractions from necessary mitigation commitments. Interest resurged in the mid-2000s, associated with the Royal Society's publication of its 2009 report and followed by various scientific and policy assessments on Geoengineering have followed, including by the Umweltbundesamt (2011). The political and scientific debate surrounding climate change and geoengineering has since evolved to increasingly differentiate between Carbon Dioxide Removal (CDR) and SRM.

SRM is controversial and uncertain, with questions about its efficacy, potential unwanted effects, and specific risks associated with different technologies. *Stratospheric aerosol injection (SAI)* aims at scattering incoming sunlight by increasing the amount of aerosol particles (such as sulfur dioxide) in the stratosphere (above about 20 km). The primarily model-based research leaves doubts about the reliability of projections, particularly concerning of the effects at both global and regional scales. While there is general agreement that SAI would lead to a reduction

in global temperatures, uncertainties persist concerning the magnitude of this cooling effect and the broader impacts on various climate systems. Potential adverse climatological effects are a key concern, including alterations in precipitation and storm patterns as well as carbon uptake, which may exhibit regional variability and transient impacts limited to the daylight side of the planet. Another critical uncertainty pertains to the potential depletion of stratospheric ozone due to increased aerosol levels, which could result in heightened UV radiation at the Earth's surface. Additional uncertainties surround the potential impact of SAI on agricultural productivity, and ecological systems. Questions persist regarding the safest and most effective methods for implementing SAI, including considerations of aerosol types and strategies for distributing them in the stratosphere. These uncertainties not only pose scientific challenges but also have significant political implications, potentially leading to geopolitical tensions.

Marine Cloud Brightening (MCB) aims to cool the Earth by increasing the reflectivity of low-hanging clouds over parts of the ocean. This involves introducing more particles into clouds to create more nuclei around which droplets can form, thereby increasing their reflectivity. However, there are significant uncertainties regarding MCB's potential effects, including its cooling potential and interaction with clouds, aerosols, and precipitation patterns. Most research on MCB is model-based, but there are inconsistencies among models and with observational data regarding aerosol-cloud interactions. This raises doubts about the reliability of model projections for MCB's effectiveness and risks. Additionally, the technical implementation of MCB is still lacking, and its potential impacts on marine ecosystems are uncertain. Questions remain about how to set up and monitor MCB research projects and when to halt them if adverse effects arise.

Most other proposed technologies are considered unviable for providing global cooling due to economic costs, technical uncertainties, projected efficacy, and potential risks. These include space mirrors, whitening of infrastructures, genetically modifying plants for albedo enhancements, and using moon dust to shield the Earth from sunlight. One alternative with potential, albeit only regionally, is *Cirrus Cloud Thinning (CCT)*. CCT involves thinning cirrus clouds in the upper troposphere to allow more longwave radiation to escape, thereby potentially cooling the climate. However, CCT is poorly understood, and its effectiveness and feasibility are uncertain. While it may offer advantages over MCB and SAI in allowing more longwave radiation to escape, it also carries risks and uncertainties regarding its impact on regional precipitation, exact cooling potential, and feasibility. Researchers suggest that if successful, CCT may only be effective in cooling Antarctic regions rather than achieving global cooling.

The governance, research, and potential implementation of Solar Radiation Management (SRM) present complex challenges, intertwined with geopolitical and justice concerns. Fundamental disagreements persist regarding SRM's role in climate policy, with consensus emerging on several points: SRM cannot replace rapid decarbonization efforts, it may temporarily mask warming but fails to address its root cause, and SRM technologies for global cooling are highly uncertain and risky. Governance concerns include the potential deterrence from mitigation policies, locking in SRM technologies, military and securitization effects, challenges to democratic decision-making, and global justice in implementation and knowledge production. In response, many scientists and governance scholars advocate for an international non-use agreement on SRM, aiming to prohibit its development, outdoor experiments and deployment. Many agree on the urgency of a moratorium on SRM use. However, disagreements persist regarding the strict regulations and partial defunding of SRM research and development proposed in the agreement. This was reflected in the two SRM expert workshops convened by the UBA, in which scientists referred to the 'paucity of knowledge' as leading to glaring uncertainties about their effectiveness, risks, and costs. Some of the scientists viewed this as a vital reason for more (including state-funded) research and also expressed the hope that this could help invalidate SRM as a simplistic solution to climate change. Most experts agreed on the need for a non-*use* agreement and stricter research governance. Public funding was deemed crucial for transparency, although concerns remain about the normalization and implementation of SRM. Overall, the two SRM workshops underscored the need for robust governance, transparency, and democratic processes in SRM research and potential deployment.

Decisions made today will shape the governance of SRM for years to come, illustrating the entanglement of research, policy, and political dynamics. Overall, there is consensus on the need for international cooperation and governance mechanisms to address the geophysical, ecological, and political risks associated with SRM. It is widely acknowledged that SRM cannot serve as a panacea for climate change and should not replace mitigation efforts.

Whether it could act as a safeguard against the most severe impacts of climate change remains a contentious topic. Consequently, we propose:

- Pursuing a multilateral moratorium on SRM implementation, or alternatively, forming a coalition of willing parties to abstain from its use.
- Establishing a rigorous framework for SRM research, developed collaboratively by researchers from diverse backgrounds. This framework should address the intent, scale, funding, transparency, and participatory processes of SRM research, with a focus on political and societal risks. Self-governance within the research community should be discouraged.
- Withholding support for further development of SRM technologies in the absence of stricter research governance, particularly regarding public consultation and diversity of perspectives.
- Providing incentives and resources for researchers to engage in developing comprehensive governance frameworks in partnership with funding agencies. In essence, we advocate for an urgent adoption of a non-use agreement on SRM, drawing from the principles outlined in the CBD Dec. X/33. The merits and limitations of existing proposals for such an agreement warrant continued debate, both within political and academic spheres.

1 Introduction

In expert workshops held on 15 September and 19 October 2022, the German Environment Agency (Umweltbundesamt, UBA) in collaboration with the Copernicus Institute of Sustainable Development, Utrecht University, discussed the scientific, technical, and geopolitical viability and desirability of different SRM technologies. In this discussion paper, we present a blended overview of the academic literature on these technologies and the positions expressed at these expert workshops, as well as personal assessments and opinions from the authors. If not otherwise indicated, the findings presented here are based on assessment reports and the scientific literature. In case a position is taken by the authors or is a direct statement or directly inferred from the workshops, it will be clearly indicated.

Solar radiation modification (also referred to as solar radiation management, climate intervention, and solar geoengineering) describes a set of proposed technologies that aim to counteract anthropogenic climate change through reducing solar insolation into the earth climate system. SRM technologies are also called albedo modification techniques because they aim to enhance the albedo, the diffuse reflection of solar radiation. Doing so would limit the amount of energy in the climate system, and hence lead to less warming. Within the academic literature, various technologies appear as potential SRM methods, ranging from increasing the reflectivity of ocean surfaces via microbubbles to injecting aerosols in the stratosphere to scatter and reflect incoming sunlight. The idea emerged as early as the 1960s, but sparked increasing interest in the 2000s, as evidenced by a growing number of scientific and policy advisory studies on the proposed technologies. Using the disputable argument that achieving the 1.5° and 2° goals is out of reach, some atmospheric scientists have seen present SRM research as imperative. In this view, SRM could mask the 'overshoot' of carbon dioxide concentrations while carbon dioxide removal brings those concentrations back down safe levels or as an insurance against catastrophic warming (Irvine et al. 2019; Wagner 2021). Numerous other researchers criticize SRM approaches for various reasons, including but not limited to: failing to address the root cause of climate change (Hulme 2014; Lovelock 2008), being incompatible with fair and democratic governance (Biermann et al. 2022; Szerszynski et al. 2013), raising serious geopolitical and security issues (Chalecki/Ferrari 2018; Heyen/Horton/Moreno-Cruz 2019; McLaren/Corry 2021a; b), presenting major ecological risks (McDonald 2022; Trisos et al. 2018a), and above all, potentially causing a dangerous delay of emissions reduction (McLaren 2016; Tsipiras/Grant 2022). Given current geopolitical insecurities and the enduring difficulties of climate politics, this is a debate not likely to be resolved.

The most prominent options of these speculative technologies are stratospheric aerosol injection and marine cloud brightening. Stratospheric aerosol injection (SAI) aims at scattering incoming sunlight by increasing the amount of aerosol particles in the stratosphere (above about 20 km). Marine cloud brightening (MCB) aims to cool the earth by brightening the reflectivity of low-hanging and continuous cloud cover over parts of the ocean. Other technologies in scientific view are cirrus cloud thinning (CCT), which aims to increase the amount of longwave radiation leaving the atmosphere by thinning thin wispy clouds in the upper troposphere, and the ocean surface albedo modification, aiming to enhance the reflectivity of ocean surfaces in various ways, as well as space shields (or mirrors) and surface albedo enhancements, most notably in deserts. In the most recent assessment report of the National Academies of the Sciences, for example only SAI, MCB, and CCT are mentioned extensively (National Academies of Sciences 2021). While this does not mean that other SRM methods are necessarily unviable, it does point to an emerging scientific convergence around SAI and MCB being the most scientifically promising proposals. For global cooling, CCT seems less promising or even counterproductive (Gasparini et al. 2020; Gasparini/Lohmann 2016; Lohmann/Gasparini 2017).

Proposals for SRM technologies and their research have led to strongly polarized and contentious debates. It is a debate in constant flux. Initially, research mostly focused on the assessment of the feasibility of SRM technologies. Increasingly, however, researchers are also calling for developmental SRM research, arguing that given the extremity of climate change on the horizon, SRM research is self-evidently necessary. We observe these developments with concern and hold the position that it is not at all self-evident that research into these technologies is desirable. All proposed interventions would entail serious and largely unforeseeable technological, ecological, and geopolitical risks. Due to the danger of deterring from necessary emission reductions and the risk of a termination shock, it could even exacerbate the climate crisis. Considerable scientific disagreement exists around the extent of these risks, how such risks relate to increased risks of climate change, and whether such uncertainties could be resolved (Oomen, 2021; NAS, 2021). These disagreements are typically related to divergent ways of weighing relative risks and benefits, differing readings of the contemporary political world, and different worldviews and values (Oomen 2021). As such, they constitute a largely intractable conflict between values and worldviews. It is unlikely that these disagreements, including ostensibly neutral scientific questions around model validity and direct effects of SRM, will ever fully be resolved. This has both to do with the fundamental uncertainty of complex climate systems and with diverging opinions on good scientific research. For these reasons, an likewise growing group of researchers calls for restrictions and prohibitions of the development of SRM technologies (e.g. Biermann, 2021; Biermann et al., 2022; Stephens et al., 2021; Surprise, 2022). At the very least, we would argue these these intractable conflicts are a reason to proceed with extreme caution (precautionary principle) – and to resist the simple narrative that more scientific research is always preferable.

Considerable uncertainties and knowledge gaps also exist around the interactions with the politically agreed upon Sustainable Development Goals (SDGs). On the one hand, proponents of SRM argue that a potential deployment may ameliorate negative effects for all SDGs that are affected by the progression of climate change, such as SDGs 1, 2, 3, 14, and 15. On the other hand, many of the above described potentially adverse effects of SAI likewise point towards clear detrimental implications for the SDGs. Prominently, change in local climate parameters such as precipitation may impair food security (SDG 2), water availability (SDG 6) or the safety of human settlements (SDG 11) (Honegger et al. 2018; Barnes et al. 2019). Potential acidification effects on surface water and soils might impair sensitive ecosystems (SDGs 14, 15) (Honegger et al. 2018; Honegger/Michaelowa/Pan 2021; Visioni et al. 2018). The governance challenges outlined, in turn, are also reflected in complex interactions with the SDGs such as in potential security risks (SDG 16) and questions of representation and democratic governance (SDGs 1, 10). The underrepresentation of women in SRM research has been cited as a knowledge gap regarding gender imbalances in governance considerations (SDG 5) (Buck/Gammon/Preston 2014; Honegger/Michaelowa/Pan 2021). Finally, the risk of mitigation deterrence negatively affects SDG 13 with its focus on urgent action to combat climate change.

2 Geoengineering in (very) brief

The term geoengineering encompasses a wide range of diverging technologies and interventions, historically connoting a wide range of large-scale interventions in the planetary environment. It is used widely both in relation to anthropogenic climate change (e.g. National Academies of Sciences, 2021; National Academy of the Sciences, 1992; Royal Society, 2009; Umweltbundesamt, 2011) and lithosphere geoengineering (e.g. Civil Engineering Research Foundation [CERF], 1994; Morgenstern, 2000; National Research Council, 2006, p. 1), as well as occasionally in ecology in relation to treating hypoxic dead zones in seas and lakes (Lürling et al. 2016; Stigebrandt et al. 2015). Although these interventions share a family resemblance in terms of the underlying rationality and aims (Oomen/Meiske 2021), in the public eye geoengineering has increasingly come to be synonymous with 'climate (geo)engineering'. Scientific and political interest in geoengineering predates 'climate science' as a discipline, being as old as the scientific recognition of the link between carbon dioxide concentrations and global temperature (Baskin 2019; Fleming 2010; Oomen 2021). In relation to climate change, geoengineering technologies were among the first proposals when the issue arrived on the political agenda (The White House 1965). However, by the time climate change became a major political issue in the 1980s and the 1990s, geoengineering technologies had become controversial. Both scientists and politicians viewed such technologies as dangerous distractions from necessary conventional mitigation commitments, although 'geoengineering' did make it into a prominent 1992 report on climate change by the National Academy of the Sciences. Interest in geoengineering thus remained marginal until the mid-2000s, when it experienced a resurgence, notably marked by the Royal Society's 2009 report, which at the time included both carbon dioxide removal (CDR) methods and SRM. Since then, the term 'geoengineering' has increasingly been used along the lines of the Royal Society's 2009 definition of the term: 'deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming' (Royal Society, 2009: ix). In 2011, the UBA published its own position paper on geoengineering, likewise as a broad technological category (Umweltbundesamt, 2011). A series of scientific and policy assessments and commitments of SRM followed suit (e.g. National Academies of Sciences, Engineering, and Medicine, 2021; National Research Council, 2015; United Nations Environment Programme, 2023; Williamson & Bodle, 2016). Most recently, the European Commission and the European High Representative for Foreign Affairs jointly published a communication in which they stated the EU 'will support international efforts to assess comprehensively the risks and uncertainties of climate interventions, including solar radiation modification' (European Commission/High Representative of the Union for Foreign Affairs and Security Policy 2023, p. 20). In June 2023, the White House published a report including a congressionally mandated research plan focusing on atmospheric SRM methods (especially SAI and MCB). The report explicitly does not represent a policy decision by the executive branch of the Biden administration, but develops theoretical guidelines for transparent and equitable SRM research and approaches for national and international coordination (OSTP 2023). Since 2011, much has changed in the political and scientific debate around climate change and geoengineering – although many of the same uncertainties remain. For one, CDR and SRM have become increasingly differentiated and increasingly treated in isolation from one another. As a result, the term 'geoengineering' has also become less common, especially in relation to CDR. In this discussion paper series, we recognise this differentiation, acknowledging both the inevitable imperfection and necessity of classifying geoengineering. This first paper addresses SRM as a technological category. The second discussion paper will address land-based (terrestrial) CDR and direct air capture (DAC). The third in the series zooms in on marine forms of carbon dioxide removal.

3 Solar Radiation Modification: The Technologies

The assessment of the U.S. National Academic of Sciences, Engineering, and Medicine (NAS) indicated last year that SRM technologies might *potentially* offer an additional strategy for responding to climate change – although this is highly uncertain. At the same time, it can never be a substitute for reducing GHG emissions: "This is in part because [SRM]

- does not address the underlying driver of climate change (increasing GHG concentrations in the atmosphere) or the key impacts of rising atmospheric CO_2 such as ocean acidification;
- raises concerns about new risks, uncertainties, and unintended impacts on natural ecosystems, agriculture, human health, and other critical areas of concern for society;
- cannot provide a reliable means to restore global or regional climate to some desired prior state; and
- entails unacceptable risks of catastrophically rapid warming if the intervention were ever terminated (if it were used to offset a large amount of warming without simultaneously deploying measures to reduce GHG emissions)" (National Academies of Sciences, 2021: p. 2-4).

SRM is deeply controversial and uncertain. Technically and climatologically, there are questions about the efficacy of SRM at large scales and the potential for unwanted effects. Such questions apply for SRM as a broad category, such as concerns over precipitation patterns or attribution of effects to specific SRM interventions. Specific technologies also present specific risks and uncertainties. For SAI, for example, these include effects on hydrological cycles (Cheng et al. 2019; Tilmes et al. 2013) and on stratospheric ozone (Tilmes et al. 2021, 2022), as well as its regional and seasonal effects (Abiodun et al. 2021; Krishnamohan/Bala 2022; Visioni et al. 2020). Additionally, there are concerns about knowledge production. The reliability and validity of model-based projections, on the one hand, are debated (Fasullo/Richter 2022). Field experiments, on the other, are deeply controversial (Mettiäinen et al. 2022). Finally, social and political concerns about SAI raise questions about whether SAI could be governed fairly and democratically (Grieger et al. 2019; McLaren/Corry 2021a).

Insights from the SRM expert workshops

As the expert workshops made clear, considerable disagreement exists within the scientific community about the extent to which these risks apply to specific technologies, and whether those uncertainties could be solved. However, the experts present in the workshop agreed that they were working with a 'paucity of knowledge'. The state of research is so rudimentary, they concurred, that it is exceedingly difficult to make any definitive statements about: the efficacy of different SRM methods, the risks of those methods, the technical feasibility of implementing such measures, and the potential cost of implementing such methods. At the same time, the expert community disagrees to what extent more research could improve risk assessment and whether remaining risks could be reduced to acceptable levels. Moreover, many fundamental questions, geophysical and bioecological as well as geopolitical, could never be solved until implementation at scale (known unknowns). A further important observation from the expert workshops was that detailed research often reduced strong claims about the extent to which SRM could be useful in combating global warming to far more modest proportions. For most scientists present in the workshop, empirical SRM research answers the questions 'what not to do' and 'can SRM methods work at all', as well as questions around the development and implementation of SRM.

3.1 What we (don't) know about SAI

Almost all climatological research into SAI has been model-based, using model projections to gauge its potential effects. There are significant uncertainties about the potential effects of SAI, including its cooling potential. Although there is a rough consensus that SAI would lower global average surface temperatures, "large uncertainties remain regarding the cooling potential with injection amount, location, and type and regarding the effects of an increased aerosol burden on atmospheric chemistry, transport, and resulting regional and local effects on climate; these contribute to uncertainty in climate response and resulting impacts around the world" (National Academies of Sciences, 2021: 4). The risks and efficacy of solar geoengineering remain poorly understood (Barrett et al. 2014; Kravitz/MacMartin 2020; Lawrence et al. 2018; Schneider/Kaul/Pressel 2020). Key uncertainties include:

- **Whether SAI might have adverse climatological effects:** SAI may heavily affect climatological systems. It is very likely to alter precipitation distributions (Abiodun et al. 2021; Krishnamohan/Bala 2022) and affect terrestrial carbon uptake responses. Importantly, SAI would likely have regionally different effects (Kravitz et al. 2017; National Academies of Sciences 2021), which would lead to severe political, social, and ecological consequences. A decisive difference between the use of SAI and the reduction of greenhouse gas emissions is that the former does not have a permanent effect on all sides of the planet, but rather only on the daylight side. This would result in completely new spatial differences and patterns in the energy fluxes of the atmosphere.

- **Whether the predictive capacity of current model projections is reliable:** There remains a major uncertainty how well climate models represent the potential effects of SAI. This is „a major uncertainty surrounding the potential implementation of this solar climate intervention strategy"(Fasullo & Richter, 2022: p. 1), that includes questions around the global and regional climatological effects of SAI as well as chemical and physical effects of introducing aerosols into the stratosphere.

- **How injected aerosols might affect stratospheric ozone:** Increasing stratospheric aerosols such as SO_2 would reduce stratospheric ozone levels (Tilmes et al. 2021), leading to increased UV radiation at the planetary surface. Currently, research investigates how to safely avoid ozone loss by finding suitable replacements for SO_2 (Huynh/McNeill 2020; Kravitz/MacMartin 2020; Tilmes et al. 2022).

- **How SAI might affect precipitation and other (global and regional) climate systems:** one of the primary climate risks of SAI is the risk of regional hydrological cycle changes. Currently, it is unclear what the effects of SAI on regional precipitation might be, although it is likely to influence rainfall patterns and storm patterns (Cheng et al. 2019; National Academies of Sciences 2021; Tilmes et al. 2013). Likewise, uncertainties remain about the effects of SAI on agriculture and crop yields (Trisos et al. 2018b), as well as terrestrial and marine ecosystems (Zarnetske et al. 2021). Severe uncertainties about the accuracy of model projections of rainfall patterns under SAI conditions remain.

- **Whether and how SAI could be implemented in a safe, effective, and controllable manner:** many modelling studies presuppose an 'optimal' implementation of SAI. It is, however, an open question what types of implementation would provide best results. Questions about latitude of implementation, season of implementation, types of aerosols are all topics of research (Krishnamohan/Bala 2022; Lee et al. 2021; Lockley/MacMartin/Hunt 2020; Visioni et al. 2020; Zhao et al. 2021). Again, uncertainties about the accuracy of such projections remain, as well as serious doubts over whether optimal implementation would be feasible in reality.

It should be noted that all such uncertainties interact. For example, the uncertainty about the effects of aerosol in the stratosphere reinforces questions about the predictive accuracy of models. Uncertainties also have potential political repercussions. Altered precipitation patterns may lead to disrupted monsoons, which could result in major crop loss, hunger, poverty, and severe geopolitical tensions. Likewise, uncertainty around regional differentiation of effects might also lead to dispute over the 'optimal' distribution of SAI technologies.

3.2 What we (don't) know about Marine Cloud Brightening (MCB)

Marine cloud brightening would cool the Earth by increasing the reflectivity of low-hanging cloud over parts of the ocean. The basic premise is that by introducing more particles into the clouds, there would be more nuclei around which droplets could form. As a result, clouds with the same water content could be made more reflective due to a larger internal surface Most climatological research into MCB has been model-based, using model projections to gauge its potential effects. There are significant uncertainties about the potential effects of MCB, including its cooling potential. No SRM technologies could reverse climate change. However, there are many open questions about the efficacy, technical implementation, and risks of marine cloud brightening. These include uncertainties about:

- **How clouds and aerosols would interact:** currently, there is a limited understanding of the interactions between aerosols and clouds, how this may affect the cloud's lifespan and precipitation (Stjern et al. 2017), as well as what this might mean for the cooling potential of MCB.

- **How MCB might affect precipitation and other climate systems:** like SAI, MCB presents a lot of uncertainties in terms of how it might interact with the climate system. MCB would be implemented regionally – while its effects aim to be global – but the interaction between the regional implementation of MCB and its global and ecological effects (e.g Latham et al., 2013) is still poorly understood, e.g. both in terms of the potential to affect crop growth (Parkes/Challinor/Nicklin 2015) and tropical productivity (Muri/Niemeier/Kristjánsson 2015).

- **The inconsistency of model projections:** The models disagree both with each other and with observational data about aerosol cloud interactions, albedo enhancement, and regional/global effects (National Research Council 2015, p. 118). Again, this raises serious questions about the reliability and validity of model projections.

- **Whether the predictive capacity of current model projections is reliable:** like in the case of SAI, projections of the effectiveness of MCB are based on model studies. Here too, there remains a major uncertainty how well climate models represent the potential effects of MCB. Currently, they are certainly not yet reliable enough to provide good estimates of efficacy and risks of MCB (Ahlm et al. 2017; National Research Council 2015) – and it is uncertain whether they could be.

- **How MCB might be implemented and how it might affect local ecosystems:** Currently, the technical capacities for the implementation of MCB are lacking. It is also unclear how MCB would impact marine ecosystems. Serious uncertainty remains on how to set up a research project and when to stop it if it has unwanted effects (Diamond et al. 2022).

3.3 What we (don't) know about other technologies

Beyond SAI and MCB, many different technologies have been proposed in the past. These include ideas such as space mirrors (e.g. Ferraro et al., 2015; Moore et al., 2010), the whitening of infrastructures, genetically modifying plants to enhance the albedo of their leaves (Ridgwell et al. 2009), and using moon dust to shield the Earth from incoming sunlight (Bromley/Khan/Kenyon 2023). However, SRM researchers regard most of these technologies as unviable in terms of their potential to provide global cooling because of a) their economic costs and technical uncertainties (space mirrors, moon dust), b) the projected efficacy (whitening of infrastructure), and potential risks (genetically modifying plants for albedo enhancements, moon dust). The one alternative that may have some potential, but only regionally, is cirrus cloud thinning:

Cirrus Cloud Thinning: Cirrus clouds are thin, wispy clouds in the upper troposphere that warm the atmosphere because they inhibit outgoing longwave radiation more than they reflect incoming solar radiation. Nevertheless, CCT is treated as an SRM method in most literature since it would be also done with the intent to cool the climate, regionally or globally. To some extent, it would also provide similar effects and risks. The theory behind CCT is that thinning such clouds might provide a net cooling of the planetary system. This could perhaps be done by seeding cirrus clouds with ice nuclei, around which larger ice crystals could form. This might in turn lead to a quicker fall of such crystals, reducing the lifetime of such clouds. This could only work when the meteorological conditions are exactly right. Currently, CCT is poorly understood. Its major potential advantage over MCB and SAI would be that it could allow the escape of more longwave radiation – which is what increasing CO_2 concentrations prevent. However, at this point it is unclear if it could work. Researchers have serious concerns that it could also lead to higher warming. If it did work, research suggests it would not be effective for global cooling but may only help to cool (Ant)arctic regions (Gasparini et al. 2020; Gasparini/Lohmann 2016; Lohmann/Gasparini 2017). Major uncertainties also still exist around: effects on regional precipitation, exact cooling potential and feasibility (National Academies of Sciences 2021; National Research Council 2015).

Insights from the SRM expert workshops

From the expert workshops, it became clear that most experts, including those who work on other technologies, see MCB and SAI as the most promising technologies – although deep disagreements continue to exist about that promise. Other technologies, such as space-based reflection methods are either too expensive, too technologically advanced, or too uncertain to work. Recent research by Blaz Gasperini and Ulrike Lohmann, for example, has shown that it is unlikely that CCT will work on global scales – although it may have some isolated uses in protecting the icecaps at the poles. Although most experts who support SRM research favoured researching a broad suite of different SRM technologies, SAI and MCB should be prioritised in their opinion, as these technologies could both affect the global temperature and could be ready for implementation within several decades.

Between MCB and SAI, some experts expressed a preferences or priority for MCB research, as they deemed it less risky. This specifically pertained to the timescale of implementation: MCB interventions, once stopped, would stop having an effect within weeks. Stratospheric aerosols would remain in the stratosphere for a year or two. That said, scientists agreed both technologies are so risky that they should have never been considered had it not been for catastrophic climate change. Given the likelihood of extreme climate change, however, scientists supporting SRM still favoured serious research and potential development of these technologies. Importantly, this includes political and social research into decision-making, monitoring, and questions of justice and equity.

Our personal assessment is that SRM research has become increasingly acceptable in the scientific community over the past years, in no small part due to ever-increasing concerns over the effects of climate change. Nonetheless, researchers disagree about which technologies provide the most promise, the most pronounced risk, and whether SRM could be implemented and sustained at all.

4 The potential of SRM: Agreements and disagreements

Given the major uncertainties around SRM, it is no surprise that deep disagreements about the role of SRM in climate policy persist. For some, SRM is anathema, too risky, politically charged and uncertain to consider seriously. According to others, SRM might possibly provide some alleviation of the worst damages of climate change. Despite those disagreements, researchers generally agree on the following:

- SRM is not an alternative for rapid and complete decarbonization. It cannot substitute conventional emission reduction and mitigation.
- SRM could potentially mask warming but does not address the cause of global warming and cannot reverse global warming perfectly.
- SRM technologies aimed to counteract warming on a global scale are highly risky and uncertain.
- Small-scale outdoor SRM research does not present immediate ecological and geophysical risks but does pose serious political concerns and sensitivities. On the other side, many researchers doubt the value of small-scale experiments.
- SRM might lower average global temperatures, but regional effects remain highly uncertain. Additionally, SRM may affect global precipitation patterns.
- SRM does not address detrimental effects of climate change beyond those directly related to warming. For example, it does not address serious impacts such as ocean acidification.
- SRM may lead to unexpected and unforeseeable detrimental and occasionally beneficial effects.
- In general, although scientific and ecological risks are significant, the most intractable risks of SRM are issues of governance, justice, power, security and geopolitics.

At the same time, considerable and intractable disagreement exists about the risks, efficacy, and political dimensions of SRM, both in terms of research and in terms of deployment. These disagreements include:

- Whether SRM can, must, or must not supplement mitigation efforts;
- The extent to which SRM technologies could address global warming and its correlated risks;
- The extent to which the impacts of SRM on precipitation, ecosystems and national security can be controlled (technically and politically);
- The promises and risks of individual SRM technologies, as well as their potential interaction with each other and the changing global climate;
- The desirability and political risks of SRM research, including the likelihood of mitigation deterrence through research and the risk of rendering SRM deployment inevitable;
- The desirability and geopolitical risks of potential SRM deployment, including questions of justice, national security, democratic decision-making, and historical culpabilities;
- The validity and reliability of model-based projections of the effects and efficacy of SRM deployment;

- The question of whether the risks associated with SRM can be sufficiently minimized by further research;
- The distinction between research and development, in particular regarding field experiments.

5 Governance, research, and moratoria

The thorniest issues with SRM are undoubtedly questions of geopolitics, governance, and justice. Mike Hulme (2014) once called SRM undesirable, ungovernable, and unattainable. His concerns are still valid. Current modelling research on SRM often presumes a level of coordination of implementation that will likely be impossible in the real world (Corry 2017; Low/Honegger 2020; McLaren 2018). Fundamental disagreements exist about whether the effects of SRM could ever fully be understood well enough before implementation (Oomen 2021). Moreover, the literature on governance issues expresses great concerns about how to govern SAI in a just and democratic manner (Flegal et al. 2019; Flegal/Gupta 2018; Jinnah et al. 2019; McLaren/Corry 2021a). Already, there is fierce opposition to field experiments and research (Grieger et al. 2019). Research and implementation of SRM cannot be disentangled from political realities and scientific convictions. As such, it is key to see how SRM might intersect with not only climate policy but also with other political aims of the world. Likewise, it is important to pay attention to the ways in which SRM research itself is part of and complicit in economic and political configurations. Such questions include questions around who funds and controls such technologies (Surprise, 2022), how SRM research intersections with military and economic interests, and what worldviews and ideologies underpin both knowledge construction and the relevant networks around SRM. In the academic literature, several key governance concerns reoccur. These key governance concerns include, but are not limited to:

- **SAI may deter from mitigation policies:** most scholars agree that there is a risk that SRM will come to play a political role in which these technologies, implicitly or explicitly, become a distraction from comprehensive decarbonization. Political actors might be tempted to argue for SRM options in order to present solutions and promising activities to avoid unpopular emission reductions or expensive climate adaptation measures. Alternatively, scientific assessments or political procedures may implicitly or inadvertently come to count on the successful implementation of SRM, leading to inadvertent delays in decarbonization or may be wielded politically (McLaren 2016).

- **Locking in the use of these technologies as an infrastructure and/or policy option:** It is a well-known observation in policy studies that implemented politics or established institutions justify themselves to prolong their existence. A prominent concern in the academic literature is that setting up a research infrastructure around SRM may lead to a self-justificatory process or infrastructure which makes SRM implementation inevitable (e.g., Cairns, 2014; Flegal et al., 2019; McKinnon, 2019; McLaren & Corry, 2021)

- **Military and securitization effects of SAI:** SRM cannot be disentangled from power struggles and geopolitical conflict. Almost all SRM researchers agree that the governance of SRM, certainly implementation but also research, may lead to severe geopolitical tensions. The uneven distribution of impacts, e.g., on precipitation patterns or the risk of extreme weather events between regions and countries holds the potential for geopolitical tensions. Furthermore, the technologies themselves may be interpreted as security risks by militaries and politicians, and tensions over the control or effects of SRM may lead to mistrust and political or even military conflict (e.g., Chalecki & Ferrari, 2018; Corry, 2017; Heyen et al., 2019; Robock, 2015). The history of geoengineering suggests such a development is not unprecedented (Baskin 2019; Fleming 2010; Oomen 2021). We would add that it is quite likely.

- **Incompatibility with democratic decision-making:** In an early paper, Szerszynski and colleagues expressed concerns about whether SRM could ever be governed in a democratic manner (Szerszynski et al. 2013). Although the paper was controversial (e.g. Horton et al., 2018), concerns over whether SRM might not favour autocratic, technocratic, or simply undemocratic decision-making remain.

- **Justice in terms of implementation, research, and mitigation politics:** Many critics worry about whether SRM would be implemented in a fair and just manner (e.g. Grasso, 2022; McLaren, 2018). As Clive Hamilton expressed early on, it would be naïve to expect SRM to be researched or implemented in ways that are more concerned about justice and equity than climate policy at large (Hamilton 2013a, Hamilton 2013b). At the same time, proponents of SRM research argue it would be unjust to rule out potentially beneficial technologies because of a distaste in academic circles or political concerns. However, this argument assumes that SRM would have only positive effects.
- **Tension between just implementation and national (or even commercial) interests:** Most assessments assume that SRM would be implemented in ways that are roughly optimised and agreed upon, or even just. Yet this is not at all self-evident, as such implementation might (and most likely will) stand in direct tension with national or even commercial interests (e.g. Morrow, 2020).

Based on these uncertainties and concerns, a group of over 500 scientists and governance scholars have recently called for an international non-use agreement on solar geoengineering, supported meanwhile also by more than 1900 civil society organizations. This call for a non-use agreement has been explicitly positioned as a reaction to the increasing normalization of SRM research, and is has been supported, among others, by Frank Biermann, Melissa Leach, Dirk Messner, Janez Potočnik, and Jeroen Oomen, who all co-authored with other colleagues the first article laying out the contours of such a non-use agreement (Biermann et al., 2022). This non-use agreement could include the following provisions:

1. The commitment to prohibit their national funding agencies from supporting the development of technologies for solar geoengineering, domestically and through international institutions.
2. The commitment to ban outdoor experiments of solar geoengineering technologies in areas under their jurisdiction.
3. The commitment to not grant patent rights for technologies for solar geoengineering, including supporting technologies such as for the retrofitting of airplanes for aerosol injections.
4. The commitment to not deploy technologies for solar geoengineering if developed by third parties.
5. The commitment to object to future institutionalization of planetary solar geoengineering as a policy option in relevant international institutions, including in assessments by the Intergovernmental Panel on Climate Change.' (Biermann et al, 2022).

The call for a non-use agreement has sparked a lot of discussion among SRM researchers, with both positive and negative reactions and new open letters published in support of SRM research (e.g. "climate-intervention-research-letter"). From the side of SRM researchers, many agree that a moratorium on the use of SRM would be timely and necessary. At the same time, many SRM researchers disagree with the strict regulations and partial defunding of SRM research and development. As a consequence, the merits and shortcomings of the proposal for a non-use agreement are subject to academic debate.

Insights from the SRM expert workshops

In the expert workshops on SRM, which were mostly of a technical nature, the non-use agreement was only partially subject to debate. However, it appeared that many of the scientific experts were opposed to a blanket ban on SRM research and development. Moreover, most natural science researchers felt that public funding should play a key role in SRM research, as without public funding SRM research might become less transparent or simply too limited. Many scientists also disagreed that SRM research would inevitably lead to normalization, development, and implementation of SRM. Often, they pointed out, research has proved SRM to be less effective and more dangerous than expected. As such, in this view very strong arguments against SRM implementation might be the result of more SRM research.

At the same time, the vast majority of participants to the workshops agreed that both a non-*use* agreement and far stricter forms of research governance are necessary. Existing frameworks such as Responsible Research and Innovation (RRI) might be a good starting point but cannot cover the unique and significant political risks of SRM.

Scientists also argued for a democratization of SRM research. Who decides what knowledge is important? Who pays? And what are the implications of such questions?

For the moment, the authors of this discussion paper do not take a position on the specifics of a necessary non-use agreement. Yet we do assert that while the specific shape of an eventual political agreement on the undesirability of SRM implementation and the potential undesirability of SRM research is open for debate, the *need* for such an agreement is not. As outlined in this paper, the use of SRM based on current knowledge would entail unacceptable and irredeemable geophysical, bioecological, and political risks. While not necessarily physically dangerous, research itself does present political risks as well. We ought to recognise those risks. As such, we do not take a position on the funding of research per se. However, we do concur with the urgent need for a non-use agreement on SRM that affirms and operationalizes the CBD Dec. X/33.

6 Conclusion

SRM is highly controversial. The implementation of these invasive technologies would entail serious and largely unforeseeable technological, ecological, and geopolitical risks. Considerable scientific disagreement exists around the extent of these risks, how such risks relate to increased risks of climate change, and whether such uncertainties could be resolved (Oomen, 2021; NAS, 2021). These disagreements relate to divergent ways of seeing technical risks and benefits, political sensitivities, and to different worldviews and values. In that light, SRM governance, both of research and of implementation is both a pressing concern and an intractable challenge. Research and policy decisions made in the present will shape SRM governance for decades to come. Clearly, SRM research and governance questions cannot be disentangled from a political system in which painful choices are often avoided by pointing to speculative technological solutions. Such assumptions can even be embedded in scientific projective modelling, also on SRM. This means that 'Just doing the research' does not and cannot exist. Research often plies itself to existing governance and policy demands and policy, in turn, is shaped by current research. Moreover, research norms and definitions might prefigure policy through *de fact*o rather than *de jure* governance (Gupta/Möller 2019). This means caution with SRM research - and its conditions - is highly advisable.

All experts agree that SRM is not and cannot be a solution for climate change. It cannot replace mitigation efforts. If it *could* be an insurance policy against the worst excesses of climate change remains a heated debate. As such, we advice:

- Consistent and continued efforts towards **a multilateral moratorium on the *use of SRM*.** In absence of a multilateral agreement, a non-use agreement could also take the form of a coalition of the willing.
- To develop a **restrictive framework for research**, in collaboration with researchers from diverse geographical and academic backgrounds. Such a framework does not need to prohibit SRM research but rather govern it based on a) intent, b) scale, c) funding, d) transparency, and e) participatory processes. Instead of technical and scientific questions, this framework should take political and socetial risks as its vantage point. While existing frameworks such as Responsible Research and Innovation (RRI) can offer some guidance, they cannot cover the unique and significant political risks of SRM. As such, they need to be extended. **Self-governance of research** should not be an option.
- **To withhold support for further development of SRM technologies** in absence of stricter research governance, especially in terms of public consultation and diversity of views.
- To provide **incentives and opportunities for researchers** in terms of time and funding to develop such frameworks in collaboration with research funders.

In short, we stress the urgent need for a non-<u>use</u> agreement on SRM that draws from the operationalization of the CBD Dec. X/33. The merits and shortcomings of existing calls for a non-use agreement remain open to both, political and academic debate.

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A Appendix

A.1 Agenda Expert*innengespräch on Stratospheric Aerosol Injection, September 15th, 2022 (online)

In recent years, there have been increasingly serious discussions about geoengineering, large-scale interventions in planetary systems to counteract climate change. Geoengineering ranges from technologies to remove carbon from the atmosphere (carbon dioxide removal, CDR) to technologies that aim to reflect incoming solar radiation (solar radiation modification, SRM). Both CDR and SRM are coming under scrutiny.

The crucial question for these technologies is if and how they could fit into effective, just, and sustainable climate measures. What forms of geoengineering will safeguard a habitable planet? How can they be implemented in a durable way? Can such technologies be governed safely, effectively, and justly? What sort of risks do these technologies present, both physically and politically?

In this Expert*innengespräch, we want to discuss the potential risks and benefits of SAI, predominantly from a technological and physical standpoint. What are the potential risks and benefits of SAI? Should SAI be researched at all? What degree of certainty could we reach about the effects of SAI? How could SAI be governed? Could SRM play a role in effective, just, and sustainable climate policies?

With contributions from:

- Dr. Claudia Wieners
- Dr. Wilfried Rickels
- Dr. Ulrike Niemeier
- Dr. Hauke Schmidt
- Dr. Babatunde J. Abiodun
- Dr. Simone Tilmes
- Dr. Dhanasree Jayaram

A.1.1 Session 1 - What is SAI? The Question of the Global Thermostat. 9.30 - 10.45 CET

In this first session, we will discuss what stratospheric aerosol injection (SAI) is, what its major promises and risks are, and how it connects to the central concern of anthropogenic climate change (temperature). Through the contributions of Claudia Wieners and Wilfried Rickels, we will discuss both why scientists think SAI might be unavoidable and why it will be unlikely that we can find agreement on how to implement SAI.

Opening by Dr. Jeroen Oomen Tour-de-table: introductions

Dr. Claudia Wieners (Utrecht University): "*Solar Radiation Management: What is it, can we do it, can we do without?*"

Dr. Wilfried Rickels (Kiel Insitut für Weltwirtschaft): "*Incentives for Solar Geoengineering Deployment. Who turns the global thermostat and by how much?*"

Open discussion between all participants and invited experts (moderated by Jeroen Oomen)

A.1.2 Session 2- What can we know about SAI? 11.15 - 12.30 CET

In the second session, we turn to a central question for SAI: how do we know what we know? And can we trust what we know? Can we have any form of certainty about the effects of SAI? About how it interacts with climate change at large? The presentations by Ulrike Niemeier and Hauke Schmidt will raise such questions, zooming in specifically on climate simulations through models.

Dr. Ulrike Niemeier (Max-Planck-Insitut für Meteorologie, Germany): *"Uncertainties in the simulation of transport and aerosol formation in the stratosphere"*

Dr. Hauke Schmidt (Max-Planck-Insitut für Meteorologie, Germany): *"Uncertainties in the simulation of climate effects of SAI"*

Open discussion between all participants and invited experts (moderated by Jeroen Oomen)

A.1.3 Session 3 – What have we already learned about SAI? 14.00 - 15.15 CET

Session 3 zooms in on what we do know about SAI, and what we have learned over the past decade of research. Simone Tilmes will speak about the state of current research and the major challenges connected to SAI. Subsequently, Babatunde Abiodun will discuss a thorny question connected to SAI: what will its regional effects be? And how should we address those?

Dr. Simone Tilmes (National Center for Atmospheric Research, USA): *"Current research and challenges of Stratospheric Climate Interventions"*

Dr. Babatunde J. Abiodun (University of Capetown, South Africa*): "Potential impacts of stratospheric aerosol injection on drought risk managements over major river basins in Africa"*

Open discussion between all participants and invited experts (moderated by Jeroen Oomen)

A.1.4 Session 4 – What to do about SAI? Implications for the UBA. 15.45 - 17.00 CET

The final session will be an open discussion between all those present about what the state of SAI research implies for the position of the Umweltbundesamt. How does SAI relate to climate policy at large? Can it ever be countenanced? Could it be governed? Of special interest in this discussion are how SAI might interact with other important political goals of international politics, such as the SDGs. This ties into questions of geopolitical tensions, potential regional damages, and the risk of mitigation deterrence due to SAI research.

The session will consist of a discussion moderated by Jeroen Oomen, in which all UBA participants can field the major questions that the day has raised.

General conclusions, round off by Jens Tambke & Jeroen Oomen

A.2 Agenda Expert*innengespräch on Solar Radiation Modification, October 19th, 2022 (online)

In recent years, there have been increasingly serious discussions about geoengineering, large-scale interventions in planetary systems to counteract climate change. Geoengineering ranges from technologies to remove carbon from the atmosphere (carbon dioxide removal, CDR) to technologies that aim to reflect incoming solar radiation (solar radiation modification, SRM). Both CDR and SRM are coming under increasing scrutiny. The crucial question for these technologies is if and how they could fit into effective, just, and sustainable climate measures. What forms of geoengineering will safeguard a habitable planet? How can they be implemented in a durable way? Can such technologies be governed safely, effectively, and justly? What sort of risks do these technologies present, both physically and politically?

In this workshop, we want to discuss the potential risks and benefits of SRM, predominantly from a technological and physical standpoint. What potential interventions are there? What are their might their effects be, both positive and negative? What degree of certainty could we reach about the effects of SRM? Could SRM play a role in effective, just, and sustainable climate policies?

With contributions from:

- Prof. Dr. Herman Russchenberg
- Dr. Shaun Fitzgerald
- Prof. Dr. Ulrike Lohmann
- Dr. Julia Crooks
- Dr. Cheryl Harrison
- Dr. Kelsey Roberts
- Dr. Jonathan Proctor

Morning Sessions: SRM technologies

In this first morning, we address several SRM technologies from a scientific perspective. One, marine cloud brightening (MCB), is under wide research as a potential SRM method, with an emerging consensus that technically, it may work to cool the climate. The two other technologies we discuss, cirrus cloud thinning (CCT) and ocean albedo modification by microbubbles are more speculative. There is not a wide research field on either technology but there are theoretical ideas about why they might work.

A.2.1 Session 1 – Marine Cloud Brightening. 9.30 - 10.45 CET

In this first session, we will discuss one of two most researched SRM methods: marine cloud brightening (MCB). Next to stratospheric aerosol injection, MCB is the most well-researched potential SRM intervention. Currently, research is being conducted if it could work, how it might be made to work, what its major risks are, and what we can and can't know about MCB based on doing the research.

Opening by Dr. Jeroen Oomen

Tour-de-table: introductions

Prof. Dr. Herman Russchenberg: "*Marine Cloud Brightening: What is it? What can it do? What can it not do? What are its risks?*"

Dr. Shaun Fitzgerald: "*Marine Cloud Brightening: How would it work, technically? What is the engineering challenge, and what research would be needed?*"

Open discussion between all participants and invited experts (moderated by Jeroen Oomen)

A.2.2 Session 2- Cirrus Cloud Thinning and Ocean Albedo Modification. 11.15 - 12.30 CET

In the second session, we turn to two more speculative SRM methods: CCT and ocean albedo modification. Again, we centrally focus on the core premises of the technologies, what their effects may be, how they might work, if they could work at all, and what the major risks are.

Session structure:

Prof. Dr. Ulrike Lohmann: "Cirrus Cloud Thinning: What is it? What can it do? What can it not do? What are its risks?"

Dr. Julia Crook: "Ocean Albedo Modification (Microbubbles): What is it? What can it do? What can it not do? What are its risks?"

Open discussion between all participants and invited experts (moderated by Jeroen Oomen)

Afternoon: Ecological impacts and general discussion

In the afternoon, we leave the technological specificity of the morning behind and turn to overarching questions about the potential ecological impacts of SRM. We address both impacts on land and in the sea. From there, we move to a final discussion about the implications for the UBA: what does all of this mean?

A.2.3 Session 3 – What are the potential ecological impacts of SRM methods? 14.00 - 15.15 CET

Session 3 zooms in on the ecological impacts of SRM. In two presentations, our experts will address some key concerns and questions around the impacts that SRM may have. First, we turn to Kelsey Roberts, who will introduce the work she is doing with Cheryl Harrison and Phoebe Zarnetske around marine ecosystem aspects. Subsequently, we will be joined by Jonathan Proctor, who will discuss the potential impacts of SRM on agriculture.

Dr. Kelsey Roberts: Potential Marine Ecosystem impacts connected to SRM

Dr. Jonathan Proctor: Potential agricultural impacts connected to SRM

Open discussion between all participants and invited experts (moderated by Jeroen Oomen)

A.2.4 Session 4 – What to do about SRM? Implications for the UBA. 15.45 - 17.00 CET

The final session will be an open discussion between all those present about what the days input on SRM research implies for the position of the Umweltbundesamt. How does SRM relate to climate policy at large? Can it ever be countenanced? Could it be governed? Of special interest in this *discussion are how SRM might interact with other important political goals of international politics, such as the SDGs. This ties into questions of geopolitical tensions, potential regional damages, and the risk of mitigation deterrence due to SRM research.*

The session will consist of a discussion moderated by Jeroen Oomen, in which all UBA participants can field the major questions that the day has raised.

General conclusions, round off by Jens Tambke & Jeroen Oomen