One Atmosphere:

An independent expert review on Solar Radiation Modification research and deployment

UN environment programme

ISBN: 978-92-807-4005-9
Job number: EO/2503/NA

Disclaimers

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory or city or area or its authorities, or concerning the delimitation of its frontiers or boundaries. For general guidance on matters relating to the use of maps in publications please go to http://www.un.org/Depts/Cartographic/english/htmain.htm

Mention of a commercial company or product in this document does not imply endorsement by the United Nations Environment Programme or the authors. The use of information from this document for publicity or advertising is not permitted. Trademark names and symbols are used in an editorial fashion with no intention on infringement of trademark or copyright laws.

The findings, interpretations, and conclusions expressed in this publication are entirely those of the authors and do not necessarily reflect the views of their affiliated organizations or the views and policies of their national governments. Unless otherwise specified, statements regarding consensus or agreement refer to this group of authors only. The identified actions and recommendations do not reflect the views of their respective member states. The authors consulted in the development of this report declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported.

The views expressed in this publication do not necessarily reflect the views of the United Nations Environment Programme.

Suggested citation: United Nations Environment Programme (2023). One Atmosphere: An independent expert review on Solar Radiation Modification research and deployment. Kenya, Nairobi.

Production: United Nations Environment Programme
https://wedocs.unep.org/handle/20.500.11822/41903

Managing Editors
Andrea Hinwood, Jason Jabbour

Foreword

Make no mistake: there are no quick fixes to the climate crisis. Increased and urgent action to slash greenhouse gas emissions and invest in adapting to the impacts of climate change is immutable. Yet current efforts remain insufficient. As a result, increasing voices are calling for and preparing alternative "emergency" options to keep global temperature rise in check.

Among actions under examination is Solar Radiation Modification (SRM), and in particular Stratospheric Aerosol Injection (SAI) – which aims to cool the planet by reflecting sunlight back into space. SRM is a complex, controversial and under-studied group of technologies. Yet some scientists and companies are accelerating towards deployment: empirical research and experimentation are being pursued, and technologies and schemes are being discussed at the highest levels, without a full understanding of the implications. This is contrary to the precautionary principle, which must be applied in the case of a technology that would modify the atmosphere.

To gain a better understanding of the potential risks of SRM, the United Nations Environment Programme (UNEP) convened a multidisciplinary expert panel to undertake a rapid review of the state of scientific research on SRM – keeping in mind climate, stratospheric ozone, environmental, human health and social aspects. The review outlines a range of informed views, and includes issues of governance of small-scale outdoor experiments, technology development, financing and governance of operational deployment.

The review finds that there is little information on the risks of SRM and limited literature on the environmental and social impacts of these technologies. Even as a temporary response option, large-scale SRM deployment is fraught with scientific uncertainties and ethical issues. The evidence base is simply not there to make informed decisions.

Critical unresolved issues around equity, ethics and consent are evident. There needs to be significantly more scientific research into the potential impacts of SRM technologies on low- and middle-income countries, which are on the frontlines of climate change, should they be considered for deployment. Of particular concern is the issue of consent for indigenous peoples and local communities. These groups are largely excluded from decision-making and their knowledge is scarcely reflected in science. They are already bearing the brunt of the triple planetary crisis of climate change, nature and biodiversity loss and pollution and waste. As a result, their livelihoods and cultures are under threat.

It is therefore essential to establish a robust, equitable and rigorous trans-disciplinary scientific review process to reduce uncertainties associated with SRM and better inform decision-making. In turn, decision-making must embrace the precautionary approach and apply it in a manner that is open, informed and democratic, and includes all potentially affected parties.

Given the levels of current activity, the international community must invest in understanding the potential risks and uncertainties of SRM technologies. We only have one atmosphere. We cannot risk further damaging it through a poorly understood shortcut to fixing the damage we already caused.

SRM is currently a speculative technology and is no substitute for emissions reductions, as it does not remove carbon from the atmosphere. Nor will SRM improve the environment or tackle the root causes of climate change. Our best bet for a prosperous and equitable future remains putting in the unavoidable hard work to achieve climate stability by reducing greenhouse gas emissions, to create a pollution-free planet and societies that live in harmony with nature.

Inger Andersen
Executive Director, UNEP

Acknowledgements

AUTHORS AND THEIR AFFILIATION

Govindasamy Bala, Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bengaluru, Karnataka 560012, India

Ken Caldeira, Department of Global Ecology, Carnegie Institution for Science, Stanford, CA 94305, USA and Breakthrough Energy

Ines Camilloni, Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Ciencias de la Atmósfera y los Océanos and CONICET – Universidad de Buenos Aires. Centro de Investigaciones del Mar y la Atmósfera, Argentina

Heleen de Coninck, Industrial Engineering and Innovation Sciences, Eindhoven University of Technology, P O Box 513, 5600 MB Eindhoven

David W. Fahey, NOAA Chemical Sciences Laboratory, 325 Broadway, R/CSL, Boulder, CO 80305 USA

Jim Haywood, Faculty of the Environment, Science and Economy, University of Exeter, Exeter EX4 4QF, UK

James W. Hurrell, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523, USA

Kate Ricke, Climate, Atmospheric Sciences & Physical Oceanography, Scripps Institution of Oceanography, UC San Diego, 9500 Gilman Dr #0519, La Jolla, CA 92093-0519, USA

Christopher Trisos, African Climate and Development Initiative (ACDI), University of Cape Town, Cape Town 7700, South Africa

Coordinators: Andrea Hinwood, Jason Jabbour

Copyeditors: Michael Logan, Amanda Lawrence-Brown

Layout and design: Beverley McDonald

The technical assistance from Shinto Roose, and Thejna Tharammal, Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bengaluru, India is gratefully acknowledged.

Table of contents

Key findings

1. **While international efforts must focus on rapid emissions mitigation and adapting to anthropogenically induced climate change, Solar Radiation Modification (SRM) is being discussed as an additional approach to offset some impacts and avoid global temperature exceeding the limits set in the Paris Agreement, while the global energy system is being transformed.**

    - In current climate model simulations, well-designed SRM deployments offset some effects of greenhouse gases (GHG) on global and regional climate change by reflecting more sunlight into space.

    - SRM is the only option that could cool the planet within years. To be effective at limiting global warming, SRM would need to be maintained for several decades to centuries, depending on the pace of emissions reductions and carbon removal.

    - The estimated direct costs for deploying SRM, without considering costs of possible adverse impacts, may be tens of billions of US dollars per year per 1°C of cooling.

    - SRM is not a substitute for mitigation. Impacts from excess carbon dioxide (CO_2), such as ocean acidification and ecological degradation, would continue.

2. **An operational SRM deployment would introduce new risks to people and ecosystems.**

    - Strong concerns around large-scale SRM deployment include damaging the ozone layer, overcompensating climate change at regional scales and increasing or redistributing climate change impacts on society and ecosystems.

    - SRM deployment, if abruptly terminated, would lead to rapid climate change that would increase risks for humans and ecosystems.

    - SRM research could reduce efforts to mitigate GHG emissions by drawing resources away from mitigation efforts.

    - An SRM deployment could increase power imbalances between nations, spark conflicts and raise ethical, moral, legal, equity and justice issues.

3. **With many unknowns and risks, there is a strong need to establish an international scientific review process to identify scenarios, consequences, uncertainties and knowledge gaps.**

    - The possible consequences of an SRM deployment need to be understood and weighed against the consequences in a world without SRM.

    - An international assessment may reduce risks to society by identifying in advance the possible negative consequences of a proposed SRM deployment.

    - This expert panel considers that the scientific, technical, social and environmental aspects of a large-scale deployment of SRM have not been fully assessed and deployment is not warranted at present.

4. **A governance process would be valuable to guide decisions around research activities, including indoor research, small-scale outdoor experiments and SRM deployments.**

   - SRM indoor research, which is mostly theoretical analyses and climate modelling, has been going on for over 50 years. In the interests of academic freedom, it is suggested by this expert panel that norms, guidelines and voluntary codes of conduct for indoor research could help balance societal concerns with scientific inquiry.

   - The views of the panel on the need to impose governance on small-scale outdoor experimentation and operational deployment diverge because of differences in perceived risk. Governance of small-scale outdoor experimentation could limit the potential of a 'slippery slope' from experimentation to large-scale deployment. Governance of large-scale deployment would be valuable given the inherent risks.

   - This panel unanimously suggests a broader framework for the governance of the stratosphere, which would, amongst other things, address the changes that occur in this layer of the atmosphere from stratospheric aerosol injection (SAI) experiments or deployment.

5. **SRM research and deployment decisions require an equitable, transparent, diverse and inclusive discussion of the underpinning science, impacts, risks, uncertainties and governance.**

   - This process would need to involve discussion with, and more research from, all stakeholders as most from the global south are not sufficiently engaged in current SRM discussions. The UN is well-positioned to promote a globally inclusive conversation on SRM.


Photo: Shutterstock

Executive summary

We have ‘One Atmosphere’. Everyone is a stakeholder.

Since the beginning of the industrial era, carbon dioxide (CO_2) and other greenhouse gases (GHGs) have been accumulating in the atmosphere due to fossil fuel burning and changes in land use such as deforestation. As a result, anthropogenic climate change is now affecting every region across the globe. The consequences of continued GHG emissions will be severe and long-lasting, including exceedance of temperature targets; increases in the frequency, intensity and persistence of extreme weather and climate events; reductions in sea and land ice, snow cover and permafrost; and sea level rise.

Through the United Nations Framework Convention on Climate Change (UNFCCC) and other processes, the international community has been working to reduce GHG emissions. However, action and current commitments are not yet sufficient to meet the Paris Agreement’s temperature goals.

This situation has led to increased interest in understanding whether an operational large-scale Solar Radiation Modification (SRM, or sometimes called ‘solar geoengineering’) deployment might be able to help protect humans and the ecosystems upon which humanity depends.

The expert panel considers that a near and mid-term large-scale SRM deployment is not currently warranted and would be unwise. This view may change if climate action remains insufficient.

In most proposed SRM approaches (Figure 1; Annex 1), a small amount of sunlight is deliberately reflected to space to cool the planet. SRM is the only known approach that could be used to cool the Earth within a few years[10,15,16]. The most studied method involves the introduction of sub-micron-size reflective particles into the stratosphere (stratospheric aerosol injection – SAI – Figure 3). Other methods (Figure 1; Annex 1) have also been proposed, including approaches such as marine cloud brightening (MCB – brightening of low clouds over the ocean). Cirrus cloud thinning (CCT) is often categorized as an SRM method, although instead of altering the amount of sunlight that enters the Earth’s system, it allows more infrared radiation from Earth to escape into space.

Climate model simulations consistently show that SRM could offset some of the effects of increasing GHGs on global and regional climate, including carbon and water cycles, but there could be substantial residual or overcompensating climate change at the regional scales. The possibility that SRM may be able to reduce climate damage and alleviate climate change impacts has led to advocacy for research to establish whether SRM deployment could be a viable option in addition to mitigation and adaptation. Two framings of SRM deployment are envisioned: rapid (i.e. full deployment within a few years) and phased (i.e. full deployment ramped in over several decades or longer).

If atmospheric CO_2 concentrations continue to increase, and an SRM deployment was used to offset warming, the uncertainties and associated risk could scale with the amount and duration of SRM deployment. Impacts not compensated by SRM could be exacerbated, and the chance of a devastating impact on ecosystems of a sudden and sustained cessation of a large SRM deployment (the ‘termination shock’) would be increased. An SRM deployment does not eliminate the need to decarbonize the energy system or address other GHG emissions. The combined uncertainties of SRM – including technological maturity, physical understanding, potential impacts, governance, legality, ethics and potential impacts on sustainable development – could render SRM economically, socially or institutionally undesirable.

As SRM does not reduce GHG emissions, and it does not address the causes of anthropogenic climate change, other environmental harms from increased concentrations of CO_2 and other GHGs will continue. These risks increase with the amount of SRM, so there is strong agreement in recent literature that SRM deployment would therefore be at best a temporary measure that could operate in parallel with mitigation measures designed to achieve sustained net zero or net negative CO_2 emissions globally. Hence, SRM should not be viewed as the main policy response to climate change.

While this document encompasses several SRM approaches (Annex 1), focus is on stratospheric aerosol injection (SAI; Figures 1 and 3) because it has been the most studied and there is the largest amount of evidence relating to its potential feasibility and effectiveness. Observations of global cooling after major volcanic eruptions provide strong evidence that a deliberate injection of large amounts of reflective particles into the stratosphere would cool the Earth rapidly (Figure 4). However, the extent to which SRM can reduce climate change hazards and alleviate ecological damage and human suffering has not been robustly established. SRM deployment may also increase climate change damage or introduce a range of new risks to people and ecosystems, including risks to human health and global biodiversity. These benefits and risks may not be known fully without an actual SRM deployment. There is now only a limited set of scientific assessments of the impacts of potential SRM deployments on human and natural systems.

Many of the risks and concerns are associated with:

- the response of Earth's climate and environmental systems (e.g. air and water quality);
- how these uncertain changes will impact human health and natural ecosystems;
- whether decisions would be made in an inclusive, equitable and transparent manner;
- whether SRM discussions might shift financial, political and intellectual resources from mitigation and adaptation efforts (the 'moral hazard' problem);
- how SRM deployment could lead to societal risks, including international conflicts; and
- how SRM could raise ethical, moral, legal and justice questions.

There are important distinctions between indoor SRM research investigations, small-scale outdoor SRM experiments and potential large-scale operational SRM deployments. Indoor SRM research investigations have involved theoretical analysis, social science research, computer simulations using climate and Earth System models and laboratory experimentation. Small-scale outdoor experimentation might emit limited quantities of material over a limited time to examine critical and poorly understood SRM-related processes in the real atmosphere with negligible climatic impact. Operational SRM deployments would likely be of planetary scale and need to last for decades or more to be effective. It should, therefore, be possible to define a level beyond which an SRM experiment would no longer be small-scale.

Some scientists recommend that small-scale outdoor SRM experiments be a component of ongoing SRM research. Specific reasons offered for conducting such small-scale outdoor experiments include:

- Evaluating the potential for developing a SRM system;
- Identifying adverse consequences of SRM;
- Developing a comprehensive scientific foundation to inform policy decisions;
- Informing decisions on how to respond to possible deployment by 'rogue' parties.

An important question is how to balance general principles of freedom of scientific inquiry with the need to manage risks related to scientific and technical experimentation, especially in environments such as the stratosphere, where little exists in the way of regulatory or governance structures.

The principal reason offered not to conduct small-scale outdoor SRM experiments is that these experiments could make an operational SRM deployment more likely, and the decision to conduct experiments or deployments would be made in a process that is neither inclusive nor representative of the interest of all stakeholders (everyone on Earth). There is also concern about possible adverse direct environmental consequences of experimental activities. Further, because research capacity resides primarily in developed countries, asymmetries in SRM expertise and technological capacity could have adverse effects on the power relationship between nations. These concerns could be addressed with appropriate governance mechanisms.

It is conceivable that an operational SRM system could be deployed and be successful at reducing some physical metrics of climate change, thus reducing climate change impacts. However, the possibility of an inequitable distribution of reduced or increased risks across regions and of the power to control such a system will exacerbate or create inequities, leading to decreases in certain societal aspects of human welfare.

In anticipating any decision regarding SRM deployment, proper consideration of the interdependence of the climate system, ecosystems and human society, and the competing interests among nations, will involve resolving thorny issues. Therefore, there is a need for equitable, transparent and inclusive discussions about the science of SRM and related governance issues.

The expert panel's reflections on actions for consideration:

- **A globally inclusive, transparent and equitable scientific assessment process for SRM be established**. The aim of the assessment would be to establish the natural and social science basis of SRM to guide research and serve as a foundation for governance and decision making. An assessment process would help to review evolving SRM literature and identify key scenarios, environmental and social consequences, uncertainties and knowledge gaps.

- **Exploration of the prospects and possibilities for a multilateral SRM governance framework to evaluate and address concerns on both SRM research and potential operational deployment**. Governance could be helpful to guide decisions surrounding acceptability of various possible SRM research activities and potential deployment. Governance of SRM indoor research, small-scale outdoor experiments and large-scale operational deployment should be differentiated.

- **Creation of a broader framework for the governance of the stratosphere**, which would address the changes from SAI activities. Other activities such as rocket launches may also be considered, as few regulatory or governance structures currently exist for the stratosphere.

- **Promote inclusivity in the evolution of SRM governance and research**. This process needs to be adequately resourced to enable equitable participation and contribution in discussions on a broad range of issues with all stakeholders, especially those from developing countries, who are currently much less engaged in SRM discussion and research. The UN is well positioned to promote a globally inclusive conversation on SRM.

United Nations Climate Conference (COP27) in Sharm el-Sheikh, Egypt, in November 2022 ends with a historic decision to establish and operationalize a loss and damage fund for nations most vulnerable to the climate crisis.
Photo: ©Theenvironment2022

Photo: NASA

Introduction

The global mean surface temperature is about 1.1°C higher in the last decade (2011–2020) than in the pre-industrial period (1850–1900) as per the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report[1]. The report unequivocally attributes this warming to human activities, particularly the burning of fossil fuels, deforestation and livestock farming. The rate of warming in recent decades is unprecedented in at least the last 2,000 years. Warming has caused weather and climate extremes, such as heatwaves, heavy precipitation, droughts and more intense tropical cyclones, across every region of the globe[1]. Unless drastic cuts in greenhouse gas (GHG) emissions are implemented immediately, global mean warming is likely to exceed the Paris Agreement target of 1.5°C above the pre-industrial level within the next 10–15 years. Warming levels of 4–5°C could be reached by 2100. Such warming would further exacerbate the increases in the frequency and intensity of extreme weather, the melting of polar and glacial ice, and sea level rise[1], among other changes in the Earth system.

These physical changes are projected to produce multiple negative, and in some cases irreversible, impacts on human society and natural ecosystems. These include health impacts from heat stress, biodiversity loss and species extinctions, decreases in agricultural productivity, more severe and intense wildfires, destruction of infrastructure and displacement of people. Impacts are likely to fall disproportionately on the world's poorest, compromising the ability to meet the UN Sustainable Development Goals (SDGs)[2].

Only reaching net-zero emissions will prevent further carbon dioxide (CO_2) concentration increases and substantial further global warming[3]. Even after reaching net-zero emissions, however, global warming will persist for many decades to centuries because of the long lifetime of CO_2 in the atmosphere[1]. Thus, it is impossible to quickly reduce global mean surface temperatures through emissions reduction alone. To reverse global warming, such as in the case of an exceedance of the Paris Agreement's long-term temperature goal, carbon dioxide removal (CDR) approaches will be needed to reduce atmospheric CO_2 levels[3]. Furthermore, enhancement of adaptation will be necessary to reduce climate change impacts.

The potential severe consequences of future climate change and weak climate action have led to an interest among some scientists, non-governmental organisations (NGOs) and policy analysts in understanding if some form or forms of solar radiation modification deployment (Figure 1; Annex 1) would help to reduce global mean surface temperature change, reduce adverse climate change impacts and avoid 'tipping points' (e.g. decline of tropical forests and disintegration of the West Antarctic Ice Sheet) while humanity works to bring down atmospheric GHG concentrations[4,5].

There is strong agreement in recent literature that SRM deployment is, at best, a temporary measure that could operate in parallel with mitigation measures designed to achieve sustained net-zero or net-negative CO_2 emissions globally. SRM should not be viewed as the main policy response to climate change[6-9]. If mitigation is deemed insufficient, SRM deployment may be the only viable option left to avoid temperature overshoot and ensure the achievement of the Paris Agreement's temperature goal[10,15,16].

The term 'effects of climate change' is used here to describe the changes in physical metrics of the climate system such as temperature, precipitation, circulation, CO_2 concentration, ozone, etc. The definitions of four other key terms relating to climate change risks are reproduced in Annex 2 from the glossary of the latest IPCC report (2021).

The following six questions and answers, and the conclusions that follow, provide the basis for the key findings, executive summary and identified actions for consideration in this report.

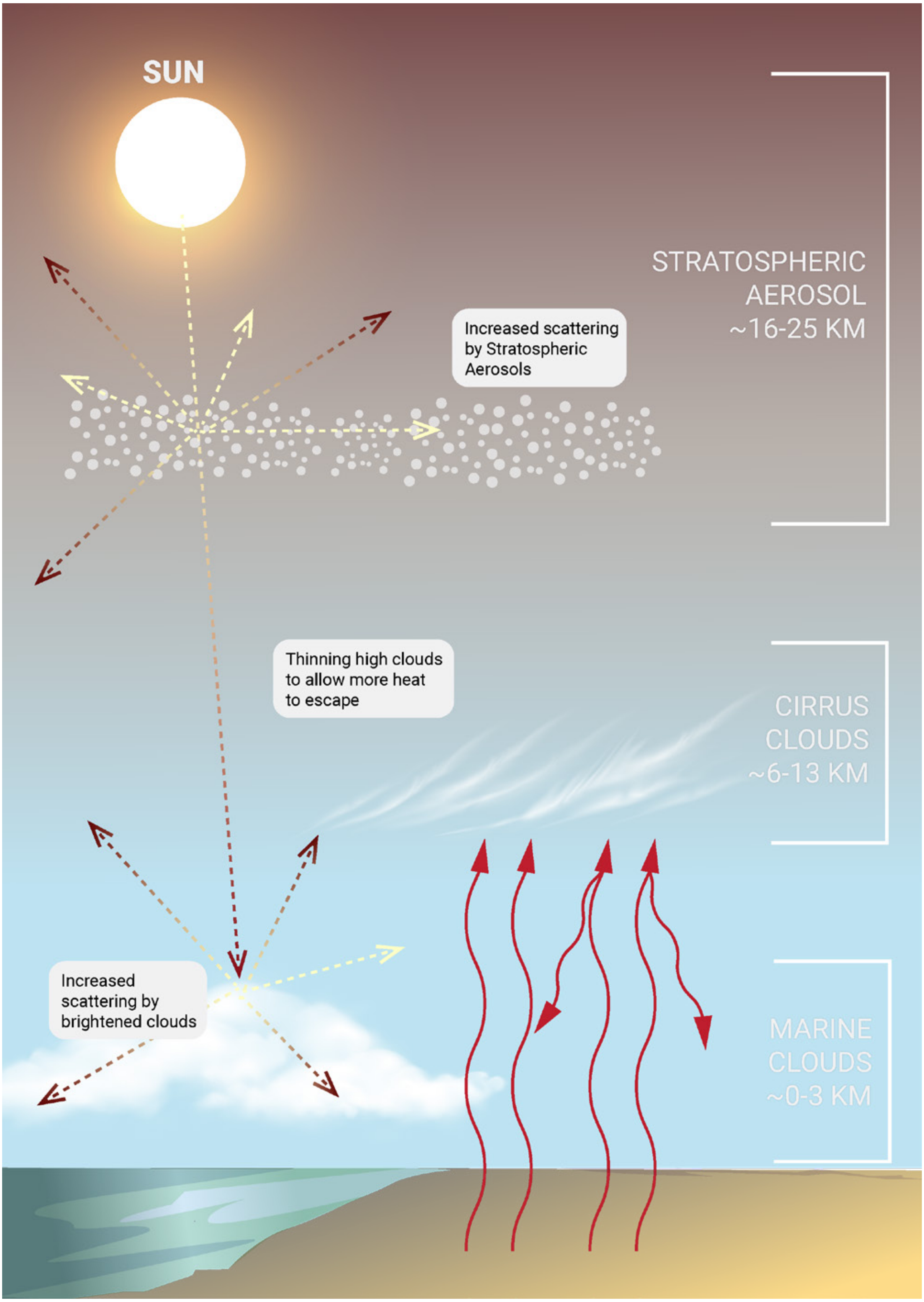

FIGURE 1: Illustration of the basic mechanisms involved in the three aerosol-based SRM approaches that have been studied using climate models: Stratospheric Aerosol Injection (SAI), Marine Cloud Brightening (MCB) and Cirrus Cloud Thinning (CCT).
Source: Adapted from NASEM 2021[9].

Key questions and answers

QUESTION 1

What is SRM and why are SRM modelling research and governance discussions increasing?

SRM refers to a range of approaches not related to GHG emission reduction or removal that seek to limit or reduce global warming[11]. There are two primary reasons for the recent increased interest in SRM research and deployment to rapidly reduce temperatures in case of severe climate change impacts around the world; SRM deployment is the only known approach that can (i) cool the planet within a few years[10,15], or (ii) limit rates or amounts of temperature increase (i.e. to meet the Paris Agreement target of well below 2°C, preferably 1.5°C), if insufficient mitigation continues (emission reduction and GHG removal).

In most proposed SRM approaches, a small additional amount of sunlight is reflected to space, or more of Earth's infrared radiation is allowed to escape to space (Figure 1 and Annex 1). Modelling studies indicate how an SRM deployment could offset some effects of anthropogenic climate change on global and regional scales.

There is a concern that current efforts to reduce GHG emissions, combined with adaptation efforts, are insufficient to avoid intolerable climate change impacts[8,12-14]. Further, a transition to a net-zero energy system that does not add any CO_2 into the atmosphere is likely to take decades[15]. Meanwhile, every ton of emitted CO_2 will cause additional warming that will last many centuries[1]. In the absence of rapid emission reductions and deployment of CDR approaches, some studies have suggested SRM deployment to reduce global warming, giving humanity more time to take measures to reduce atmospheric GHG concentrations[6,8] (Figure 2).

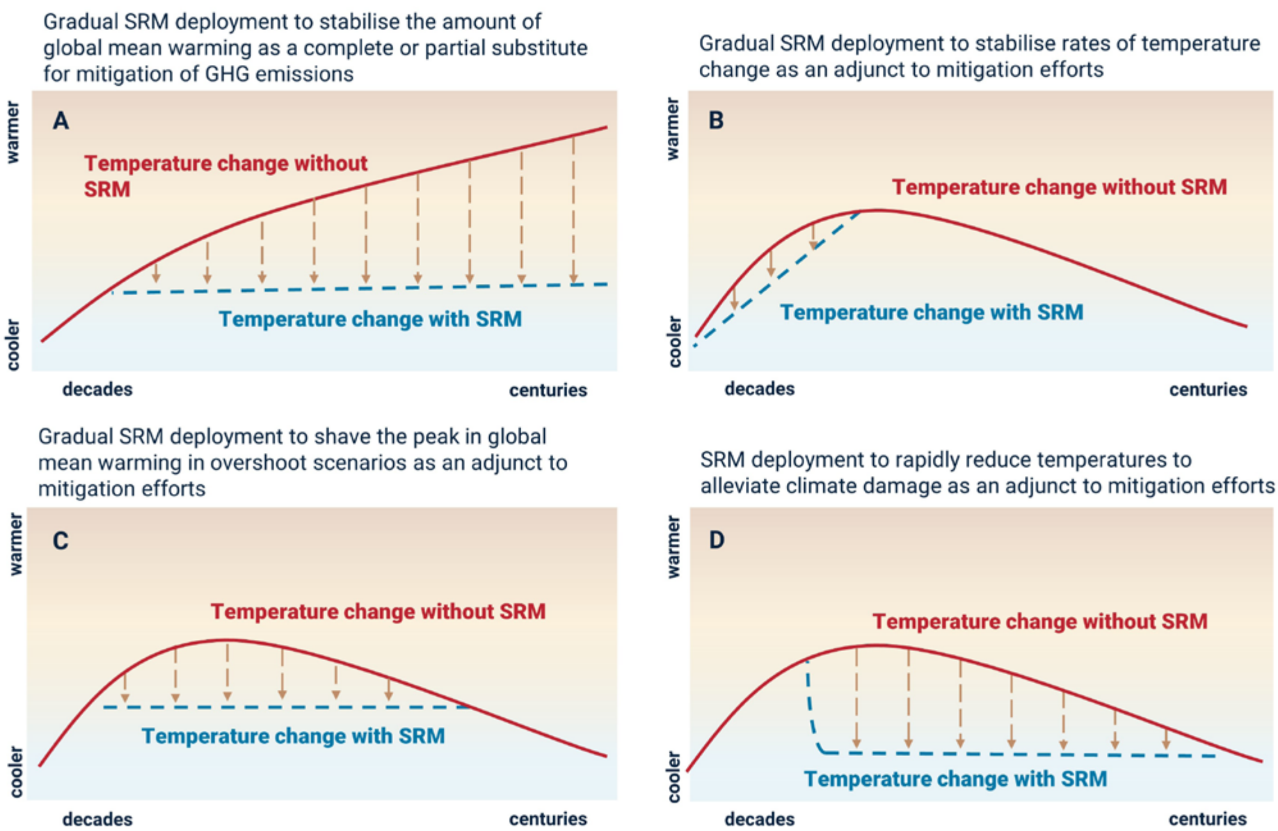

FIGURE 2: Hypothetical SRM deployment framings. Note that, in the absence of SRM deployment (red solid line), declines in global mean temperature on the timescale of decades to centuries would require substantial greenhouse gas removals. The orange arrows show the potential decrease in temperature with SRM deployment which may be able to reduce temperature to a lower level (blue dashed line) within a few years. *Source: Created by the authors of this report*

An operational SRM deployment is the only known approach that could be deliberately implemented to cool the Earth within a few years[10,15,16]. An approximate 2 per cent decrease in the amount of sunlight absorbed by the planet (~4 Wm-2) would be sufficient to offset the warming from a doubling of CO_2[4,11,72]. SRM approaches are sometimes referred to using terms such as 'climate engineering', 'climate intervention', 'solar radiation management' or 'solar geoengineering'.

Broadly, two framings of SRM deployment have been envisioned (Figure 2). In one of the framings (Figure 2 – part d), if global warming at some point produces outcomes widely seen as intolerable (e.g. widespread famines, mass migration, mass mortality and destruction of infrastructure) an operational SRM deployment as part of a 'planned' emergency response might be able to alleviate some of this suffering within a few years[17]. In the other framing, a phased operational SRM deployment becomes a normal part of climate policy to reduce the amount (Figure 2 – part a) or rate (Figure 2 – part b) of warming, or to shave a peak (Figure 2 – part c) in global warming in overshoot scenarios with deep mitigation[6-9]. In either case, SRM deployment would not markedly reduce atmospheric CO_2 concentrations; thus, some impacts, such as ocean acidification, would continue to worsen with continued CO_2 emissions.

In published modelling studies, SRM deployment is often applied to Representative Concentration Pathway (RCP) or Shared Socioeconomic Pathway (SSP) scenarios to cool the climate system to specific levels, such as pre-industrial or 1.5°C levels. Other scenarios have also been considered. In this report, we discuss only the common goals among these SRM deployment scenarios and strategies (Figure 2) and avoid discussions of the specific background emission pathways.

If atmospheric CO_2 concentrations continue to increase, and an SRM deployment was ramped up to offset warming, the uncertainties and associated risk exposure could scale with the amount and duration of SRM deployment. Impacts not compensated by SRM could be exacerbated, and the chance of a devastating impact on ecosystems of a sudden and sustained cessation of a large SRM deployment (the 'termination shock') is increased[18,19]. Therefore, an SRM deployment does not eliminate the need to decarbonize the energy system or address other sources of GHG emissions[6,20]. Furthermore, the combined uncertainties around SRM approaches – including technological maturity, physical understanding, potential impacts, governance, legality, ethics and potential impacts on sustainable development – could render SRM economically, socially or institutionally undesirable[8].

QUESTION 2

What are the different SRM approaches? What is the status of indoor SRM research, small-scale outdoor experiments, technology development and large-scale operational deployment?

Several different SRM approaches have been proposed (See Annex 1; Figure 1). While the scope of this document encompasses all SRM approaches, SAI (Figure 3) is the most studied and some argue the most feasible in terms of effectiveness, cost and timeliness[4,5,9].

SAI involves injecting highly reflective sub-micron-size particles into the stratosphere, possibly through releases from aircraft that will need to reach altitudes of 20–25 km (lower stratosphere). Relevant studies have involved theoretical analyses, social science research, climate model simulations and cost estimates. Several groups have proposed small-scale outdoor experimentation aimed at improving understanding of physical mechanisms or delivery systems, while not producing any detectable climate effect. However, no such experiments have yet been conducted (Annex 3).

Major volcanic eruptions, which introduce large amounts of sulphate particles into the stratosphere, provide a natural analogue for SRM deployment (Figure 4). For example, the 1991 Mount Pinatubo eruption[21] caused global annual-mean cooling of about 0.3–0.5°C in the following two years[22]. An SAI deployment would inject aerosols continuously into the stratosphere. It is estimated that continuous injection rates of 8–16 Tg of sulphur dioxide (SO_2) per year (approximately equivalent to the estimated injection amount of Mount Pinatubo in the single year of 1991) would reduce global mean temperature by 1°C. An operational SAI deployment could be scaled up to produce global cooling of 2–5°C, albeit with diminishing returns at higher rates of injections.

While the technology to inject large quantities of aerosol precursors at the required altitude does not exist, no show-stopping technical hurdles have been identified. It is viewed by some scientists that SAI deployment technology could be developed in under ten years[23,24]. The lowest cost of SAI deployment is estimated to be in the order of about 20 billion USD per year per 1°C of cooling[25].

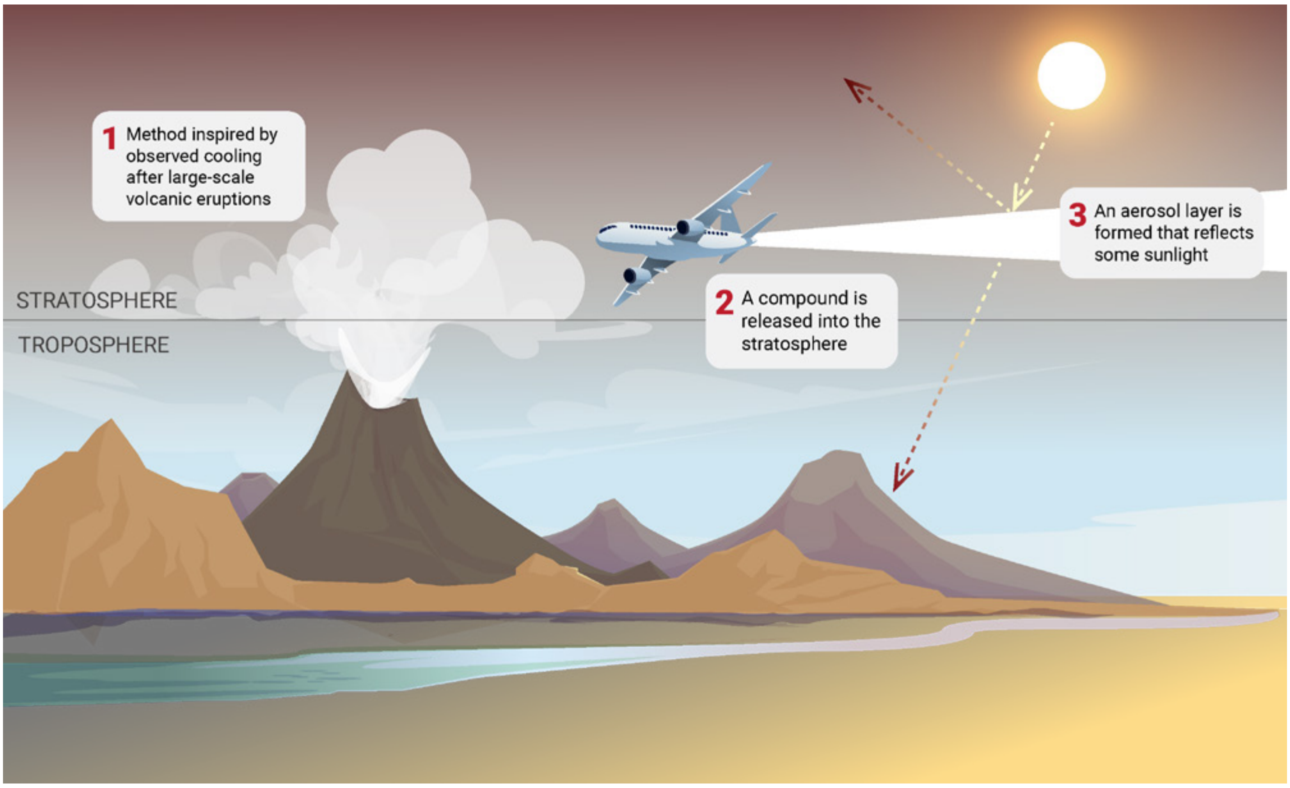

FIGURE 3: Illustration of the most studied SRM approach, and perhaps the most feasible, stratospheric aerosol injection.
Source: Adapted from Edwards 2019[26]; Lawrence et al 2018[27]; Caldeira, Bala and Cao 2013[28].

Another widely studied SRM approach is marine cloud brightening (MCB), which would increase the amount of sunlight reflected to space by low clouds in the marine atmosphere. This cooling would be achieved by introducing sea salt aerosols to produce a larger number of smaller cloud droplets, thus 'brightening' clouds. The feasibility of this approach is supported by observations of 'ship tracks' produced by the injection of aerosol particles from ship exhausts into marine stratocumulus clouds. Relevant studies involve theoretical analyses, climate model simulations and observations of ship tracks[29,30]. The ability of MCB to produce detectable cooling on a planetary scale is less well established. Engineering studies of delivery mechanisms for aerosol spray have taken place in the laboratory[31]. Recently, there has been an effort to cool ocean waters surrounding the Great Barrier Reef using MCB[32]. However, at the time of this review, there were no peer-reviewed publications describing or assessing this experiment (Annex 3).

A less studied approach is cirrus cloud thinning (CCT), which aims to decrease the amount of high cirrus clouds that trap infrared radiation emitted by Earth. The idea is that injecting ice-nucleating particles would increase the sedimentation rate of the ice crystals that compose these clouds. This would thin the clouds and allow more infrared radiation to escape to space. The feasibility of CCT is uncertain, in part because of the larger uncertainties associated with the ice nucleation processes in high clouds[33,34]. This approach has been studied through climate model simulations and theoretical analyses. No outdoor CCT field experiments have been conducted for this approach, and the expert panel is not aware of any plans to do so.

Space mirrors also have been suggested as a possible approach[35–37]. The development timescales and deployment costs appear prohibitive compared to other approaches. SRM approaches that would provide local or regional cooling also have been proposed, including regional MCB to save coral reefs or reduce the intensity of hurricanes, the injection of sulphate or sea salt aerosols into the troposphere and increasing the reflectivity of land or ocean surfaces[38-41] (Annex 1).

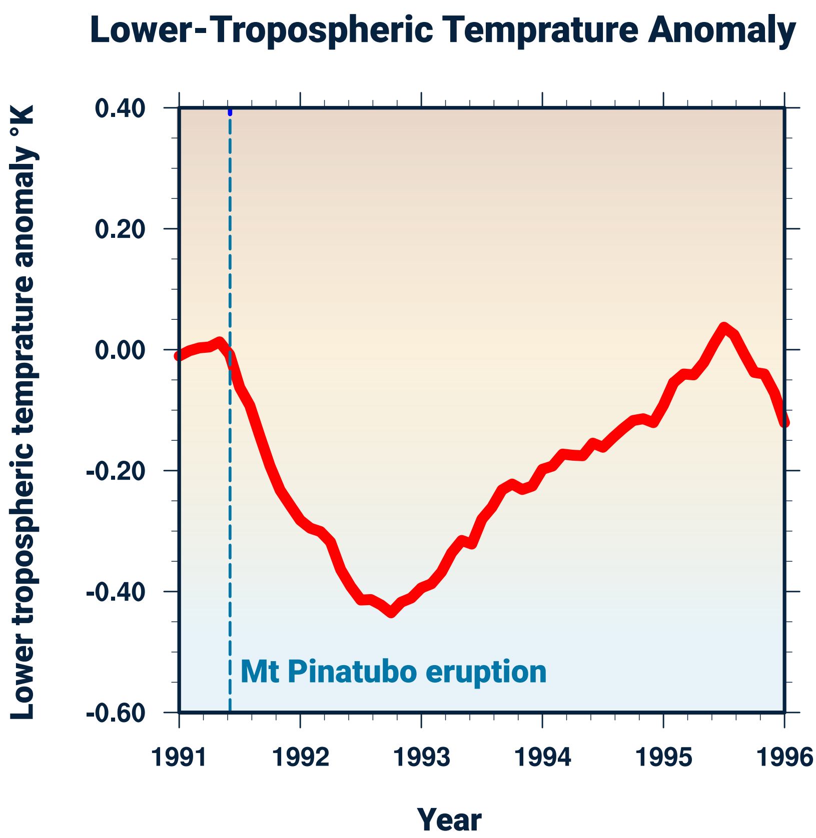

FIGURE 4: Global cooling in the years following Mount Pinatubo volcanic eruption in 1991. While there is confidence that most of the cooling in 1992 is a consequence of the eruption, separation of background natural variability from the volcano signal is challenging, especially because volcanic eruptions affect natural modes of variability such as El Nino. The time series shows the global mean anomalies (using a 1979–1998 base climatology) in monthly-mean tropospheric lower temperature from the microwave sounding unit observations[42]. The data is smoothed using a 7-month running mean. The eruption (June 1991) is marked by the dashed blue line. The observed anomalies are expressed relative to the pre-eruption value, defined here as the mean anomaly for January 1991 to May 1991. *Source: Created for this report using data from Aquila et al. 2021[43]; Mears and Wentz 2017[44].*

Rising plume of brown ash and white steam from an early stage of the eruption of Sarychev Volcano (Kuril Islands, northeast of Japan) on June 12, 2009. Photo: ©NASA/Goddard

QUESTION 3

What contribution could a potential SRM deployment make to cooling the Earth? What is the time frame and how would an SRM deployment compare with mitigation efforts?

There is unanimous agreement by the panel that international efforts need to focus on rapid mitigation and adaptation. However, if adaptation and mitigation efforts remain insufficient, both rapid and gradual SRM deployment (Figure 2) have been proposed by some scientists as temporary safety measures to potentially reduce climate change impacts while others warn of the environmental, social and economic consequences of deployment.

Mitigation (emission reduction plus GHG removal): Increasing GHG emissions are the primary cause of dangerous anthropogenic interference in the global climate system. Reducing emissions decreases this dangerous interference and reduces risk to people and ecosystems.

The long timescales of energy and infrastructure transition mean the emission reductions associated with these transitions could limit warming over several decades. The long lifetime of CO_2 in the atmosphere means that while a complete cessation of CO_2 emissions (zero emissions) would lead to limiting further warming it would not lead to substantial cooling in this century. If a goal were to substantially reverse warming trends without SRM, this could potentially be achieved through net negative GHG emissions involving large scale GHG removals over multiple decades, bringing down the concentrations of GHGs.

SRM deployment: In contrast to the longer timescales of mitigation, an SRM deployment could produce a substantial reduction in radiative forcing in as little as one year. Climate model results indicate that an operational SRM deployment could fully or partially offset the global mean warming caused by anthropogenic GHG emissions and reduce some climate change hazards in most regions (Figures 5 and 6). There could be substantial residual or possible overcompensating climate change at regional scales and seasonal timescales[11].

As indicated by climate model results, a well-designed SRM deployment that ramps in over time may reduce rates or amounts of surface temperature increase, and reduce some changes to the hydrological cycle associated with climate change across most regions[45,46] (Figures 5 and 6).

Should the effects of climate change become broadly perceived to be unbearable, and the political pressure for governments to cool the Earth rapidly become intense, an SRM deployment, at that point and given the science today, is the only known means available for governments that might feasibly cool the Earth on politically relevant time scales[10,15].

An operational SRM deployment would be distinct from weather modification. While an operational SRM deployment would potentially change the climate everywhere, weather modification typically aims to produce limited regional-scale effects (i.e. a local increase in precipitation). The intent of an operational SRM deployment would be to produce a measurable change in the planetary radiation budget and global mean surface temperature. In contrast, local weather modification has a negligible effect on the planetary radiation budget and climate.

The cooling effects of proposed SRM options would start to diminish as soon as the SRM deployment is halted. The aerosols released by SRM deployments would persist in the stratosphere for 1–3 years for SAI[47]. Tropospheric aerosols would persist for about ten days in the case of MCB. Upon SRM termination, atmospheric temperatures would adjust to higher values in the order of years. In contrast, the effects of past GHG mitigation efforts last for centuries even after mitigation efforts cease.

Annex 4 provides a summary of the key qualitative differences between mitigation and an operational SRM deployment.

Photo: Getty Images

QUESTION 4

Why are there concerns about SRM? What is known about the potential impacts on human and natural systems? What are the societal risks?

SRM would be a new and intentional interference in the climate system with potentially dangerous side-effects and risks to human society and ecosystems. This damage could be a consequence of adverse biophysical impacts, or adverse consequences related to social or political dynamics. These damages would likely be unevenly distributed across nations. The extent to which these adverse consequences might manifest and to which they might be mitigated or avoided is largely unknown. Research is valuable to further understand the dangers, risks and possible benefits of SRM and assess those relative to the dangers and risks from climate change without SRM.

Concerns exist around both small-scale outdoor SRM experiments and potential large-scale operational SRM deployment.

There is limited scientific research of the impacts of potential SRM deployments on human and natural systems[48]. Published assessments for crop yields and terrestrial ecosystem productivity are few. Because of the divergence in results from the studies, including change in crop yields and plant productivity, overall confidence is low . Comprehensive assessments on the impacts of SRM deployment on human health (e.g. UV exposure, the transmission of vector-borne disease, acid rain and air pollution) are also lacking.

Critically, integrated assessments of many impacts, both positive and negative, remain limited in scientific literature; for example, mortality and morbidity from heat stress, water resources, flood risk, storm damage, vector-borne diseases, biodiversity, food security, ocean ecosystems and fisheries. However, a recent modelling study on human health indicates that cooling in the tropics caused by SRM deployment could redistribute malaria risk among developing countries, potentially increasing the number of people at risk of malaria compared to scenarios without SRM[49].

Potential climate impacts

An operational SRM deployment would at best imperfectly offset some or all GHG-induced climate change: a deployment that aims to offset all anthropogenic global warming may result in some regions with residual warming and others with overcompensated changes[11]. For instance, SAI deployments that aim to offset global mean warming fully with a uniform aerosol layer could lead to overcompensated regional cooling in the tropics and residual warming in the polar regions (Figure 5).

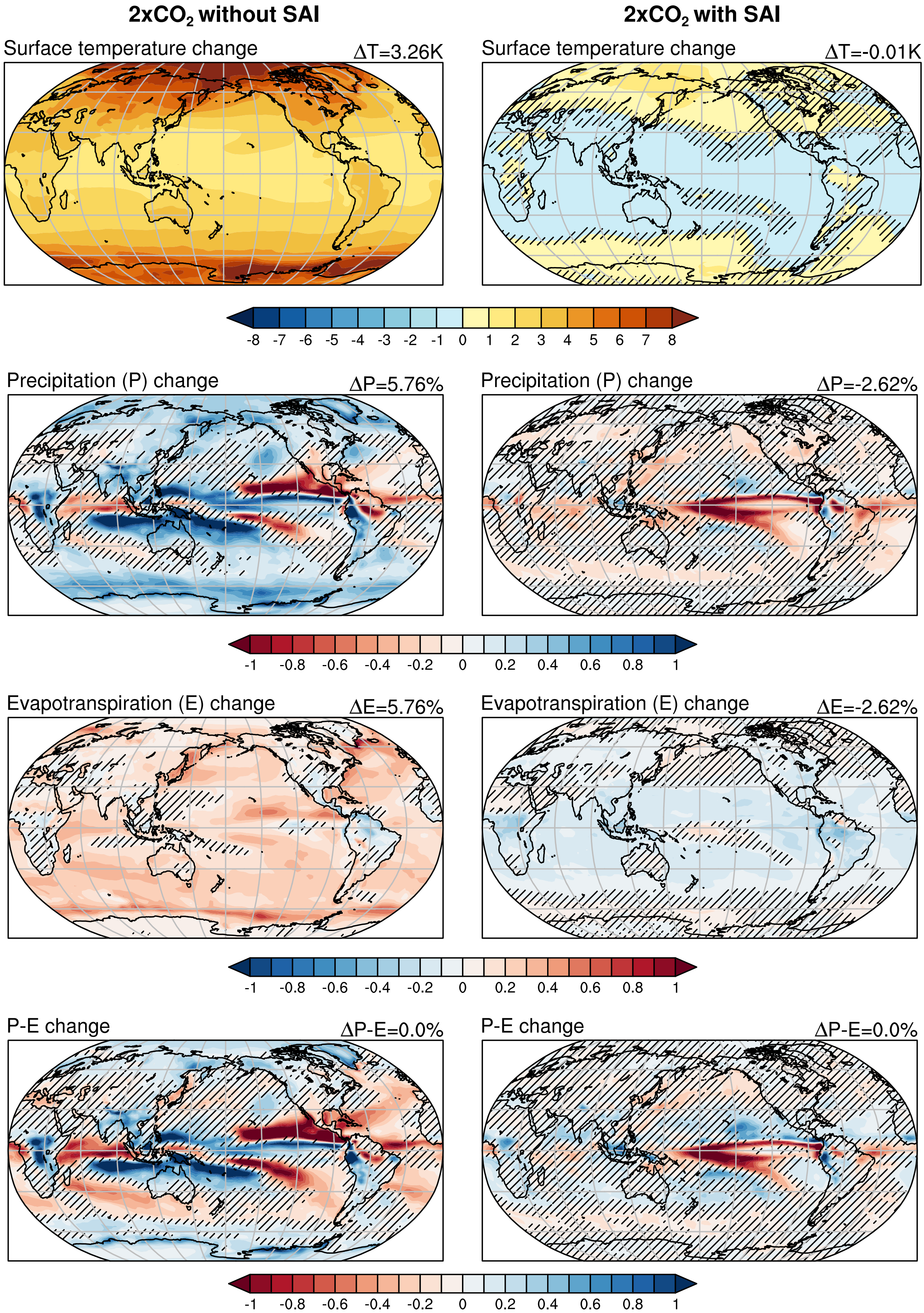

FIGURE 5: Climate model showing simulated annual mean changes in surface temperature, precipitation, evapotranspiration and precipitation minus evapotranspiration for a doubling of atmospheric CO2 concentration (from the current 410 ppm) with and without prescribed stratospheric sulphate aerosols (SSA). The slab ocean configuration of NCAR CAM4 is used for the equilibrium

simulations presented here. In the simulations with SSA, volcanic sulphate aerosols are prescribed uniformly around the planet at a height of ~22 km. The total mass of aerosols is 22.5 megatons of volcanic sulphate aerosols which have an effective radius of ~0.4 microns and are composed of 75 per cent sulphuric acid and 25 per cent water. The global and annual mean changes are shown above the top right corner of each panel. The hatching indicates the regions where the changes are not significant at 95 per cent confidence level, estimated using student's t-test. In the climate model, simulated SSA offset most of the changes in key climate metrics in nearly all regions. There are substantial uncertainties associated with these climate model results. A scientific assessment process that includes SRM modelling approaches would lead to reductions in these uncertainties.
Source: Created by the authors for this report.

An operational SRM deployment that would offset only a fraction of anthropogenic global warming may avoid overcompensated climate changes[50,51]. More sophisticated stratospheric aerosol injection strategies that have multiple injection latitudes could create larger aerosol concentrations at higher latitudes, reducing the residual warming in the polar regions [46,52,53], although risks to people and ecosystems may remain, such as the risk of redistribution of the geography of vector-borne disease transmission[49].

Other examples of poorly planned SAI deployments include deployments that produce north-south hemispheric temperature asymmetries, which could have negative consequences for tropical monsoons[54,55] and North Atlantic hurricanes.

An SAI deployment is expected to interfere with some of the natural modes of climate variability, such as the El Nino Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), the Quasi-biennial oscillation (QBO), polar vortex and the Brewer Dobson Circulation (BDC)[56-58]. Model results indicate that an SAI deployment using highly reflective sulphates (which also absorb substantial amount of shortwave radiation) could cause a more positive phase of the NAO, with more precipitation and devastating floods in parts of Northern Europe and severe droughts over parts of the Mediterranean[58]. The negative impacts of SAI on the NAO can be reduced by using reflective aerosols of chemical composition that would not absorb substantial amounts of solar radiation.

An aerial view of devastation caused by the impacts of severe floods in the city of Usta Muhammad, Islamic Republic of Pakistan. Photo: UN/Eskinder Debebe

Other environmental harms

To be effective, SRM deployment would need to be continuously maintained for decades or longer. A sustained large-scale operational SAI deployment could be highly disruptive to the lower and middle stratosphere with unknown consequences for the environment on and near Earth's surface.

If an SAI deployment were to use sulphate aerosols, rather than alternatives, there could be consequences for acid rain. Relative to anthropogenic aerosol emissions into the troposphere, which are often in populous regions on land, more of the sulphate from sulphate-aerosol SAI deployment would fall in the ocean or less-populated regions, where it would be expected to have less of an adverse effect[59]. Some recent studies indicate that even in the highest conceivable sulphate-aerosol SAI scenarios, global sulphate deposition is projected to be very similar between 2020 and 2100 because of the projected declines in anthropogenic emissions of aerosols into the troposphere in all future emission scenarios[60].

The deployment of SAI would affect stratospheric chemistry and dynamics. SAI impacts on stratospheric ozone are driven by increases in aerosol surface area in the stratosphere, which influences stratospheric ozone chemistry, and aerosol-induced heating of the stratosphere, which changes stratospheric dynamics and surface cooling. Recent studies considering sulphate aerosols indicate that stratospheric ozone depletion would be increased in the polar stratosphere, the Antarctic ozone hole recovery could be delayed by a couple of decades and the ozone hole could become deeper in the first decade of SAI deployment[46,61,62]. Decreases in stratospheric ozone would cause an increase in surface UV radiation and a decrease in tropospheric ozone[57,63-65], with consequences for human health and ecosystems. It has been suggested that SAI using calcite aerosols instead of sulphate aerosols could increase or only marginally decrease stratospheric ozone concentrations[66,67].

Modelling studies indicate that if SAI was deployed at a scale sufficient to prevent sea level rise or preserve the large ice sheets in Antarctica and Greenland, the adverse effects described above would be pronounced* (Figure 4).

The moral hazard

There is also concern that SRM research could reduce incentives to mitigate GHG emissions, either by creating expectations that an SRM deployment could reduce adverse consequences of high GHG concentrations, or by drawing financial, political or intellectual resources away from mitigation and adaptation efforts (the so-called 'moral hazard' problem).

In essence, the effects of SRM serve only to mask temperature increases and other effects of anthropogenic climate change without markedly reducing levels of GHGs. Impacts associated with elevated levels of CO_2, such as ocean acidification, would continue. Modelling studies indicate that an SAI deployment would decrease excess atmospheric CO_2 slightly (by up to 10 per cent in some scenarios) through enhanced land and ocean uptake and would leave the chemical effects of high CO_2 content on land and ocean ecosystems largely unchanged.

The dangers of halting SRM

If an SAI deployment was to be suddenly halted, the previously masked warming would manifest within a few years. If the deployment were of sufficient scale, this could produce severe adverse effects on ecosystems and biodiversity, increasing risks of extinction for thousands of species[17,19,20,51-54].

A gradual phase-out of SRM is likely to avoid the large warming rates from sudden SRM termination[20,69]. Typical responses to such concerns in other domains involves constructing distributed systems with redundancy[70].

The slippery slope of experimentation

Small-scale outdoor SRM experiments have been proposed to gain knowledge that is not available through modelling or laboratory experiments. The concerns raised are that these experiments could make an operational SRM deployment more likely and the decision to conduct experiments or deployments would be made in a process that is neither inclusive nor representative of the interest of all stakeholders, which, because we have 'One Atmosphere', means everyone on Earth. There are also concerns over potential direct environmental consequences of experiments. Furthermore, because research capacity resides primarily in developed countries, asymmetries in expertise and technological capacity would be produced that could potentially have adverse effects on the power relationship between nations.

---

* Moore *et al*. Efficacy of geoengineering to limit 21st century sea-level rise. Proceedings of the National Academy of Sciences, 2010; 107(36), 15699-15703. www.pnas.org/cgi/doi/10.1073/pnas.1008153107

Geopolitical and societal concerns

A key concern is that decisions over SRM experimentation and deployment would not be made in a globally inclusive, equitable and transparent manner, and that this would shift the power relationships between nations further in favour of already powerful nations. Related to this concern are questions regarding who would finance and control the development and deployment of SRM technologies. SRM could create societal risks including the potential for international conflicts (because of transboundary effects), unilateral SRM ('rogue' parties may opt for SRM deployment) and counter and countervailing SRM deployments. SRM deployment would therefore raise ethical, moral, legal, equity and justice questions.

The lower cost estimate of an SRM deployment (about 20 billion USD per year per 1°C of cooling)[25] puts the cost of an SRM deployment within the reach of many states and perhaps non-state actors, raising concern over how a 'rogue deployment' might be avoided or responded to.

There are also concerns that differences of opinion over whether, what kind or how much SRM to deploy could generate political and possibly even military conflict. One can assume that there will never be universal consensus in the broader community on an SRM deployment, which means that communities, nations and societies opposed to SRM deployment would be exposed to its effects against their wishes, raising ethical and legal concerns. Anthropogenic climate change has raised a similar concern, given the global north's role in historical climate change. SRM deployment would complicate considerations of loss and damage associated with climate change impacts by introducing an additional major influence on the climate system[71]. This could make it difficult to disentangle loss and damage attributable to climate change from that attributable to SRM-related changes.

Photo: Unsplash/Markus Spiske


Photo: Getty Images

QUESTION 5

What are the risks of SRM relative to the risks of climate change? Can SRM risks be identified, characterized, and quantified? Can the identified SRM risks be mitigated and managed, and, if so, how?

Decisions about SRM deployment can be conceptualized, in part, as a risk-risk trade-off, balancing risks of an SRM deployment against risks of what might happen in the absence of an SRM deployment[72]. Insufficient information exists to make this risk-risk trade-off assessment with confidence for conceivable scenarios.

Anthropogenic climate change is already causing many weather and climate extremes, such as heatwaves, heavy precipitation, droughts and intense tropical cyclones across the globe, resulting in widespread, pervasive impacts on ecosystems, people, settlements and infrastructure[73]. The pervasiveness of climate change impacts in recent decades, and the severity of projected impacts in the absence of rapid emission reductions and deployment of CDR approaches, have led to increased interest in SRM deployment.

Modelling studies have consistently shown that climate change (in terms of temperature and hydrological metrics) in nearly all regions is much smaller with a carefully designed SRM deployment than in a world with continued climate change and without an SRM deployment (Figure 5 and 6)[45,46]. The most dangerous situation would be one in which climate modelling studies indicated that an SRM deployment would reduce human suffering but an actual SRM deployment caused large unanticipated negative impacts.

The risks of SRM, outlined in question four, are likely very different depending on the scenario (Figure 2). For instance, an SRM deployment that occurs suddenly to rapidly offset most or all global warming, a deployment that is gradually ramped up or a deployment that is used to shave off some fraction of global warming as part of an integrated approach of SRM deployment, mitigation and adaptation.

An SRM deployment to offset only a fraction of global warming could reduce temperature and hydrological changes in many regions[50,51]. A large SRM deployment to offset most or all global warming could cause adverse impacts in some regions, depending on the deployment design and scenario.

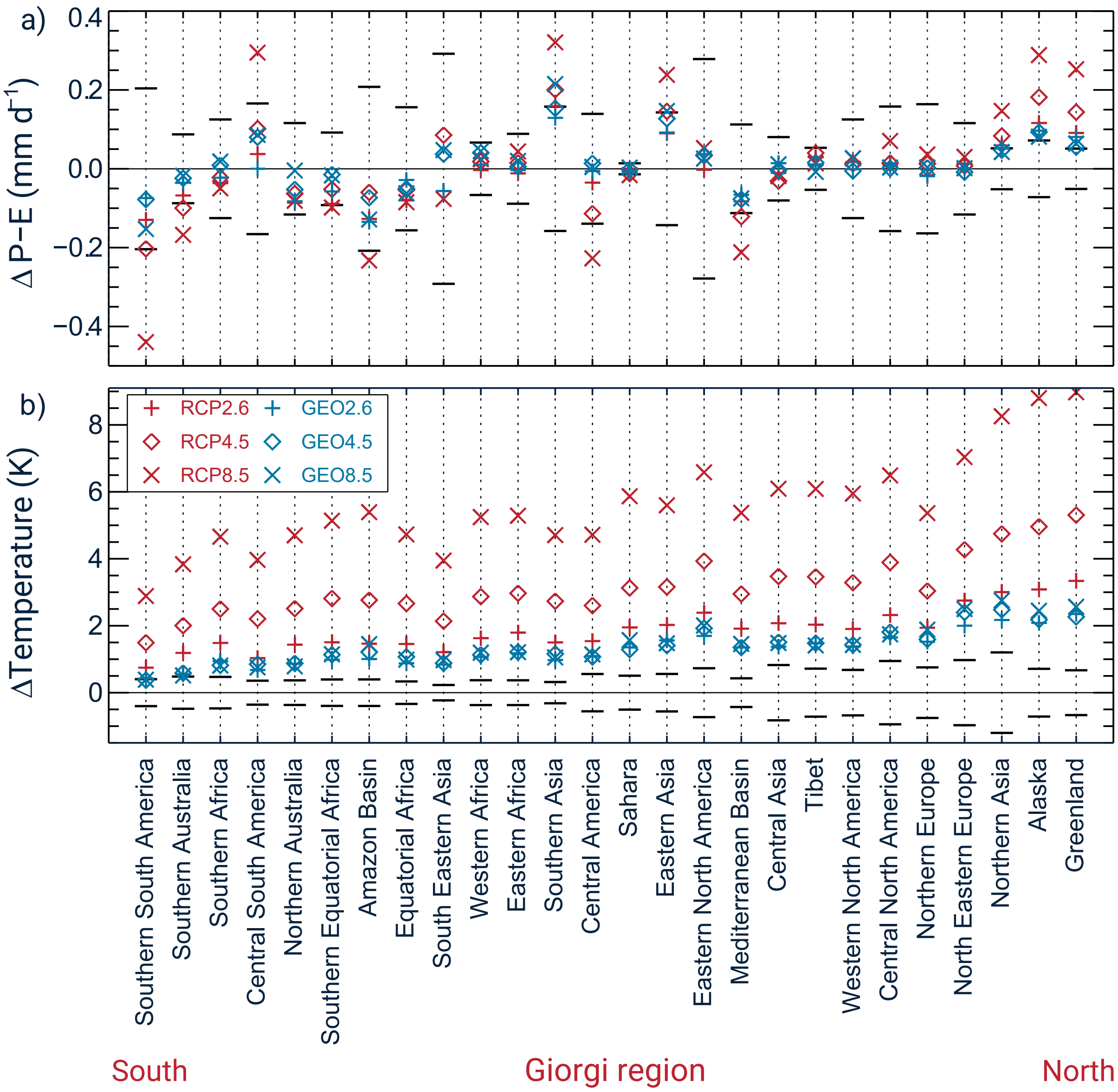

FIGURE 6: Simulated annual land-mean anomalies for 26 Giorgi regions, evaluated between the historical period (1986–2005) and 2070–2099*. Red symbols show the changes in three RCP scenarios, and the same scenarios with SAI are shown by blue symbols. Horizontal black lines denote ±1 standard deviation of the interannual precipitation/temperature in the historical period. The fully coupled atmosphere-ocean model HadGEM2-ES is used for the simulations. For the model simulations considered here, in all cases for temperature, and most cases for precipitation minus evaporation, the high CO_2 world with SAI is more similar to the historical period than is the high CO_2 world in the absence of SAI. There are substantial uncertainties associated with these climate model results. A scientific assessment process that includes SRM modelling approaches would lead to reductions in these uncertainties. *Source: Jones et al. 2018*[45]

Because of internal variability in the climate system, detection and attribution of cooling associated with an operational SRM deployment could be challenging. The effect of a gradual SRM deployment on regional temperature and precipitation may be detectable only after a decade while the effects of an abrupt SRM deployment could be detectable within a few years[74]. However, SAI deployment and its environmental consequences may be detectable in stratospheric chemistry observations, and MCB in tropospheric cloud observations. The operational aspects of an SRM deployment (e.g. planes and ships) would be of a scale to be immediately detectable through many pathways such as observation from satellites in space, tracking of financial transactions, and interception of telecommunication.

Risks could be minimized through a globally inclusive, transparent and equitable scientific assessment process for SRM. International scientific assessments that evaluate ongoing SRM research, including both the natural and social

* Giorgi, F. and Francisco, R.: Uncertainties in regional climate change prediction: a regional analysis of ensemble simulations with the HADCM2 coupled AOGCM, Climate Dynamics. 2000; 16:169–182.

sciences, could provide an important framework to evaluate the risks and benefits of SRM scenarios. The assessed risks associated with an SRM deployment may cause the implementation of SRM to be limited or avoided altogether, leaving mitigation and adaptation as the only approaches to reduce both short- and long-term climate risks.

Not assessing SRM as an additional option that could reduce global warming thereby increases the challenge of dealing with the impacts of global warming. Decisions on SRM deployment therefore must be made in a climate context in which the risks are weighed against the risks of climate change in the absence of deployment. This unavoidably requires an international governance framework that is currently not in place.

QUESTION 6

What frameworks exist to inform and manage SRM indoor research, small-scale process-oriented outdoor experiments, and large-scale SRM deployment?

Governance could apply to SRM indoor research, small-scale process-oriented outdoor experiments, and large-scale SRM deployment. No such frameworks exist for these SRM activities[75-81] (Box 1). SRM indoor research has been going on for over 50 years[82]. In the past two decades, most of this research has taken the form of theoretical analyses and climate modelling using the same climate models that are used to project climate change under global warming scenarios, although there has been some experimental work on possible deployment technologies[31]. Continued knowledge generation of SRM approaches through indoor modelling research is important to understand the potential benefits, risks, uncertainties and impacts of operational SRM deployments. In the interests of academic freedom, it is suggested that no formal governance framework for SRM indoor research is required at this time. However, it would be advantageous to develop a set of norms or voluntary code of conduct that would promote reporting, transparency, inclusiveness and data-sharing[9].

To govern small-scale outdoor SRM experiments or operational deployment of SRM systems, several existing frameworks could be relevant (Annex 5). While it may be premature to develop a formal governance framework given there are no known activities or plans to deploy SRM in the next few years, discussions could be initiated regarding whether it might be needed and what form that governance framework might take[83,84]. It should be noted that other measures, not specific to SRM, might complement SRM-specific governance and contribute to the goal of reducing SRM deployment risks. For example, a broader framework that regulates the introduction of materials into the stratosphere might be helpful. Such a broader framework for the stratosphere does not exist.

There is general agreement among this group of experts that governance of large-scale SAI deployment is valuable given the inherent risks associated with changing stratospheric conditions caused by large-scale interventions over long time periods (i.e. multiple decades). A broader framework for the governance of the stratosphere would address the changes that occur in the stratosphere from SAI experiments or deployment, and by other activities such as rocket launches, but might not address other concerns that are specific to SRM.

There are no formal governance frameworks to govern scientific or engineering SRM research beyond the national frameworks that govern other forms of scientific or engineering research[9]. These frameworks are usually designed to address direct environmental effects of experimental activities, and do not consider issues unique to SRM research. Discussions could be initiated whether formal governance of some or all SRM outdoor experiments might be needed now or in the near future, and what form that governance might take. Outdoor SRM research could be formally governed by frameworks that are specific to SRM research, or it could be formally governed by frameworks that regulate the introduction of materials into the atmosphere or specifically into the stratosphere.

International and authoritative guidance on the governance of responsible small-scale outdoor SRM experiments and SRM technology development (and if warranted governance of SRM deployments) might be the product of a process of coevolution of governance considerations and scientific assessment[9]. An inclusive process would involve discussion on a broad range of issues with all stakeholders as most, especially from the global south, are not currently engaged in the SRM discussion. The UN is well-positioned to promote a responsible global conversation on SRM (i.e. without detracting from mitigation and adaptation priorities) that could help produce this coevolution of governance consideration and SRM scientific assessment that uphold the highest standards of balance, rigour and accuracy.

The development of a voluntary code of conduct for SRM research would be another possible outcome of these discussions. Such an effort was made at a meeting in 2010 in Asilomar, California, USA involving 200 scientists[85], and such forms of governance are discussed extensively in NASEM (2021)[9.]

To date, the principal frameworks that have been used to inform and assess the development of research are the reporting production processes of several institutions. Existing efforts to assess and inform include limited sections of IPCC reports[86-88]. These reports, however, were not focused on an assessment of SRM. More focused assessments of SRM appear in other reports[4,5,9].

Several collaborative networks have provided informal frameworks for the development of SRM research. These include the Geoengineering Model Intercomparison Project (GeoMIP), which is a loose collaboration between global modelling groups. This network which has no specific funding is endorsed by the Climate Model Intercomparison Project (CMIP) of the World Climate Research Programme (WCRP). The WCRP is sponsored by the World Meteorological Organization, the International Oceanographic Commission (IOC) of UNESCO and the International Science Council (ISC). The Exeter NCAR collaborative development (EXTEND) project is a model comparison effort that is a collaboration between researchers at Exeter University, the UK Met Office and the U.S. National Center for Atmospheric Research, and funded by the UK's National Environment Research Council and Silver Lining, a private philanthropic funder of SRM research. Further, data from initial-condition ensemble simulations such as Geoengineering Large Ensemble Simulations (GLENS)[89] and Assessing Responses and Impacts of Solar climate intervention on the Earth system (ARISE)[90] are freely made available for the assessment of the uncertainty arising from internal (or unforced) climate variability in a modelled SRM world. DECIMALS Fund (Developing Country Impacts Modelling Analysis for SRM) is the first international SRM modelling fund aimed exclusively at supporting scientists in developing countries.

Photo: Getty Images

Box 1: Three types of SRM activities and their governance

In this report, the following three distinct SRM activities are discussed and considered for a governance framework that currently does not exist.

1. **Indoor SRM research** refers to research activities such as theoretical analyses, estimates of SRM effectiveness and costs, climate model simulations of SRM approaches, assessments of the impacts of SRM approaches, model evaluation using volcanic and ship-track analogies, laboratory studies of potential injection materials and their reactivities, injector development and social science and humanities research.

2. **Small scale outdoor SRM experiments** refer to field experiments conducted outdoors to study SRM climate processes such as aerosol microphysics, chemistry, aerosol-cloud interaction and transport. The typical spatial and temporal scale of experiments proposed to date are meters to 100 km and minutes to about 10 days and the amount of material introduced into the atmosphere would be on the order of a kilogram to a ton. These small-scale outdoor experiments would be designed to prevent detectable climate effect and could help to improve understanding of physical mechanisms or delivery system engineering. Several groups have proposed small-scale outdoor field experiments, but no such experiments have yet been reported in the peer-reviewed literature (Annex 3). There have been press reports of a Marine Cloud Brightening experiment (MCB) in Australia.

3. **Large-scale operational SRM deployment** refers to the implementation of an SRM approach at spatial and temporal scales large enough to have an observable cooling influence on the Earth. Such deployments would be of a planetary scale, last for many years to decades and produce a detectable climate effect. In the case of stratospheric aerosol injection (SAI), the injection of a few megatons of sulphates per year into the stratosphere for two or more decades might be considered the threshold for deployment as sporadic explosive volcanic eruptions release megatons of sulphur dioxide (SO_2) into the stratosphere and cool the planet by a few tenths of 1°C. The technology for delivery at this scale does not exist now. Because of the internal variability in the climate system, an SRM experiment (testing) of this scale cannot always be differentiated from an actual deployment – the near-term climate response to an SAI experiment (testing) and initial deployment would be the same.

A continuum of spatial and temporal scales exists between small-scale outdoor SRM experiments and large-scale SRM deployments. Outdoor experiments at the intermediate scales are also possible. While there may be little distinction between an outdoor SRM experiment that is large enough to produce detectable climate effects and an operational SRM deployment, it should be possible to create a boundary between small-scale SRM experimentation and large-scale operational SRM deployment through definitions of amounts of material released, duration of release or other properties of the proposed activity or its consequences.

Continued knowledge generation on SRM through indoor research is important for evaluating SRM risks and benefits, and increases confidence that an SRM deployment could theoretically achieve its stated goal of cooling the planet. In the interests of academic freedom for scientific inquiry, no formal governance framework beyond normal responsible research principles for SRM indoor research like climate modeling is suggested. The views on the need to impose governance on small-scale outdoor experimentation and operational deployment diverge because of differences in perceived risk. Governance of small-scale outdoor experimentation could limit the potential of a 'slippery slope' from small-scale experimentation to large-scale deployment. There is a general agreement that governance of large-scale deployment would be valuable given the inherent risks associated with changing the Earth's climate system with such a deployment over long periods. The group unanimously suggests a broader framework for the governance of the stratosphere which would address the changes that occur in the stratosphere from SAI experiments or deployment. Few regulatory or governance structures currently exist for the stratosphere. Any governance framework would be partly informed by a rigorous scientific and technical assessment process.

In the case of small-scale outdoor field experiments, there could be an overlap between climate science experiments and SRM experiments. In these cases, 'intent' is the key that distinguishes climate science experiments and SRM experiments. Intent can differ among participants in a research effort, and it is unclear whose intent matters and how this intent would be determined. The overlap between climate science and SRM experiments is exemplified by the National Oceanic and Atmospheric Administration (NOAA) Earth Radiation Budget (ERB) program which is dedicated to understanding stratospheric chemistry, composition, radiation and dynamics related to understanding SRM processes. The program conducts indoor research and makes new atmospheric observations in the background atmosphere and volcanic eruptions using small balloons and stratospheric aircraft. The outdoor observations are climate science research activities and are not SRM experiments, but these observations could be relevant to SRM research.

Conclusions and course of action

Having undertaken a rapid review of the state of scientific research on SRM, the expert panel recommends four priority actions:

1. A robust scientific review processes for SRM by a global body

International focus needs to remain on the mitigation of greenhouse gas emissions and adaptation to whatever climate change cannot be avoided through emissions reduction. This panel further recognizes that SRM, like the climate change crisis, is a global commons problem, and hence emphasises 'One Atmosphere' that is shared by all.

A multi-dimensional periodic scientific review that compares the risks of an SRM deployment with climate change risks without SRM deployment requires the participation of a broad array of relevant stakeholders with diverse backgrounds, values, perspectives and interests. Proposed scenarios for SRM deployment (Figure 2) could be comprehensively evaluated for intended and unintended consequences, based on models, observations and theoretical understanding. Even if an SRM deployment were successful at reducing climate change risks, it could introduce or exacerbate environmental and societal risks. Uncertainties in physical processes of central importance to SRM approaches, the effectiveness of SRM in offsetting climate change and SRM impacts on humans and natural ecosys robust, equitable and rigorous trans-disciplinary scientific review tems need to be better understood. If a robust, equitable and rigorous trans-disciplinary scientific review demonstrates that an SRM deployment would lead to negative consequences and impacts, consideration of deployment could be taken off the table and mitigation and adaptation would become the only approaches to reduce both short- and long-term climate risks.

The panel anticipates that periodic scientific assessments, including both the natural and social sciences, would be valuable for guiding future research and for defining the foundation for decision processes associated with an international discussion about SRM issues such as governance of small-scale outdoor experiments, technology development, financing, deployment options and governance of large-scale operational deployment. Therefore, this panel suggests the establishment of a globally inclusive, transparent and equitable scientific review process for SRM.

2. A governance framework (or frameworks) for possible small-scale outdoor SRM experiments and large-scale operational SRM deployments

Governance could be helpful to guide decisions surrounding the acceptability of possible SRM research activities and SRM deployment strategies. Governance options range from voluntary norms to legal requirements. Any governance framework would be partly informed by a rigorous scientific and technical assessment process.

Governance of SRM indoor research, small-scale outdoor experiments and large-scale operational deployment should be differentiated. Continued knowledge generation of SRM approaches through indoor theoretical, numerical modelling, experiments and social science and humanities research is important to reduce uncertainty and to ensure that SRM could achieve stated goals. In the interests of academic freedom for scientific inquiry, this group suggests no governance framework beyond normal responsible research principles for SRM indoor research such as climate modelling. The development of norms, guidelines and codes of conduct could help balance perceived societal risks with principles of freedom of scientific inquiry.

The views in this expert panel on the need to impose governance frameworks on small-scale outdoor experimentation and operational deployment diverge because of differences in perceived risk. Governance of small-scale outdoor experimentation could limit the potential of a 'slippery slope' from small-scale experimentation to large-scale deployment. There is a general agreement that governance of large-scale deployment of SRM would be valuable given the risks inherent in conducting large-scale interventions in Earth's climate system over long time periods.

In the case of small-scale outdoor field experiments, there could be an overlap between climate science experiments and SRM experiments. In these cases, "intent" is the key distinguishing feature.

In summary, this panel suggests the prospects and possibilities for a multilateral SRM governance framework be explored to evaluate and address concerns on both small-scale outdoor SRM experimentation and potential large-scale operational SRM deployment.

3. A broader framework for the governance of the stratosphere

As a complement to other SRM-specific governance, this group unanimously suggests SAI be considered within a new broader framework for the governance of the stratosphere. This framework would address the changes that occur in the stratosphere from SAI experiments or deployment. Other activities such as rocket launches may also be considered as little regulatory or governance structures presently exist for the stratosphere.

4. A globally inclusive conversation of SRM be promoted

The conversation process on SRM needs to involve discussion on a broad range of issues with all stakeholders, as many, especially from the global south, are not currently engaged in SRM discussion and research. In this conversation, an important decision will be whether the process of scientific assessment of SRM should precede the establishment of a governance framework for experiments and deployment. This panel suggests a process of coevolution of governance considerations and a rigorous, ongoing scientific assessment process for SRM approaches.

Credit: Getty Images

References

1. IPCC. Summary for Policymakers. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Masson-Delmotte, V. *et al.*) 1–31. In Press; 2021.
2. WMO. Climate Indicators and Sustainable Development: Demonstrating the Interconnections. Geneva, Switzerland: World Meteorological Organization; 2021.
3. Canadell, J. G. *et al.* Global Carbon and Other Biogeochemical Cycles and Feedbacks. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Masson-Delmotte, V. *et al.*) 673–816. Cambridge University Press; 2021. https://doi.org/10.1017/9781009157896.007.
4. Royal Society. Geoengineering the climate: science, governance and uncertainty. Royal Society (RS Policy document, 10/29), London https://royalsociety.org/-/media/Royal_Society_Content/policy/publications/2009/8693.pdf (2009).
5. NASEM. Climate Intervention: Reflecting Sunlight to Cool Earth. National Academies Press; 2015. https://doi.org/10.17226/18988.
6. MacMartin, D. G., Ricke, K. L. and Keith, D. W. Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2018; 376, 20160454
7. Buck, H., Geden, O., Sugiyama, M. and Corry, O. Pandemic politics—lessons for solar geoengineering. Communications Earth and Environment. 2020; 1,16.
8. de Coninck, H. *et al.* Strengthening and Implementing the Global Response. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, (eds. Masson- Delmotte, V. *et al.*) 313–444. Cambridge University Press; 2018. https://doi.org/10.1017/9781009157940.006.
9. NASEM. Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. National Academies Press; 2021. https://doi.org/10.17226/25762.
10. Parker, A. and Geden, O. No fudging on geoengineering. Nature Geoscience. 2016; 9: 859–860.
11. Lee, J.-Y. *et al.* Future Global Climate: Scenario-Based Projections and Near-Term Information. in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Masson-Delmotte, V. *et al.*). Cambridge University Press; 2021. 553–672 https://doi.org/10.1017/9781009157896.006.
12. Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H. *et al.* Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature. 2016; 534: 631–639.
13. Millar, J. R., Nicholls, Z. R., Friedlingstein, P. and Allen, M. R. A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. Atmospheric Chemistry and Physics. 2017; 17: 7213–7228.
14. Tollefson, J. IPCC says limiting global warming to 1.5 °C will require drastic action. Nature. 2018; 562:172–173.
15. Patt, A., Rajamani, L., Bhandari, P., Ivanova Boncheva, A., Caparrós, A. Djemouai, K. *et al.* International cooperation. In: IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022. https://doi.org/10.1017/9781009157926.016.
16. Matthews, H. D. and Caldeira, K. Transient climate–carbon simulations of planetary geoengineering. Proceedings of the National Academy of Sciences. 2007; 104: 9949–9954.
17. Caldeira, K. and Keith, D. The Need for Climate Engineering Research. Issues in Science and Technology. 2010; 27: 57–62.
18. Jones, A., Haywood, J.M., Alterskjaer, K., Boucher, O., Cole, J.N.S., Curry, C.L. *et al.* The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres. 2013; 118: 9743–9752.
19. Trisos, C. H., Amatulli, G., Gurevitch, J., Robock, A., Xia, L. and Zambri, B. Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination. Nature Ecology and Evolution. 2018; 2: 475–482.
20. Tilmes, S., Sanderson, B. M. and O'Neill, B. C. Climate impacts of geoengineering in a delayed mitigation scenario. Geophysical Research Letters. 2016; 43: 8222–8229.

21. Bluth, G. J. S., Doiron, S. D., Schnetzler, C. C., Krueger, A. J. and Walter, L. S. Global tracking of the SO 2 clouds from the June1991 Mount Pinatubo eruptions. Geophysical Research Letters. 1992; 19: 151–154.
22. Soden, B. J., Wetherald, R. T., Stenchikov, G. L. and Robock, A. Global Cooling After the Eruption of Mount Pinatubo: A Test of Climate Feedback by Water Vapor. Science (1979). 2002; 296: 727–730.
23. Vaughan, N. E. and Lenton, T. M. A review of climate geoengineering proposals. Climate Change. 2011; 109: 745–790.
24. Smith, W. and Wagner, G. Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. Environmental Research Letters. 2018; 13.
25. Smith, W. The cost of stratospheric aerosol injection through 2100. Environmental Research Letters. 2020; 15, 114004.
26. STORMY OUTLOOK Plans to 'hack Earth's weather' could start World War 3, panicked scientists warn. The Sun. 14 June 2019.
27. Lawrence, M. G. *et al.* Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals. Nature Communications. 2018; 9: 3734.
28. Caldeira, K., Bala, G. and Cao, L. The Science of Geoengineering. Annual Review of Earth and Planetary Sciences. 2013; 41: 231–256.
29. Christensen, M. W. and Stephens, G. L. Microphysical and macrophysical responses of marine stratocumulus polluted by underlying ships: Evidence of cloud deepening. Journal of Geophysical Research. 2011; 116: D03201.
30. Chen, Y.-C., Christensen, M. W., Xue, L., Sorooshian, A., Stephens, G. L., Rasmussen, R. M. *et al.* Occurrence of lower cloud albedo in ship tracks. Atmospheric Chemistry and Physics. 2012; 12: 8223–8235.
31. Cooper, G., Foster, J., Galbraith, L., Jain, S., Neukermans, A., Ormond, B. *et al.* Preliminary results for salt aerosol production intended for marine cloud brightening, using effervescent spray atomization. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2014; 372: 20140055.
32. Tollefson, J. Can artificially altered clouds save the Great Barrier Reef? Nature. 2021; 596: 476–478.
33. Gasparini, B. and Lohmann, U. Why cirrus cloud seeding cannot substantially cool the planet. Journal of Geophysical Research: Atmospheres. 2016; 121: 4877–4893.
34. Penner, J. E., Zhou, C. and Liu, X. Can cirrus cloud seeding be used for geoengineering? Geophysical Research Letters. 2015; 42: 8775–8782.
35. Roy, K. The solar shield concept: Current status and future possibilities. Acta Astronautica. 2022; 197: 368-375. https://doi.org/10.1016/j.actaastro.2022.02.022.
36. Bewick, R., Sanchez, J. P. and McInnes, C. R. Gravitationally bound geoengineering dust shade at the inner Lagrange point. Advances in Space Research. 2012; 50: 1405–1410.
37. Fuglesang, C. and de Herreros Miciano, M. G. Realistic sunshade system at L1 for global temperature control. Acta Astronautica. 2021; 186: 269–279.
38. MacCracken, M. C. The rationale for accelerating regionally focused climate intervention research. Earths Future. 2016; 4: 649–657.
39. Field, L., Ivanova, D., Bhattacharyya, S., Mlaker, V., Sholtz, A., Decca, R. *et al.* Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering. Earths Future. 2018; 6: 882–901. https://doi.org/10.1029/2018EF000820.
40. PCAST. Restoring the Quality of Our Environment, Appendix Y4, Atmospheric Carbon Dioxide. Report by the US President's Scientific Advisory Committee. 1965; 111–133.
41. Seneviratne, S. I., Phipps, S. J., Pitman, A. J., Hirsch, A. L., Davin, E. L., Donat, M. G. *et al.* Land radiative management as contributor to regional-scale climate adaptation and mitigation. Nature Geoscience. 2018; 11: 88–96.
42. Mears, C. A. and Wentz, F. J. A Satellite-Derived Lower-Tropospheric Atmospheric Temperature Dataset Using an Optimized Adjustment for Diurnal Effects. Journal of Climate. 2017; 30(19): 7695–7718.
43. Aquila, V., Baldwin, C., Mukherjee, N., Hacken, E., Li, F., Marshak, J. *et al.* Impacts of the Eruption of Mount Pinatubo on Surface Temperatures and Precipitation Forecasts with the NASA GEOS Subseasonal-to-Seasonal System. Journal of Geophysical Research: Atmospheres. 2021; 126(16).
44. Mears, C. A. and Wentz, F. J. A Satellite-Derived Lower-Tropospheric Atmospheric Temperature Dataset Using an Optimized Adjustment for Diurnal Effects. Journal of Climate. 2017; 30: 7695–7718.
45. Jones, A. C., Hawcroft, M. K., Haywood, J. M., Jones, A., Guo, X. and Moore, J. C. Regional Climate Impacts of Stabilizing Global Warming at 1.5 K Using Solar Geoengineering. Earths Future. 2018; 6: 230–251.
46. Tilmes, S., MacMartin, D. G., Lenaerts, J. T. M., van Kampenhout, L., Muntjewerf, L., Xia, L. *et al.* Reaching 1.5 and 2.0°C global surface temperature targets using stratospheric aerosol geoengineering. Earth System Dynamics. 2020; 11, 579–601.
47. Niemeier, U., Schmidt, H. and Timmreck, C. The dependency of geoengineered sulfate aerosol on the emission strategy. Atmospheric Science Letters. 2011; 12: 189–194.
48. Irvine, P. J., Kravitz, B., Lawrence, M. G., Gerten, D., Caminade, C., Gosling, S. N. *et al.* Towards a comprehensive climate impacts assessment of solar geoengineering. Earths Future. 2017; 5: 93–106.

49. Carlson, C. J., Colwell, R., Hossain, M. S., Rahman, M. M, Robock, A., Ryan, S. J. *et al.* Solar geoengineering could redistribute malaria risk in developing countries. Nature Communications. 2022; 13: 2150.

50. Irvine, P. J. and Keith, D. W. Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards. Environmental Research Letters. 2020; 15: 044011.

51. Irvine, P., Emanuel, K., He, J., Horowitz, L., Vecchi, G. and Keith, D. Halving warming with idealized solar geoengineering moderates key climate hazards. Nature Climate Change. 2019; 9: 295–299.

52. Kravitz, B., MacMartin, D. G., Mills, M. J., Richter, J. H., Tilmes, S., Lamarque, J-F. *et al.* First Simulations of Designing Stratospheric Sulfate Aerosol Geoengineering to Meet Multiple Simultaneous Climate Objectives. Journal of Geophysical Research: Atmospheres. 2017; 122(23): 12,616-12,634.

53. Richter, J. H., Tilmes, S., Mills, M. J., Tribbia, J. J., Kravitz, B., MacMartin, D. G. *et al.* Stratospheric Dynamical Response and Ozone Feedbacks in the Presence of SO 2 Injections. Journal of Geophysical Research: Atmospheres. 2017; 122 (23): 12,557-12,573

54. Haywood, J. M., Jones, A., Bellouin, N. and Stephenson, D. Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. Nature Climate Change. 2013; 3: 660–665.

55. Krishnamohan, K. S. and Bala, G. Sensitivity of tropical monsoon precipitation to the latitude of stratospheric aerosol injections. Climare Dynamics. 2022; 59: 151-168.

56. Aquila, V., Garfinkel, C. I., Newman, P. A., Oman, L. D. and Waugh, D. W. Modifications of the quasi-biennial oscillation by a geoengineering perturbation of the stratospheric aerosol layer. Geophysical Research Letters. 2014; 41: 1738–1744.

57. Richter, J. H., Tilmes, S., Glanville, A., Kravitz, B., MacMartin, D. G., Mills, M. J. *et al.* Stratospheric Response in the First Geoengineering Simulation Meeting Multiple Surface Climate Objectives. Journal of Geophysical Research: Atmospheres. 2018; 123: 5762–5782.

58. Jones, A., Haywood, J. M., Scaife, A. A., Boucher, O., Henry, M., Kravitz, B. *et al.* The impact of stratospheric aerosol intervention on the North Atlantic and Quasi-Biennial Oscillations in the Geoengineering Model Intercomparison Project (GeoMIP) G6sulfur experiment. Atmospheric Chemistry and Physics. 2022; 22: 2999–3016.

59. Kravitz, B., Robock, A., Oman, L., Stenchikov, G. and Marquardt, A. B. Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols. Journal of Geophysical Research Atmospheres. 2009; 114: 1–7.

60. Visioni, D., Slessarer, E., MacMartin, D. G., Mahowald, N. M, Goodale, C. L. and Xia, L. What goes up must come down: impacts of deposition in a sulfate geoengineering scenario. Environmental Research Letters. 202; 15(9): 094063.

61. Tilmes, S., Richter, J. H., Kravitz, B., MacMartin, D. G., Glanville, A. S., Visioni, D. *et al.* Sensitivity of Total Column Ozone to Stratospheric Sulfur Injection Strategies. Geophysical Research Letters. 2021; 48: 1–10.

62. Tilmes, S., Visioni, D., Jones, A., Haywood, J., Seferian, R., Nabat, P. *et al.* Stratospheric ozone response to sulfate aerosol and solar dimming climate interventions based on the G6 Geoengineering Model Intercomparison Project (GeoMIP) simulations. Atmospheric Chemistry and Physics. 2022; 22: 4557–4579.

63. Pitari, G., Aquilla, V., Kravitz, B., Robock, A., Watanabe, S., Cionni, I. *et al.* Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres. 2014; 119: 2629–2653.

64. Xia, L., Nowack, P. J., Tilmes, S. and Robock, A. Impacts of stratospheric sulfate geoengineering on tropospheric ozone. Atmospheric Chemistry and Physics. 2017; 17: 11913–11928.

65. Tilmes, S., Richter, J. H., Mills, M. J., Kravitz, B., MacMartin, D. G., Garcia, R. *et al.* Effects of Different Stratospheric SO 2 Injection Altitudes on Stratospheric Chemistry and Dynamics. Journal of Geophysical Research: Atmospheres. 2018; 123: 4654–4673.

66. Keith, D. W., Weisenstein, D. K., Dykema, J. A. and Keutsch, F. N. Stratospheric solar geoengineering without ozone loss. Proceedings of the National Academy of Sciences of the United States of America. 2016; 113: 14910–14914.

67. Dai, Z., Weisenstein, D. K., Keutsch, F. N. and Keith, D. W. Experimental reaction rates constrain estimates of ozone response to calcium carbonate geoengineering. Communications Earth and Environment. 2020; 1: 63.

68. Parson, E. A. Climate Engineering in Global Climate Governance: Implications for Participation and Linkage. Transnational Environmental Law. 2014; 3: 89–110.

69. Keith, D. W. and MacMartin, D. G. A temporary, moderate and responsive scenario for solar geoengineering. Nature Climate Change. 2015; 5: 201–206.

70. Parker, A. and Irvine, P. J. The Risk of Termination Shock From Solar Geoengineering. Earths Future. 2018; 6: 456–467.

71. Craik, N. Solar radiation modification and loss damage: mapping interactions between climate responses. In: Research Handbook on Climate Change Law and Loss & Damage 287–302 (Edward Elgar Publishing, 2021). https://doi.org/10.4337/9781788974028.00022.

72. Felgenhauer, T. *et al.* Solar Radiation Modification: A Risk-Risk Analysis, Carnegie Climate Governance Initiative (C2G). March, New York, NY, www.c2g2.net (2022).

73. H.-O. Pörtner, *et al.* IPCC WG2: Summary for policymakers. (2022).

74. Bürger, G. and Cubasch, U. The detectability of climate engineering. Journal Geophysical Research. 2015; 120: 11,404-11,418.

75. Reynolds, J. L. Is solar geoengineering ungovernable? A critical assessment of governance challenges identified by the Intergovernmental Panel on Climate Change. WIREs Climate Change. 2021; 12.

76. Reynolds, J. L. The Governance of Solar Geoengineering. (Cambridge University Press, 2019). https://doi.org/10.1017/9781316676790.

77. Reynolds, J. L. and Parson, E. A. Nonstate governance of solar geoengineering research. Climate Change. 2020; 160: 323–342.

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

79. Biermann, F. Beyond the intergovernmental regime: Recent trends in global carbon governance. Current Opinion in Environmental Sustainability. 2010; 2: 284–288.

80. McLaren, D. and Corry, O. The politics and governance of research into solar geoengineering. WIREs Climate Change. 2021;12: e707.

81. Lloyd, I. D. and Oppenheimer, M. On the Design of an International Governance Framework for Geoengineering. Global Environmental Politics. 2014; 14: 45–63.

82. Caldeira, K. and Bala, G. Reflecting on 50 years of geoengineering research. Earths Future. 2017; 5: 10–17.

83. Reynolds, J. L. Solar geoengineering to reduce climate change: a review of governance proposals. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2019; 475: 20190255.

84. SRMGI. Solar radiation management: the governance of research. 2011. https://royalsociety.org/-/media/Royal_Society_Content/policy/projects/solar-radiation-governance/DES2391_SRMGI-report_web.pdf.

85. Kintisch, E. 'Asilomar 2' Takes Small Steps Toward Rules for Geoengineering. Science (1979). 2010; 328: 22–23.

86. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovern- mental Panel on Climate Change. Cambridge University Press, 2013.

87. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. 2018.

88. Climate Change 2021 - the Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2021.

89. Tilmes, S., Richter, J. H., Kravitz, B., MacMartin, D. G., Mills, M. J., Simpson, I. R. *et al.* CESM1(WACCM) stratospheric aerosol geoengineering large ensemble project. Bulletin of the American Meteorological Society. 2018; 99: 2361–2371.

90. Richter, J., Visioni, D., MacMartin, D., Bailey, D., Rosenbloom, N., Lee, W *et al.* Assessing Responses and Impacts of Solar climate intervention on the Earth system with stratospheric aerosol injection (ARISE-SAI). EGUsphere [preprint]. 2022. https://doi.org/10.5194/egusphere-2022-125.

91. Tilmes, S., Richter, J. H., Mills, M. J., Kravitz, B., MacMartin, D. G., Vitt, F. *et al.* Sensitivity of aerosol distribution and climate response to stratospheric SO2 injection locations. Journal of Geophysical Research: Atmospheres. 2017; 122: 12,591-12,615

92. Proctor, J., Hsiang, S., Burney, J., Burke, M. and Schlenker, W. Estimating global agricultural effects of geoengineering using volcanic eruptions. Nature. 2018; 560: 480–483.

93. Niemeier, U. and Timmreck, C. What is the limit of stratospheric sulfur climate engineering? Atmospheric Chemistry and Physics Discussions. 2015; 15: 10939–10969.

94. World Meteorological Organization. Scientific Assessment of Ozone Depletion: 2018 Executive Summary. 2018.

95. Irvine, P. J., Kravitz, B., Lawrence, M. G. and Muri, H. An overview of the Earth system science of solar geoengineering. Wiley Interdisciplinary Reviews Climate Change. 2016; 7: 815–833.

96. Ferraro, A. J. and Griffiths, H. G. Quantifying the temperature-independent effect of stratospheric aerosol geoengineering on global-mean precipitation in a multi-model ensemble. Environmental Research Letters. 2016; 11.

97. Latham, J., Bower, K., Choularton, T, Coe, H., Connolly, P., Cooper, G. *et al.* Marine cloud brightening. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2012; 370: 4217–4262.

98. Stjern, C. W., Muri, H., Ahlm, L., Boucher, O., Cole, J. N. S., Ji, D. *et al.* Response to marine cloud brightening in a multi-model ensemble. Atmospheric Chemistry and Physics. 2018; 18: 621–634.

99. Kravitz, B., Foster, P. M., Jones, A., Robock, A., Alterskjaer, K., Boucher, O. *et al.* Sea spray geoengineering experiments in the geoengineering model intercomparison project (GeoMIP): Experimental design and preliminary results. Journal of Geophysical Research: Atmospheres. 2013; 118(19): 11,111-175,186.

100. Adeniyi, M. O. and Bassey, B. E. I. Precipitation and temperature response to sea salt injection into low marine clouds over West Africa. SN Applied Sciences. 2021: 3.

101. Ahlm, L., Jones, A., Stjern, C. W., Muri, H., Kravitz, B. and Kristjansson, J. E. Marine cloud brightening – as effective without clouds. Atmospheric Chemistry and Physics. 2017; 17: 13071–13087.

102. Diamond, M. S., Gettelman, A., Lebsock, M. D. and Mccomiskey, A. To assess marine cloud brightening's technical feasibility, we need to know what to study — and when to stop. Proceedings of the National Academy of Sciences of the United States of America. 2022; 119(4).

103. Salter, S. H., Stevenson, T. and Tsiamis, A. Engineering Ideas for Brighter Clouds. In: Geoengineering of the Climate System. Royal Society of Chemistry; 2014. Chapter 6, 131–161. https://doi.org/10.1039/9781782621225-00131.

104. Akbari, H., Menon, S. and Rosenfeld, A. Global cooling: Increasing world-wide urban albedos to offset CO_2. Climate Change. 2009; 94, 275–286.

105. Akbari, H., Damon Matthews, H. and Seto, D. The long-term effect of increasing the albedo of urban areas. Environmental Research Letters. 2012; 7.

106. Doughty, C. E., Field, C. B. and McMillan, A. M. S. Can crop albedo be increased through the modification of leaf trichomes, and could this cool regional climate? Climate Change. 2011; 104: 379–387.

107. Evans, J., Stride, E., Edirisinghe, M., Andrews, D. and Simons, R. Can oceanic foams limit global warming? Climate Resilience. 2010; 42: 155–160.

108. Kravitz, B., Rasch, P. J., Wang, H., Robock, A., Gabriel, C., Boucher, O. *et al.* The climate effects of increasing ocean albedo: An idealized representation of solar geoengineering. Atmospheric Chemistry and Physics Discussions. 2018; 1–29 https://doi.org/10.5194/acp-2018-340.

109. Gabriel, C. J., Robock, A., Xia, L., Zambri, B. and Kravitz, B. The G4Foam Experiment: Global climate impacts of regional ocean albedo modification. Atmospheric Chemistry and Physics. 2017; 17: 595–613.

110. Cvijanovic, I., Caldeira, K. and MacMartin, D. G. Impacts of ocean albedo alteration on Arctic sea ice restoration and Northern Hemisphere climate. Environmental Research Letters. 2015; 10: 44020.

111. Mengis, N., Martin, T., Keller, D. P. and Oschlies, A. Assessing climate impacts and risks of ocean albedo modification in the Arctic. Journal of Geophysical Research: Oceans. 2016; 121: 3044–3057.

112. Jackson, L. S., Crook, J. A. and Forster, P. M. An intensified hydrological cycle in the simulation of geoengineering by cirrus cloud thinning using ice crystal fall speed changes. Journal of Geophysical Research: Atmospheres. 2016; 121, 6822–6840.

113. Lohmann, U. and Gasparini, B. A cirrus cloud climate dial? Science. 2017; 357: 248–249.

114. Gasparini, B., McGraw, Z., Storelvmo, T. and Lohmann, U. To what extent can cirrus cloud seeding counteract global warming? Environmental Research Letters. 2020; 15: 054002.

115. Gasparini, B., Münch, S., Poncet, L., Feldmann, M. and Lohmann, U. Is increasing ice crystal sedimentation velocity in geoengineering simulations a good proxy for cirrus cloud seeding? Atmospheric Chemistry and Physics.2017; 17: 4871–4885.

116. Storelvmo, T., Boos, W. R. and Herger, N. Cirrus cloud seeding: A climate engineering mechanism with reduced side effects? Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2014; 372.

117. Storelvmo, T. and Herger, N. Cirrus cloud susceptibility to the injection of ice nuclei in the upper troposphere. Journal of Geophysical Research: Atmospheres. 2014; 119: 2375–2389.

118. Stilgoe, J. Geoengineering as Collective Experimentation. Science and Engineering Ethics. 2016; 22: 851–869.

119. Stilgoe, J., Watson, M. and Kuo, K. Public Engagement with Biotechnologies Offers Lessons for the Governance of Geoengineering Research and Beyond. PLoS Biology. 2013; 11.

120. Cressey, D. Geoengineering experiment cancelled amid patent row. Nature. 2012. https://doi.org/10.1038/nature.2012.10645.

121. Dykema, J. A., Keith, D. W., Anderson, J. G. and Weisenstein, D. Stratospheric controlled perturbation experiment: A small-scale experiment to improve understanding of the risks of solar geoengineering. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2014; 372.

122. Tollefson, J. The sun dimmers. Nature. 2018; 563: 613–615.

123. Golja, C. M., Chew, L. W., Dykema, J. A. and Keith, D. W. Aerosol Dynamics in the Near Field of the SCoPEx Stratospheric Balloon Experiment. Journal of Geophysical Research: Atmospheres. 2021; 126: 1–12.

124. Geoengineering briefing: Marine Cloud Brightening Project. 2018. https://www.geoengineeringmonitor.org/wp-content/uploads/2018/04/geoeng_briefing-MCBP.pdf.

125. 'Ship tracks' over the ocean reveal a new strategy to fight climate change. 2021. https://spectrum.ieee.org/climate-change.

126. Geoengineering briefing: The Ice 911 Project. 2018. https://www.geoengineeringmonitor.org/wp-content/uploads/2018/04/geoeng_briefing-ice911-1.pdf.

Annexes

ANNEX 1

Some of the proposed SRM approaches and their features

SRM option	Scale	Proposed mechanism	Effectiveness in terms of the magnitude of the global mean negative radiative forcing (for reference, a doubling of CO_2 causes a radiative forcing of ~4 W m-2)	Potential climate effects (other than cooling the surface temperature)	Potential impacts on human and natural systems	Estimates of deployment time, lifetime of effect and cost[4,23]
Stratospheric Aerosol Injection (SAI)[63,65,91-96]	Global	Injection of aerosols or their precursors into the stratosphere which scatter sunlight back to space; sulphates, calcium carbonate, carbonyl sulphide, and titanium oxide have been proposed.	-1 to -8 Wm-2, depending on the type and amount of material injected; forcing would also depend on aerosol microphysics, transport and the latitude, altitude and season of injection; forcing could be nearly uniform for equatorial or global implementation; large uncertainties associated with aerosol microphysics, radiative properties, injection location and transport.	Changes in regional precipitation pattern; decrease in direct sunlight and increase in diffuse sunlight at the surface; stratospheric warming and increase in stratospheric water vapour; changes to stratospheric circulation and chemistry; potential delay in ozone hole recovery and increase in surface UV radiation.	Changes in crop yields; changes in land and ocean ecosystem productivity; acid rain (if using sulphate); reduced risk of heat stress to corals.	~10 years; 1–3 years; ~18 billion USD per year per 1oC of global mean cooling[25].
Marine cloud brightening (MCB)[97-102]	Regional	Injection of sea salt aerosols to increase the albedo of marine stratocumulus clouds.	-1 to -5 W m^{-2}, depending on the scale and amount of sea salt injection; radiative forcing would be heterogeneous; large uncertainties associated with cloud microphysics and aerosol–cloud-radiation interactions.	Large changes in regional circulations; increase in land-sea contrast; uncertain regional changes in precipitation patterns; sea salt deposition on land.	Changes in regional ocean productivity; changes in crop yields; reduced heat stress for corals; changes in ecosystem productivity on the land.	~10 years; ~ 1–7 days: on the order of 1–2 billion USD per year per Wm^{-2} of negative radiative forcing[103].
Whitening the roofs of urban buildings[41,104,105]	Local	Painting the roof of buildings to increase the reflectivity.	Maximum potential radiative forcing of about -0.1 W m^{-2}; highly localized radiative forcing.	Potential changes to urban climate and local circulations.	Unresearched	~10 years; ~10 years; ~300 billion USD per year for a few tenths of a Wm^{-2} of negative radiative forcing.

SRM option	Scale	Proposed mechanism	Effectiveness in terms of the magnitude of the global mean negative radiative forcing (for reference, a doubling of CO2 causes a radiative forcing of ~4 W m-2)	Potential climate effects (other than cooling the surface temperature)	Potential impacts on human and natural systems	Estimates of deployment time, lifetime of effect and cost[4,23]
More reflective crops[41,106]	Regional	Genetically modify the colour of crops to increase sunlight reflection.	Maximum potential radiative forcing of about -0.5 W m^{-2}; heterogeneous radiative forcing; May help reduce heating in urban environments.	Changes to regional precipitation and circulation patterns.	Reduction in photosynthetic activity and changes in crop yields and biodiversity.	~ 10 years; ~1 year; cost estimates are not available.
Desert albedo increase[41]	Regional	Covering deserts with a reflective material such as polyethylene-aluminium surface to increase the mean albedo from 0.36 to 0.8.	2–3 W m^{-2}; highly localized regional radiative forcing.	Decrease in land-sea contrast; Changes to regional precipitation and circulation patterns.	Major environmental and ecological effects on desert ecosystems; Changes in photosynthetic activity, land carbon uptake and biodiversity.	~ 10 years; < 10 years; several trillion USD per year for producing ~2 Wm^{-2} of negative radiative forcing.
Ocean albedo increase[107–111]	Regional	Add reflecting particles on the ocean surface or create microbubbles by stirring the ocean surface.	Radiative forcing of several Wm^{-2} is achievable; heterogeneous radiative forcing; land-sea contrast in radiative forcing.	Large changes in ocean circulations; Increase in land-sea contrast; Regional changes in precipitation patterns.	Unresearched	~ 10 years; < 1 year; cost estimate is not available.
Cirrus cloud thinning (CCT)[33,112–117]	Regional	Inject ice nuclei in the upper troposphere to reduce the amount of cirrus clouds to allow more longwave radiation to escape to space.	1–2 W m^{-2}, depending on cirrus microphysical response and seeding strategy; heterogeneous radiative forcing; loss in cirrus clouds could also cause significant shortwave forcing regionally; risk of overseeding and consequent warming.	Changes in regional temperature and precipitation patterns; Increase in solar radiation reaching surface.	Altered photosynthesis and carbon uptake.	~ 10 years; ~10 days; cost estimates are not available.
Space sunshades[35–37]	Global	Placement of mirrors or reflecting particles in space between the Sun and Earth to reflect sunlight back to space.	Blocking of about 2% of the incoming solar radiation would yield a negative radiative forcing of ~ 4 W m^{-2}; nearly uniform radiative forcing.	Less intense global hydrological cycle in the tropics; amplitude of the seasonal cycle is reduced.	Decrease in sunlight for photosynthesis.	>20 years; ~ 20 years; a few trillion USD for the launch.

ANNEX 2

Key terms relating to risk associated with climate change. The definitions are reproduced from the glossary of the latest IPCC report (2021).

Climatic impact-drivers (CIDs)

CIDs are physical climate system conditions (e.g. means, events and extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral or a mixture of each across interacting system elements and regions.

Hazard

The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.

Impacts

The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services) and infrastructure. Impacts may be referred to as consequences or outcomes and can be adverse or beneficial.

Risk

The potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species. In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. Hazards, exposure and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence, and each may change over time and space due to socio-economic changes and human decision-making.

ANNEX 3

SRM field experiments

Experiment Name / Country	SRM option	Objective	Current status
Stratospheric Particle Injection for Climate Engineering (SPICE) project, UK[118,119]	SAI	Demonstration of carrying materials to the stratosphere through a 1km long hose. The experiment attempted to carry 150L of water through a hosepipe connected to a balloon. Project has three parts: evaluating candidate particles; delivery systems; climate and impacts modelling.	Experimental deployment was halted in 2012 because of a patent row and the lack of rules that govern geoengineering experiments[120]
Stratospheric Controlled Perturbation Experiment (SCoPEx) Advisory committee for SCoPEx is exclusively US-based Harvard University[121–123]	SAI	Small-scale experiments to quantify the risks posed by SAI to activation of halogen species and subsequent erosion of stratospheric ozone.	After several unsuccessful plans to conduct field tests, the field test flight to release calcium carbonate particles into the stratosphere SCoPEx was scheduled for June 2021 in Sweden, but again halted because of objections from local communities.
The Marine Cloud Brightening Project[124,125]	MCB	Quantify how the addition of sea salt particles changes the number of droplets in marine low clouds, and study how clouds behave when they have more droplets.	Field tests were initially planned for 2016 but have been delayed.
Reef Restoration and Adaptation program[32]	MCB	To cool the ocean waters near the Great Barrier Reef to save the Corals. MCB is one component of the broader effort “Reef restoration and adaption program”. The project is about local adaptation and not global geoengineering.	Experiments (injection of seawater) were conducted in March 2020 and March 2021. Results are not published yet. The Principal investigator argues that the project is more akin to cloud-seeding operations that are designed to promote rain and that are not considered to be geoengineering.
ICE 911[126]	Surface albedo increase over ice	Deployment of millions of glass microspheres over the Arctic ice to reflect sunlight in the summer months and delay melting of ice.	The ICE 911 experiment that covered 17,500 square metres of ice was conducted in 2017 in Alaska. Results are not published.

ANNEX 4

A qualitative comparison of SRM and mitigation

Feature	SRM	Mitigation (Emission reduction + removal of GHGs)
Mechanism	Reduce climate change by reflection of more sunlight to space, thereby reducing the amount of sunlight absorbed by the planet.	Reduce climate change by preventing the accumulation of GHGs in the atmosphere via reduced emissions or increased removal of GHGs from the atmosphere.
Duration of the surface cooling effect	As long as deployment is maintained (1–3 years for SAI and ~10 days for MCB).	Effect is nearly permanent.
Level of GHGs in the atmosphere	High levels of GHGs would persist in the atmosphere. Hence, the root cause of climate change which is the accumulation of GHGs in the atmosphere is not addressed.	Accumulation of GHGs in the atmosphere would be prevented.
Timescale to cool	Can rapidly reduce global within a few years with abrupt introduction.	Potential feasible pathways take at least several decades to reduce global warming.
Ocean Acidification	Ocean acidification would not be addressed as high levels of CO_2 would persist in the atmosphere.	Ocean acidification would be addressed.
Technology readiness	SRM approaches are conceptual now. SRM technologies at scale do not exist.	Some technologies for emission reduction exist (e.g. solar and wind energy). GHG removal technologies at scale do not exist.
Termination shock	Sudden and sustained termination would produce rapid temperature increases proportional to the aerosol radiative forcing at the end of the SAI deployment.	----
Cost estimates	Estimates of direct costs range from billions to tens of billions of USD per year per degree cooling for most of the options (except whitening roofs and space sunshades which are more costly).	Hundreds of billions to trillions of USD per year are estimated.
New physical hazards	Altered precipitation patterns, depletion of stratospheric ozone, increase in surface UV radiation, enhanced air pollution and acid rain, sea salt deposition on terrestrial ecosystems (MCB).	----
Possible societal consequences	International conflicts, moral hazard, free driving unilateral SRM, counter and countervailing SRM, ethical, moral, legal, equity and justice issues.	----
UN process	UN process for governing research, field experiments, deployment and maintenance does not exist now.	The UN meetings of the Conference of Parties review, develop and implement the UNFCCC, Kyoto Protocol and Paris Agreement.

ANNEX 5

Existing international treaties and UN Resolutions relevant to SRM

Convention / Treaty	Year	
Outer Space Treaty Liability Convention	1967 1972	The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty) and the associated 1972 Convention on International Liability for Damage Caused by Space Objects; Liability Convention provides that a launching State shall be absolutely liable to pay compensation for damage caused by its space objects on the surface of the Earth or to aircraft, and liable for damage due to its faults in space. The Convention also provides for procedures for the settlement of claims for damages. **https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html**
ENMOD Convention	1977	The Convention on the Prohibition of Military or any other Hostile Use of Environmental Modification Techniques (ENMOD Convention) is an instrument of international disarmament law specifically intended to protect the environment in the event of armed conflict. It prohibits hostile action to modify the environment as a means of warfare. Although SRM may have benevolent motivations, it could be that reckless disregard of the countervailing risks of SRM might rise to the type of actions addressed by the ENMOD Convention. The provisions of Protocol of 1977 additional to the Geneva Conventions of 1949 form an essential complement to those of the ENMOD Convention, as they directly prohibit damage to the environment during armed conflict. **https://treaties.un.org/doc/Treaties/1978/10/19781005%2000-39%20AM/Ch_XXVI_01p.pdf**
Vienna Convention / Montreal Protocol	1985	Parties agree to adopt measures to reduce or prevent human activities that have or are likely to have adverse effects resulting from modification of the ozone layer.
Convention on Environmental Impact Assessment in a Transboundary Context (UNECE)	1991	The UN Convention on Environmental Impact Assessment in a Transboundary Context (under the UN Economic Commission for Europe 1991) calls for parties to undertake environmental impact assessment, potentially including for SRM activities. **https://unece.org/fileadmin/DAM/env/eia/documents/legaltexts/Espoo_Convention_authentic_ENG.pdf**
UNFCCC Article 3.3	1992	The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost.
UN Resolutions, draft resolutions, MEA/ COP decisions		
CBD - Decision X/33	2010	"Ensure. . . in the absence of science-based, global, transparent and effective control and regulatory mechanisms for geo-engineering. . . that no climate-related geoengineering 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, except for small scale scientific research studies that would be conducted in a controlled setting. . ."

UNEP/CBD/SBSTTA/16/INF/28	2012	Impact of Climate-related Geoengineering on Biological Diversity. Note by the Executive Secretary – Chapter 4: Potential impacts on biodiversity of generic SRM that causes uniform dimming. **https://sustainabledevelopment.un.org/content/documents/1740cbd2.pdf**
London Protocol Amendment on Marine Geoengineering	2013	Contracting Parties' concern about the potential impacts of ocean fertilization and other marine geoengineering activities on the marine environment, and their 'determination' to put in place 'a science based, global, transparent, and effective control and regulatory mechanism for such activities'. The London Protocol amendment on marine geoengineering seeks to establish a stable, legally-binding framework for the regulation of marine geoengineering, while also allowing for regulatory flexibility and adaptability to respond to new scientific and technological proposals that may adversely affect the marine environment in the future based on a precautionary approach. 'Marine geoengineering' is defined in the amendment as a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and its impacts, and that have the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe.
Draft resolution on Geoengineering for UNEA-4	2019	*Draft Resolution* for consideration for the 4th United Nations Environment Assembly. (***This draft resolution*** was put forward by Burkina Faso, Federated States of Micronesia, Georgia, Liechtenstein, Mali, Mexico, Montenegro, Niger, Republic of Korea and Senegal but **was not tabled**)
The Montreal Protocol Decision XXXI/2: Area of focus for 2022 Scientific Assessment Panel	2021	Potential areas of focus for the 2022 quadrennial reports of the Scientific Assessment Panel, the Environmental Effects Assessment Panel and the Technology and Economic Assessment Panel: "…An assessment of information and research related to solar radiation management and its potential effect on the stratospheric ozone layer".
Security Council SC/14732 (*Draft resolution*)	Dec 2021	Security Council Fails to Adopt Resolution Integrating Climate-Related Security Risk into Conflict-Prevention Strategies. The Security Council today, in a contentious meeting, rejected a draft resolution that would have integrated climate-related security risk as a central component of United Nations conflict prevention strategies aiming to help counter the risk of conflict relapse.
General Assembly Resolution A/76/473, para. 12	2021	76/112. Protection of the atmosphere – Resolution adopted by the General Assembly on 9 December 2021 [on the report of the Sixth Committee (A/76/473, para. 12)]. Guideline 7 - Intentional large-scale modification of the atmosphere Activities aimed at intentional large-scale modification of the atmosphere should only be conducted with prudence and caution, and subject to any applicable rules of international law, including those relating to environmental impact assessment.
Human Rights Council A/HRC/RES/48/14, para. 6	2022	48/14. Mandate of the Special Rapporteur on the promotion and protection of human rights in the context of climate change [Resolution adopted by the Human Rights Council on 8 October 2021] Paragraph 6 – Requests the Advisory Committee of the Human Rights Council to conduct a study and to prepare a report, in close cooperation with the Special Rapporteur, on the impact of new technologies for climate protection on the enjoyment of human rights, and to submit the report to the Council at its fifty-fourth session.

UN
environment
programme