Strengthening regional capacities to address the risk of and from overshooting 1.5°C global warming in Latin America and the Caribbean

Background paper

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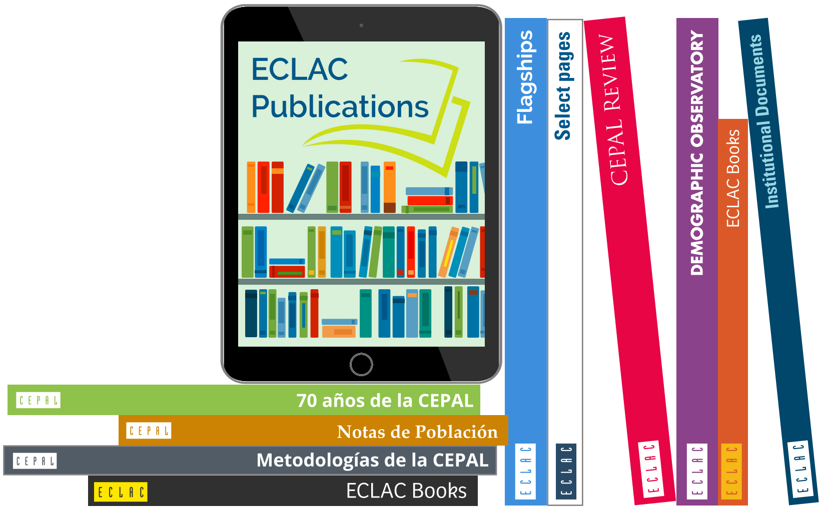

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Introductory note

The main objective of this background paper is to raise awareness and support Latin American and Caribbean (LAC) governments and non-state actors to strengthen their capacities to engage in and/or lead global conversations on how to manage the risk of temporary overshoot and the role -if any- of Solar Radiation Modification (SRM) in the context of achieving and safeguarding delivery of the Sustainable Development Goals (SDGs). This document was prepared by Fundación Torcuato Di Tella (FTDT), funded by the Carnegie Climate Governance Initiative (C2G), and produced in collaboration with the United Nations Economic Commission for Latin America and the Caribbean (ECLAC).

Abstract

According to recent modelling of global emission pathways, global average temperature rise is increasingly likely to exceed 1.5°C during the 21st century (IPCC 2021). According to the United Nations Framework Convention on Climate Change (UNFCCC), Nationally Determined Contributions (NDCs) embody efforts by each country to reduce national greenhouse gas emissions and adapt to the impacts of climate change[1]. Moreover, the emissions gap between NDCs and pathways that limit warming to 1.5°C with no or limited overshoot, is substantial. Moreover, the scenarios consistent with the 2°C and 1.5°C goals at the Latin America and the Caribbean (LAC) regional level involve a 39% and 55% reduction with respect to Business as Usual (BAU) (ECLAC 2022). LAC's actual yearly mitigation investment flows lag behind the average annual needs by a factor between x4 and x8 (lower and upper range).

Under this overall scenario of increasingly likely overshoot with its risks and challenges, an approach known as Solar Radiation Modification (SRM) has gained attention in the scientific community. During the last decade, SRM has begun to be considered by some as a possible "emergency option" with the potential to offset warming within one or two decades and ameliorate some climate hazards, whilst at the same time introducing new and complex risks (Kravitz et al. 2021). SRM approaches (also known solar radiation management) aim to address a symptom of climate change (global warming), by allowing more heat to escape the earth's atmosphere or reflecting more solar radiation into space, and thereby cooling the Planet.

The main SRM approaches include: Stratospheric Aerosol Injection (SAI), Marine Cloud Brightening (MCB), Cirrus Cloud Thinning (CCT), Ground-Based Albedo Modifications (GBAM), and Ocean Albedo Change (OAC). Although still fragmented and with considerable knowledge gaps, SRM research is progressing over time.

In this paper, we review the status of knowledge of related key issues: firstly, the IPCC findings on the likelihood of overshoot of 1.5°C and the challenges of managing the risks of and from a temporary overshoot; the status of the mitigation and adaptation response in the LAC region against the progress of regional NDCs; progress made in research regarding the different SRM approaches, its science basis and readiness. Moreover, the knowledge of possible risks and benefits of SRM to support decision making and the governance dimensions to implement these approaches. Finally, a set of potential options is presented for the next steps.

There is a growing consensus among some policy makers and academia that there are significant international governance gaps in relation to SRM approaches, representing a potential key area of future work. In this context, further trans-disciplinary research and multilateral/global discussions may be required to inform decisions about the use or non-use of SRM.

Main Study Areas: Climate change, public policies, governance, environment, science, technology and innovation, SDGs, risk management, NDCs, temperature overshoot, IPCC pathways, climate-altering technologies, solar radiation modification, Latin America and the Caribbean.

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[1] The Paris Agreement (Article 4, paragraph 2) requires each Party to prepare, communicate and maintain successive nationally determined contributions (NDCs) that it intends to achieve.

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List of acronyms

AgMIP	Agricultural Model Intercomparison and Improvement Project
AR6	Assessment Report #6
AR6 SYR	AR6 Synthesis Report
BAU	Business As Usual
C2G	Carnegie Climate Governance Initiative
CBD	Convention on Biological Diversity
CCT	Cirrus Cloud Thinning
CIMA	Centro de Investigaciones del Mar y la Atmósfera
COMEST UNESCO	World Commission on the Ethics of Scientific Knowledge and Technology
Conacyt	National Council of Science and Technology
CP	Cool pavements
CUpEx	Chilean Upwelling Experiment
DEGREES	DEveloping country Governance REsearch and Evaluation for SRM
EbA	Ecosystem-based Adaptation
ECLAC	Economic Commission for Latin America and the Caribbean
ENMOD	Environmental Modification Convention
ERF	Effective Radiative Forcing
GBAM	Ground-Based Albedo Modifications
GeoMIP	Geoengineering Model Intercomparison Project
GHG	Greenhouse gases
GLENS	Geoengineering Large Ensemble
GtCO2-eq yr.–1	Giga tons of carbon dioxide equivalent per year
IAI	Inter-American Institute for Global Change Research
IFAECI	Instituto Franco-Argentino sobre Estudios de Clima y sus Impactos
IFPI	Brazilian Instituto Federal do Piauí
INPE	Instituto Nacional de Pesquisas Espaciais
INPs	Ice nucleation processes
IPCC	Intergovernmental Panel on Climate Change
LAC	Latin American and Caribbean
LC/LP	London Convention/London Protocol
LULUCF	Land use, land use-change and forestry
MCB	Marine Cloud Brightening
MCT	Mixed-phase regime cloud thinning
NASEM	US National Academies of: Sciences, Engineering, Medicine
NCAR	National Center for Atmospheric Research
NDCs	Nationally Determined Contributions

NOAA	US National Oceanic and Atmospheric Administration
OAC	Ocean Albedo Change
OSTP	White House Office of Science and Technology Policy
PARC	Palo Alto Research Center
RRAP	Reef Restoration and Adaptation science Program
RRM	Retro-reflective materials
SABRE	Stratospheric Aerosol processes, Budget and Radiative Effects
SAI	Stratospheric Aerosol Injection
SATAN	Stratospheric Aerosol Transport and Nucleation
SbN	Solutions based in Nature
SCoPEx	Stratospheric Controlled Perturbation Experiment
SDGs	Sustainable Development Goals
Semarnat	Ministry of Environment and Natural Resources
SG	Solar Geoengineering
SIDS	Small Island Developing States
SO_2	Sulphur dioxide
SPICE	Stratospheric Particle Injection for Climate Engineering
SRM	Solar Radiation Modification
Tg	Teragram
UFRN	Universidade Federal do Rio Grande do Norte
UHI	Urban heat island
UNCLOS	United Nations Convention on the Law of the Sea
UNEA	United Nations Environment Assembly
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USD	US Dollars
VAMOS	Variability of the American Monsoon Systems
VOCALS-Rex	Ocean–Cloud–Atmosphere–Land Study Regional Experiment
WCRP	World Climate Research Programme
WG	Working Groups Reports
WGCM	Working Group on Coupled Modelling
Wm-2	Watts per square meters

Key findings and messages - A synthesis

A main finding of the IPCC AR6 (2021) is that modelled global emission pathways consistent with Nationally Determined Contributions (NDCs) announced prior to COP26 will likely exceed 1.5°C during the 21st century[2]. Focusing on the current decade, global emissions in 2030 under policies implemented by the end of the 2020s are projected at a median of 57 GtCO2-eq yr-1. If compared to those projections under the NDCs announced prior to COP26, there is a gap of 4 to 7 GtCO2-eq yr-1 (or about 7 to 12%), depending on unconditional elements or including conditional elements, indicating a considerable "implementation gap". In addition, a major source of concern is that the emissions gap between NDCs and pathways that limit warming to 1.5°C with no or limited overshoot, is in the range of 16 to 23 GtCO2-eq yr-1 in the best-case scenario, including conditional elements.

According to Climate Watch[3], Latin America and the Caribbean (LAC) region's GHG emissions, excluding Land use, land use-change and forestry (LULUCF), totalized 3.06 GtCO2eq in 2020, representing a 6.6% share in world's GHG emissions. Most of LAC countries signatories of the Paris Agreement (29 out of 33) have updated their original NDCs. In their updated NDCs, almost all LAC countries have identified the following sectors as priorities for mitigation actions: energy (electric power generation and the use of energy for transportation, industry and buildings), forestry and other land uses (FOLU) and agriculture. The business as usual (BAU) GHG emissions scenario by year 2030 for the LAC region is estimated at 3.80 GtCO2eq. The national mitigation commitments of the individual NDCs in its unconditional commitments account for 26% emissions reduction with respect to the BAU scenario, while the conditional commitments imply a 29% reduction (summing up 2.83 and 2.68 GtCO2eq respectively). The scenarios consistent with the 2°C and 1.5°C goals at the LAC regional level involve a 39% and 55% reduction with respect to the BAU, amounting to 2.25 and 1.65 GtCO2eq respectively (ECLAC 2022). LAC's actual yearly mitigation investment flows lag behind the average annual needs by a factor between x4 and x8 (lower and upper range).

Under this scenario of likely overshoot with its risks and challenges, and keeping in mind the key priority of scaling-up mitigation efforts (to be complemented with diverse carbon removal approaches), Solar Radiation Modification (SRM) approach has gained attention in the scientific community, particularly during the last decade where SRM is being considered as a possible "emergency option" that has the potential to offset warming within one or two decades and ameliorate some climate hazards, not without introducing new and complex risks (Kravitz et al. 2021). SRM technologies (also known as solar geoengineering – SG or solar radiation management) aim to address a symptom of climate change (global warming), by allowing more heat to escape the earth's atmosphere or reflecting more solar radiation into space, and thereby cooling the Planet.

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[2] Modelled global emission pathways consistent with NDCs announced prior to COP26 will likely exceed 1.5°C during the 21st century. Those pathways that then return warming to 1.5°C by 2100 with a likelihood of 50% or greater imply a temperature overshoot of 0.15°C–0.3°C (IIPCC AR6 WGIII)

[3] Climate Watch is an online platform designed to empower policymakers, researchers, media and other stakeholders with the open climate data, visualizations and resources they need to gather insights on national and global progress on climate change. Climate Watch is managed by World Resources Institute. It is a contribution to the NDC Partnership. For more information: https://www.climatewatchdata.org/

The main SRM approaches include: Stratospheric Aerosol Injection (SAI), Marine Cloud Brightening (MCB), Cirrus Cloud Thinning (CCT), Ground-Based Albedo Modifications (GBAM), and Ocean Albedo Change (OAC). SAI is the most researched SRM approach and there is more confidence for SAI than for other SRM approaches regarding the potential reduction in surface temperatures and amelioration of some climate change risks (IPCC AR6 WGIII 2022). Although still fragmented and with considerable knowledge gaps, SRM research is slowly progressing. UNEP (2023) finds that there is little information on the risks of SRM and limited literature on the environmental and social impacts resulting from the application of these technologies.

On the other hand, several small-scale outdoor experiments were announced in the last decade, most of them cancelled or halted and only a few of them proceeding with limited scope, and none of them of them involving any measurable local climate modification. No operational large-scale SRM deployments were announced yet, nor have they taken place at the time of this paper. None of the SRM techniques is somewhere near to readiness for deployment, neither at the local nor the global reach, and, equally, neither at the small-scale nor at the large-scale. There are several key areas of further research and experimentation identified, looking forward at those closing the existing gap regarding technology readiness.

According to the IPCC, SRM deployment could offset some climate risks and reduce global warming (IPCC AR6 WGIII, 2022), but it would also introduce a set of new climates, environmental, ecosystems, economic, human, social and security risks. In addition, there are also benefits of potential SRM deployment as mentioned in the literature. The public and policymakers may encounter heuristics obstacles and biases that influence decision making regarding SRM implementation, and a risk-risk framework can contribute to strengthening the possibility of addressing the full portfolio of important impacts and help guide policies toward socially desirable outcomes informed by science (Felgenhauer et al. 2022).

Several international entities, protocols, treaties and multilateral agreements contain provisions applicable to SRM, partially covering the topic but none of them comprehensively (IPCC AR6 WGIII 2022; UNEP 2023; Geden, 2019), including the UN Convention on Biological Diversity, the UN Convention on the Law of the Sea, the Environmental Modification Convention (ENMOD), London Convention and London Protocol (LC/LP) and the Vienna Convention on the Protection of the Ozone Layer and its Montreal Protocol, UNESCO World Commission on the Ethics of Scientific Knowledge and Technology (COMEST), UN Convention on Environmental Impact Assessment in a Transboundary Context (UNECE), among the most relevant ones (Bodansky 2013; Jinnah and Nicholson 2019; Reynolds 2019; Geden, 2019).

There is a growing consensus that there are significant international governance gaps in relation to SRM approaches, being one of the key areas of future work considering the recommendations of a number of major documents recently disseminated on this field. Regarding the Latin American and Caribbean region, the lack of international and national governance schemes is also evident.

After a succinct review of recommendations on next steps from the scientific community and the international agencies addressing the risks of and from overshoot with a particular focus on SRM, a list of potential options for next steps focused on Latin American and the Caribbean region considered key are listed below:

- Managing the risks posed by climate change primarily requires addressing its root causes: the increased concentration of greenhouse gases in the atmosphere, and the consequent impacts this is having on human systems and ecosystems in the LAC region. To address these root causes, **capacity-building efforts must primarily focus on increased and urgent action across the region to reduce atmospheric greenhouse gas emissions, and investment in adaptation and building resilience** to the climate change impacts that are already unavoidable.

- In addition to building capacity for increased mitigation and adaptation, recognizing the increasing risk of and from temperature overshoot, **consideration could also be given to strengthening regional understanding of potential 'emergency' options such as Solar Radiation Modification (SRM)** that are coming under increasing scrutiny internationally.
- **Strengthening regional capacity for, and delivery of scientific research into the potential impacts of climate overshoot scenarios, and of SRM technologies (if ever implemented) – on low- and middle-income countries** could help to address issues around ethics, equity and consent relating to SRM in decision-making and governance.
- **Ensuring decision-making and governance is informed by indigenous peoples and local communities' knowledge and those of other affected or underrepresented groups such as young people** could help to address issues around ethics, equity and consent relating to SRM.
- **Building capacity for greater transdisciplinary integration in research, linking physical, social, and ethical dimensions, and enabling robust public engagement** will help to address the complex and interacting uncertainties and knowledge gaps around SRM.
- **Building capacity for undertaking risk-risk assessments in climate policy analysis and decision-making concerning SRM could help enable a more comprehensive assessment**, **comparison, and management of risks** associated with climate change, emissions reductions, carbon removal, adaptation, and SRM itself. This could also help to address issues around ethics, equity and consent relating to SRM.
- **Continued study and quantifying of the potential impacts and risks of and from a likely temperature overshoot for the LAC region** during the next decades could provide important intelligence to inform decision-making and strengthen preparedness to better manage risks.
- **Monitoring the status of SRM-related research and knowledge in the region and internationally** could help to strengthen the regional evidence-base for decision-making and identify knowledge gaps to be addressed in future research.
- **Identifying SRM-related policy questions for researchers in the LAC region to address,** could help to ensure science-policy interactions that effectively target and address knowledge gaps important for the region.

- **Collaborating with international partners to downscale climate modelling data to strengthen regional climate and SRM impact analysis** could help to strengthen both regional and international understanding of potential SRM impacts.

- **Encouraging LAC region participation and collaboration within the international SRM scientific research community**, e.g. through discussion workshops; developing regional models and simulations, among others could help build relationships and networks to strengthen both regional and international understanding and capacity.

- **Enhancing qualitative and quantitative understanding of the risks to the LAC region - in terms of environment, ecosystems, health, social, security and other dimensions - posed by a potential implementation of SRM approaches in overshoot scenarios** could help to ensure decision-making domestically, regionally, and internationally aligned with regional priorities.

- **Explore the possible financial sources available to fund a comprehensive transdisciplinary research program to better understand the potential of SRM as an emergency option and consequent impacts in the LAC region.**

- **Strengthening regulatory capacity across the region to ensure any SRM scientific research undertaken in the region is considered and implemented in a responsible way, and in compliance with agreed regional and international governance processes and frameworks** will help to ensure knowledge gaps are addressed in a socially acceptable and responsible manner.

- **Identifying and assessing diverse proposals and options for international and regional governance processes around SRM that best consider LAC interests and circumstances,** and climate political stance will help to ensure that future governance is well aligned with regional priorities.

Section A - Background Analysis

I. On Overshoot

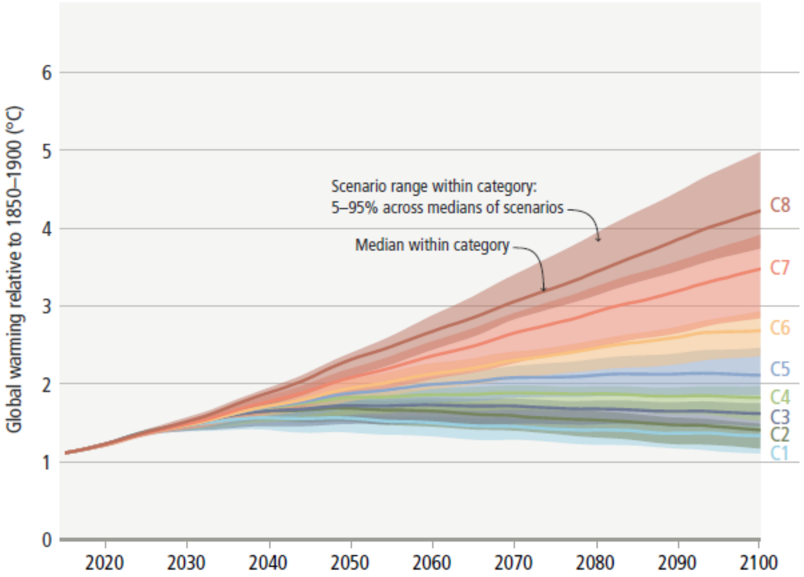
A. IPCC findings on the likelihood of overshoot of 1.5°C

The Intergovernmental Panel on Climate Change (IPCC), the United Nations body for assessing the science related to climate change, has virtually finalized its sixth assessment cycle during which it produced its sixth Assessment Report (AR6). The previous cycle and report (AR5) were concluded in 2014. The AR6 includes contributions from three Working Groups (WGI 2021 – The Physical Science Basis, WGII 2022 – Impacts, Adaptation and Vulnerability, WGIII 2022 – Mitigation of Climate Change), three Special Reports (2018 Global Warming of 1.5°C, 2019 Climate Change and Land, 2019 The Ocean and Cryosphere in a Changing Climate) and a Synthesis Report (AR6 SYR 2023).

An overshoot is defined as a pathway of emissions forcing global warming to exceed a certain threshold (in this case the goal of 1.5°C global warming under the Paris Agreement) and then returning to or going below that level before the end of a specified period of time (in this case before 2100). The duration and magnitude of the overshoot can vary. In most cases in the literature the overshoot occurs over a period of at least one decade and up to several decades. A "limited overshoot" refers to exceeding 1.5°C by up to about 0.1°C and for up to several decades, while a "high overshoot" refers to temporarily exceeding 1.5°C global warming by 0.1°C to 0.3°C for up to several decades.

A wide range of global emission pathways and scenarios were modelled in IPCC AR6 (2022) and were classified in categories C1 to C8 (some of them with variations in sub-categories). Only category C1 comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood of greater than 50% and reach or exceeded warming of 1.5°C during the 21st century with a likelihood of 67% or less. In this C1 scenario, the likelihood of peak global warming staying below 1.5°C is estimated at only 38%. On the other end of category classification, category C8 models include pathways that exceed 4°C warming.

Graph 1: Median global warming across IPCC AR6 scenarios in categories C1 to C8

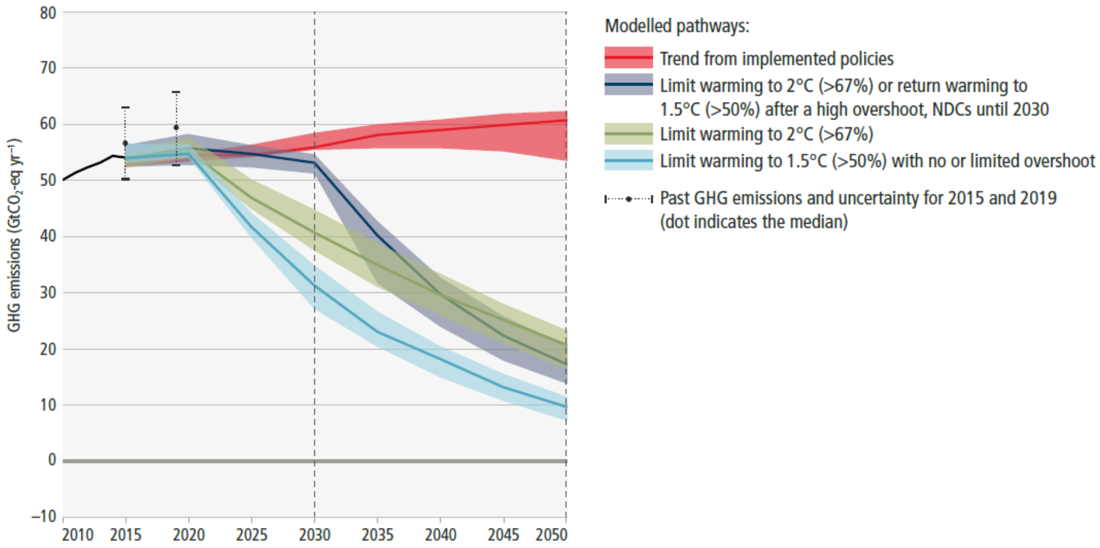


Source: IPCCAR6 WGIII (2022), Box SPM.1, Figure 1

The main finding in IPCC AR6 (2022) is that modelled global emission pathways consistent with Nationally Determined Contributions (NDCs) announced prior to COP26 will likely exceed 1.5°C during the 21st century. IPCC AR6 Synthesis report (2023) asserts that modelled pathways consistent with the continuation of policies implemented by the end of 2020 lead to global warming of 3.2 [2.2-3.5] °C (5–95% range) by 2100. In order to achieve the pathway of "limiting warming to 1.5°C (>50%) with no or limited overshoot", an 84% median GHG emissions reduction is needed compared to 2019 GHG emissions levels, assuming a rapid acceleration of mitigation efforts across all sectors after 2030. Moreover, according to AR6 those pathways that then return warming to 1.5°C by the end of the century with a likelihood of 50% or greater, imply a temperature overshoot in the range of 0.15°C to 0.3°C (such magnitudes being considered a high overshoot).

Latest IPCC AR6 publications (WGIII from April 2022 and SYR from March 2023), conclude that in comparison to IPCC AR6 Special Report 1.5°C from 2018, the likelihood of limiting warming to 1.5°C with no or limited overshoot has dropped because global GHG emissions have risen since the year 2017, therefore leading (with medium confidence) to higher near-term emissions towards 2030 and higher cumulative CO_2 emissions until the time net zero is achieved.

Graph 2: Global GHG emissions pathways in IPCC AR6



Source: IPCC AR6 WGIII (2022), Figure SPM.4; IPCC AR6 SYR (2023) Figure 2.5

Focusing on the current decade, global emissions in 2030 under policies implemented by the end of the 2020s are projected at a median of 57 GtCO2-eq yr-1. If compared to those projections under the NDCs announced prior to COP26, there is a gap of 4 to 7 GtCO2-eq yr-1 (or 7 to 12%), depending on unconditional elements or including conditional elements, indicating a considerable "implementation gap". Even more concerning, the emissions gap between NDCs and pathways that limit warming to 1.5°C with no or limited overshoot, is in the range of 16 to 23 GtCO2-eq yr-1 in the best-case scenario including conditional elements.

Table 1: Projected global emissions in 2030 associated with policies implemented by the end of 2020 and NDCs announced prior to COP26, and associated emissions gaps

Projected global emissions in 2030	Implied by policies implemented by the end of 2020 (GtCO2-eq yr.–1)	Implied by NDCs announced prior to COP26 (GtCO2-eq yr.–1)	
		Unconditional elements	Including conditional elements
*Median projected global emissions [min–max] **	57 [52–60]	53 [50–57]	50 [47–55]
Implementation gap between implemented policies and NDCs (median)	-	4	7

Projected global emissions in 2030	Implied by policies implemented by the end of 2020 (GtCO$_2$-eq yr.–1)	Implied by NDCs announced prior to COP26 (GtCO$_2$-eq yr.–1)	
		Unconditional elements	Including conditional elements
Emissions gap between NDCs and pathways that limit warming to 2°C (>67%) with immediate action	-	10-16	6-14
Emissions gap between NDCs and pathways that limit warming to 1.5°C (>50%) with no or limited overshoot with immediate action	-	19-26	16-23

Source: IPCC AR6 SPM Table SPM.1; IPCC AR6 SYR Table 2.2

B. Challenges of managing the risks of and from a temporary overshoot

In the case of overshoot pathways, IPCC AR6 (2022) finds (high confidence) there will be increased climate-related risk, with many human and natural systems facing additional severe risks, compared with remaining below 1.5°C. Depending on the magnitude and duration of overshoot, some impacts will cause release of additional greenhouse gases (medium confidence) and some will be irreversible, even if global warming is reduced (high confidence).

AR6 also anticipates that an overshoot period this century, will result in irreversible impacts on certain ecosystems with low resilience (high confidence), such as polar, mountain, and coastal ecosystems impacted by icesheet, glacier melt, or by accelerating and higher sea level rise.

Another consequence of a potential overshoot pathway is that with high confidence it substantially increases risk of carbon stored in the biosphere being released into the atmosphere due to increases in processes such as wildfires, tree mortality, insect pest outbreaks, peatland drying and permafrost thaw (IPCC AR6 WGII 2022, Tech Summary).

IPCC AR6 SYR (2023) warns that many climate-related risks are assessed to be higher than in previous assessments, and projected long-term impacts are up to multiple times higher than currently observed. Moreover, these multiple climatic and non-climatic risks are expected to interact, resulting in compounding and cascading risks across sectors and regions (Section C - Annex a of this paper). In particular for Central and South America, the key regional risks identified in IPCC AR6 SYR (2023) and IPCC AR6 WGII (2022) include the following:

- Risk to water security
- Severe health effects due to increasing pandemics, in particular vector-borne diseases
- Coral reef ecosystems degradation due to coral reef bleaching
- Risks to food security due to frequent/extreme droughts

- Damages to life and infrastructure due to floods, landslides, sea level rise, storm surges and costal erosion
- Risk of species losses (especially in the Amazon region)
- Risk of turning Amazon forest from a carbon sink into a net carbon source, due to periodic droughts bringing high tree mortality rates and basin-wide reductions in forest productivity

The larger the magnitude of the likely overshoot, the greater the amount of negative net CO_2 emissions required to return to a particular level of warming. Losses and damages, including adverse impacts in Central and South America (and other regions like Africa, Asia, Arctic, Small Island Developing States - SIDS), are projected to increase without rapid, extensive, and sustained mitigation and accelerated adaptation actions, and they will have a disproportionate effect on the most vulnerable populations, as established by the IPCC with high confidence.

All mitigation strategies confront obstacles in implementation, including technology risks, scaling, and costs (high confidence). Developing countries, notably the least developed ones, lag behind in the adoption of low-emission technologies, partly because of weaker enabling conditions for climate action, including limited finance, technology development and application, and capacity. The insufficiency of financing, political frameworks and incentives for finance are critical factors reinforcing implementation gaps for both mitigation and adaptation.

IPCC AR6 SYR (2023) warns that (with high confidence) there is a rapidly shrinking opportunity available to ensure a sustainable and habitable future for us all. A prompt and coordinated global action on adaptation and mitigation is thus crucial to avoid missing a brief and quickly vanishing opportunity to secure a sustainable and habitable future for all, with very high confidence.

Under this scenario of likely overshoot with its risks and challenges, and keeping in mind the key priority of scaling-up mitigation efforts (to be complemented with diverse carbon removal approaches), Solar Radiation Modification (SRM) approach has gained attention in the scientific community, particularly during the last decade where SRM is being considered as a possible "emergency option" that has the potential to offset warming within one or two decades and ameliorate some climate hazards, not without introducing new and complex risks (Kravitz et al. 2021). SRM technologies (also known as solar geoengineering – SG or solar radiation management) aim to address a symptom of climate change (global warming), by allowing more heat to escape the earth's atmosphere or reflecting more solar radiation into space, and thereby cooling the Planet. Section A.III of this paper dives deeper into different SRM approaches, the status of science and their readiness.

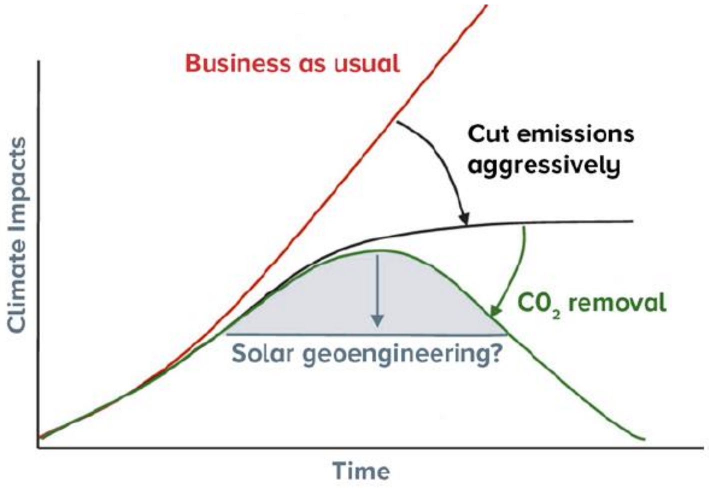
According to the US National Academies of Sciences, Engineering, Medicine (NASEM 2021) there are four main scenarios under which SRM may be deployed:

- "Peak shaving" under idealized conditions of modest climate overshoot and capacity for sustained effective governance (MacMartin et al., 2018b; Tilmes et al., 2020).
- Deployment in "climate emergency" conditions of continued rising GHG concentration, increasingly severe risks, and uncertain capacity for sustained effective governance.

- Unilateral deployment by an actor seeking to use solar geoengineering as a means to control climate or with other unknown intentions, without informing others or abiding by any international governance norms that may be established (Victor, 2019)
- Deployment under conditions of competing objectives among nations regarding temperature and impact goals (Frumhof and Stephens, 2018).

The following Figure indicates a scenario in which SRM is used to "shave off" the peak of climate impacts corresponding to warming temporarily exceeding 2°C before aggressive greenhouse gas mitigation and CO_2 removal result in lower greenhouse gas concentrations.

Graph 3: Peak-shaving SRM deployment scenario

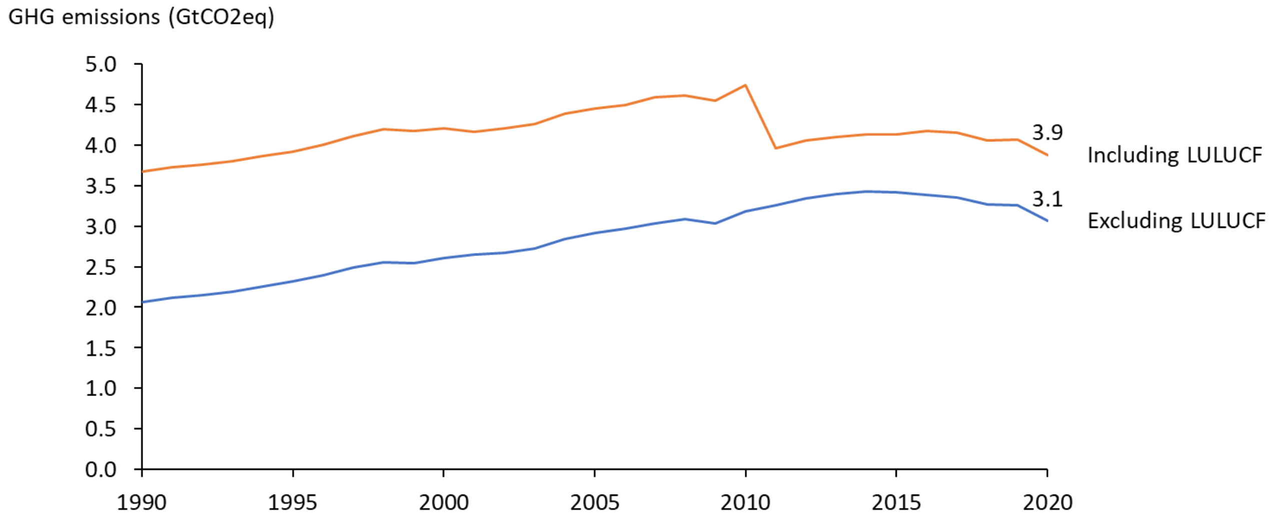


Source: MacMartin et al 2018

II. Status of the mitigation and adaptation response in the LAC region: progress of regional NDCs and related forecasts

According to Climate Watch figures, Latin America and the Caribbean region GHG emissions, excluding Land use, land use-change and forestry (LULUCF), totalized 3.06 GtCO2eq in the year 2020, representing a 6.6% share in world's GHG emissions. If LULUCF emissions are included, LAC GHG emissions increase to 3.88 GtCO2eq for the year 2020. Latest figures for the year 2021 from Potsdam Institute for Climate Impact Research (PIK), show a similar level of emissions of 3.24 GtCO2eq excluding LULUCF for the LAC region.

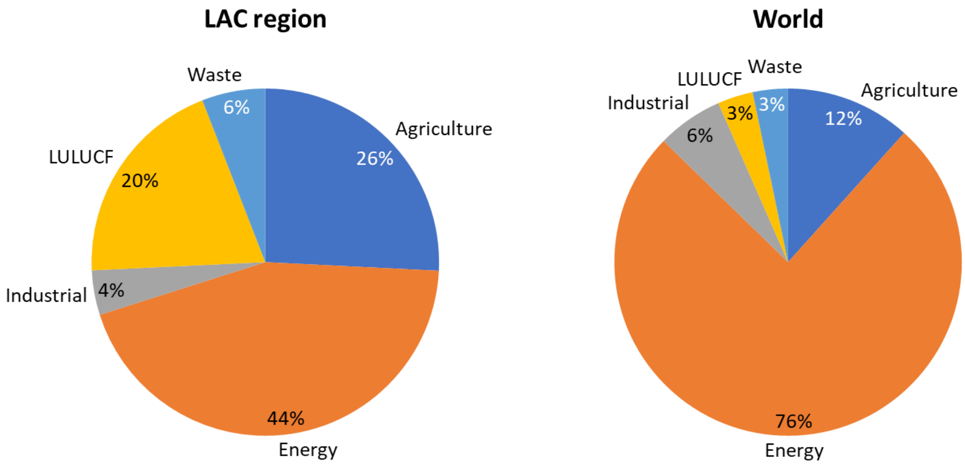
Graph 4: Historical evolution of LAC region GHG emissions



Source: Own elaboration based on Climate Watch database

In the LAC region, the consumption of fossil fuels produces 44% of total GHG emissions (vs a 76% share in World), mainly through its use for transportation, followed by electricity generation. Agricultural and livestock activities and land use change, closely related activities, are also important sources of emissions in the region, contributing with 26% and 20% of total LAC emissions, respectively. Waste and industrial processes produce approximately the remaining 10% of LAC emissions (Samaniego et al 2022).

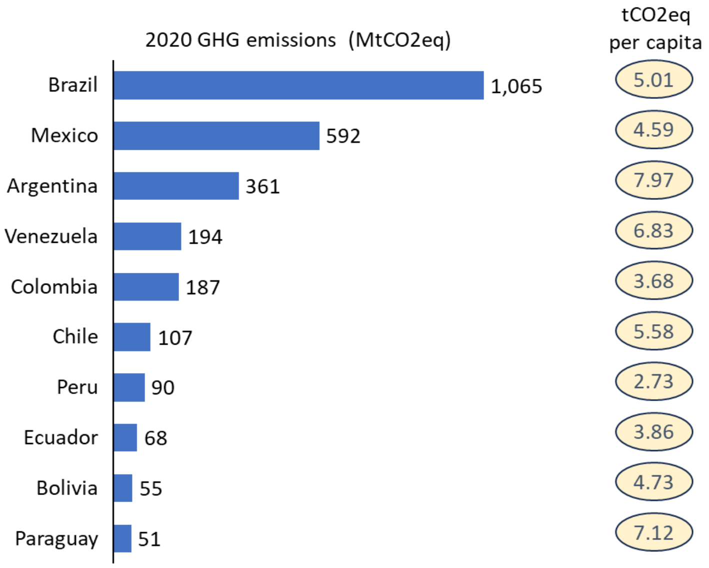
Graph 5: LAC region vs World GHG emissions by sector - *2019*



Source: Own elaboration based on Climate Watch database

Brazil, Mexico, and Argentina are the top 3 countries in GHG emissions in the LAC region, accounting for 64% of the regional emissions. Venezuela, Colombia, Chile, Peru, Ecuador, Bolivia and Paraguay complete the Top 10 LAC GHG emitters.

Graph 6: Top10 LAC countries by GHG emissions



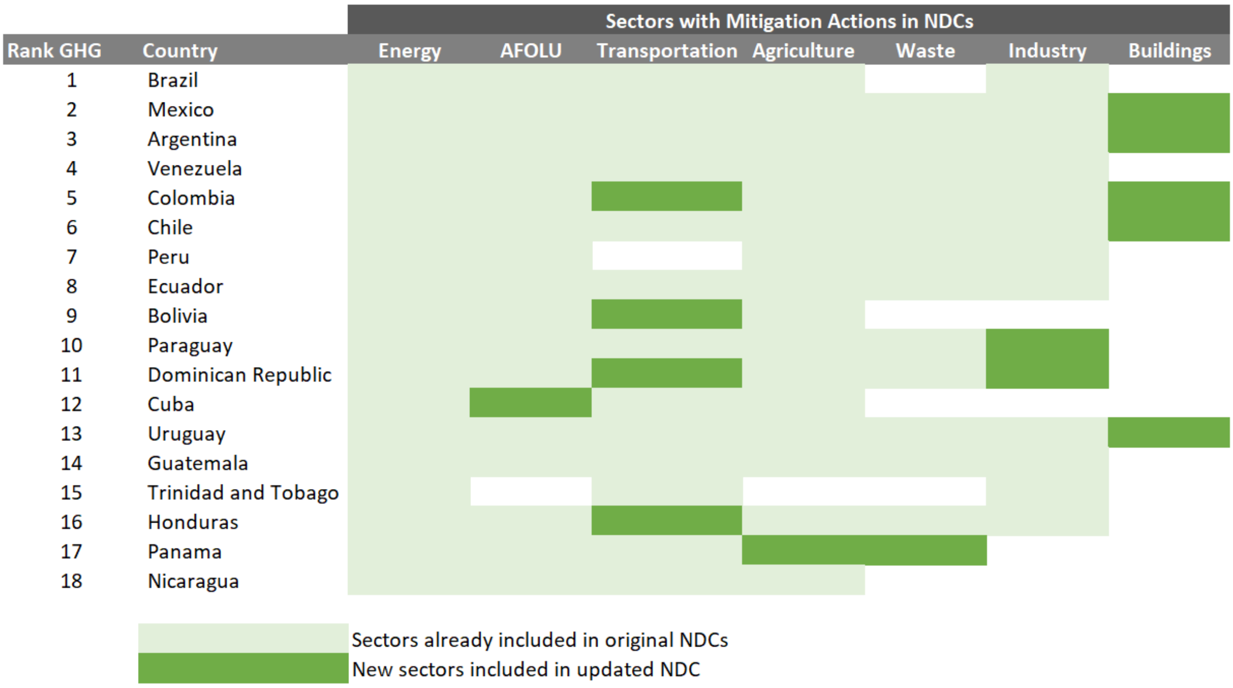
Source: Own elaboration based on Climate Watch database

ECLAC reported in 2022 (with data by mid-2021) that 17 out of 33 LAC countries signatories of the Paris Agreement had updated their original NDCs (Samaniego et al 2022). Currently, with data by May 2023, there are already 29 out of 33 LAC countries with updated NDCs, accounting for 97% of regional GHG emissions. Several countries including Uruguay, Bolivia, Mexico, Brazil, Guatemala, Haiti, Dominica and El Salvador have updated their NDCs during year 2022. Only Ecuador, Guyana, Saint Vincent and the Grenadines and Trinidad and Tobago still rely on their original and first NDCs.

1. *Mitigation*

In their updated NDCs, almost all LAC countries have identified the following sectors as priorities for mitigation actions: energy (electric power generation and the use of energy for transportation, industry and buildings), forestry and other land uses (FOLU) and agriculture (Samaniego et al 2022). The NDC updates have been helpful in adding and reinforcing less decisive sectors like waste management, residential and commercial buildings and transportation (Samaniego et al 2022). Few countries report a quantified sectoral breakdown of mitigation goals, which makes it difficult to identify the relative contribution of each sector to the national mitigation goal (Samaniego et al 2022).

Graph 7: Sectors with Mitigation Actions in LAC counties NDCs



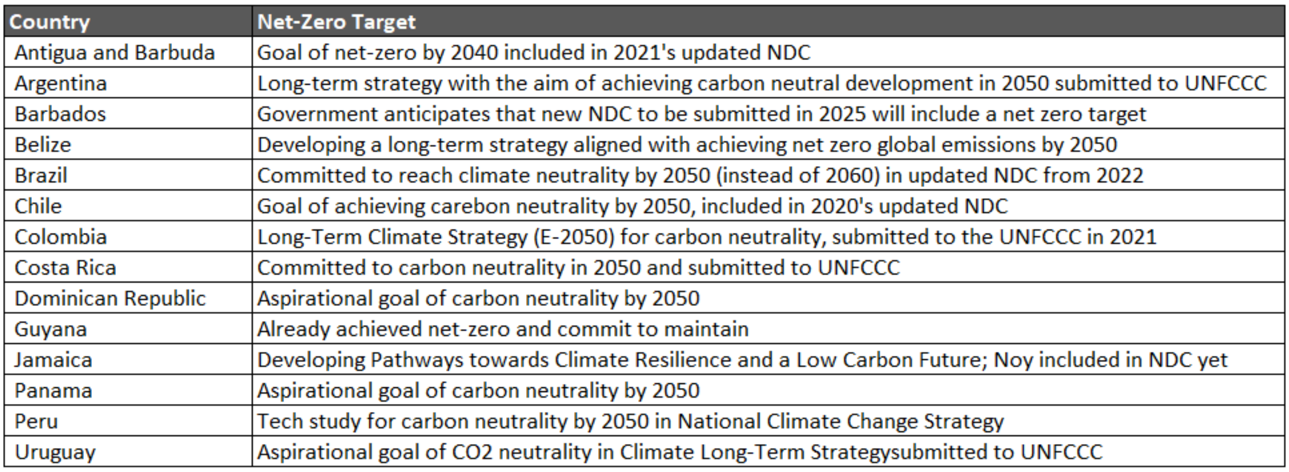
		Sectors with Mitigation Actions in NDCs						
Rank GHG	Country	Energy	AFOLU	Transportation	Agriculture	Waste	Industry	Buildings
1	Brazil	▨	▨	▨	▨		▨	
2	Mexico	▨	▨	▨	▨	▨	▨	🟩
3	Argentina	▨	▨	▨	▨	▨	▨	🟩
4	Venezuela	▨	▨	▨	▨	▨	▨	
5	Colombia	▨	▨	🟩	▨	▨	▨	🟩
6	Chile	▨	▨	▨	▨	▨	▨	🟩
7	Peru	▨	▨		▨	▨	▨	
8	Ecuador	▨	▨	▨	▨	▨	▨	
9	Bolivia	▨	▨	🟩	▨			
10	Paraguay	▨	▨	▨	▨	▨	🟩	
11	Dominican Republic	▨	▨	🟩	▨	▨	🟩	
12	Cuba	▨	🟩	▨	▨			
13	Uruguay	▨	▨	▨	▨	▨	▨	🟩
14	Guatemala	▨	▨	▨	▨	▨	▨	
15	Trinidad and Tobago	▨		▨			▨	
16	Honduras	▨	▨	🟩	▨	▨	▨	
17	Panama	▨	▨	▨	🟩	🟩		
18	Nicaragua	▨	▨	▨	▨			

▨ Sectors already included in original NDCs
🟩 New sectors included in updated NDC

Source: Own elaboration based on Samaniego et al 2022 and ECLAC 2019

Another remarkable progress in climate ambition is the adoption of a goal and/or intended ambition for carbon neutrality by 2050 by 12 LAC countries, representing over 60% of regional emissions. For example, Costa Rica has formally committed to carbon neutrality by 2050 and communicated it to the UNFCCC, including an action plan for its commitment. Chile has included the carbon neutrality objective in its Framework Law on Climate Change (approved by the Chilean Congress in March 2022), and explicitly refers to this goal in its updated NDC. Moreover, the updated NDCs of Argentina, Colombia, Panama, and the Dominican Republic also refer to an intended ambition to achieve carbon neutrality, without this having become a legally binding commitment momentarily (Samaniego et al 2022).

Table 2: Net Zero Commitments and Ambitions by LAC Countries



Country	Net-Zero Target
Antigua and Barbuda	Goal of net-zero by 2040 included in 2021's updated NDC
Argentina	Long-term strategy with the aim of achieving carbon neutral development in 2050 submitted to UNFCCC
Barbados	Government anticipates that new NDC to be submitted in 2025 will include a net zero target
Belize	Developing a long-term strategy aligned with achieving net zero global emissions by 2050
Brazil	Committed to reach climate neutrality by 2050 (instead of 2060) in updated NDC from 2022
Chile	Goal of achieving carebon neutrality by 2050, included in 2020's updated NDC
Colombia	Long-Term Climate Strategy (E-2050) for carbon neutrality, submitted to the UNFCCC in 2021
Costa Rica	Committed to carbon neutrality in 2050 and submitted to UNFCCC
Dominican Republic	Aspirational goal of carbon neutrality by 2050
Guyana	Already achieved net-zero and commit to maintain
Jamaica	Developing Pathways towards Climate Resilience and a Low Carbon Future; Noy included in NDC yet
Panama	Aspirational goal of carbon neutrality by 2050
Peru	Tech study for carbon neutrality by 2050 in National Climate Change Strategy
Uruguay	Aspirational goal of CO2 neutrality in Climate Long-Term Strategysubmitted to UNFCCC

Source: Own elaboration based on Samaniego et al 2022, Climate Watch Country Profile and NDCs

The GHG emissions BAU scenario by year 2030 for the LAC region is estimated at 3.80 GtCO2eq. The national mitigation commitments of the individual NDCs in its unconditional commitments represent a 26% emissions reduction with respect to the BAU scenario, while the conditional commitments imply a 29% reduction (summing up 2.83 and 2.68 GtCO2eq respectively). The scenarios consistent with the 2°C and 1.5°C goals at the LAC regional level involve a 39% and 55% reduction with respect to the BAU, amounting to 2.25 and 1.65 GtCO2eq respectively (Samaniego et al 2022).

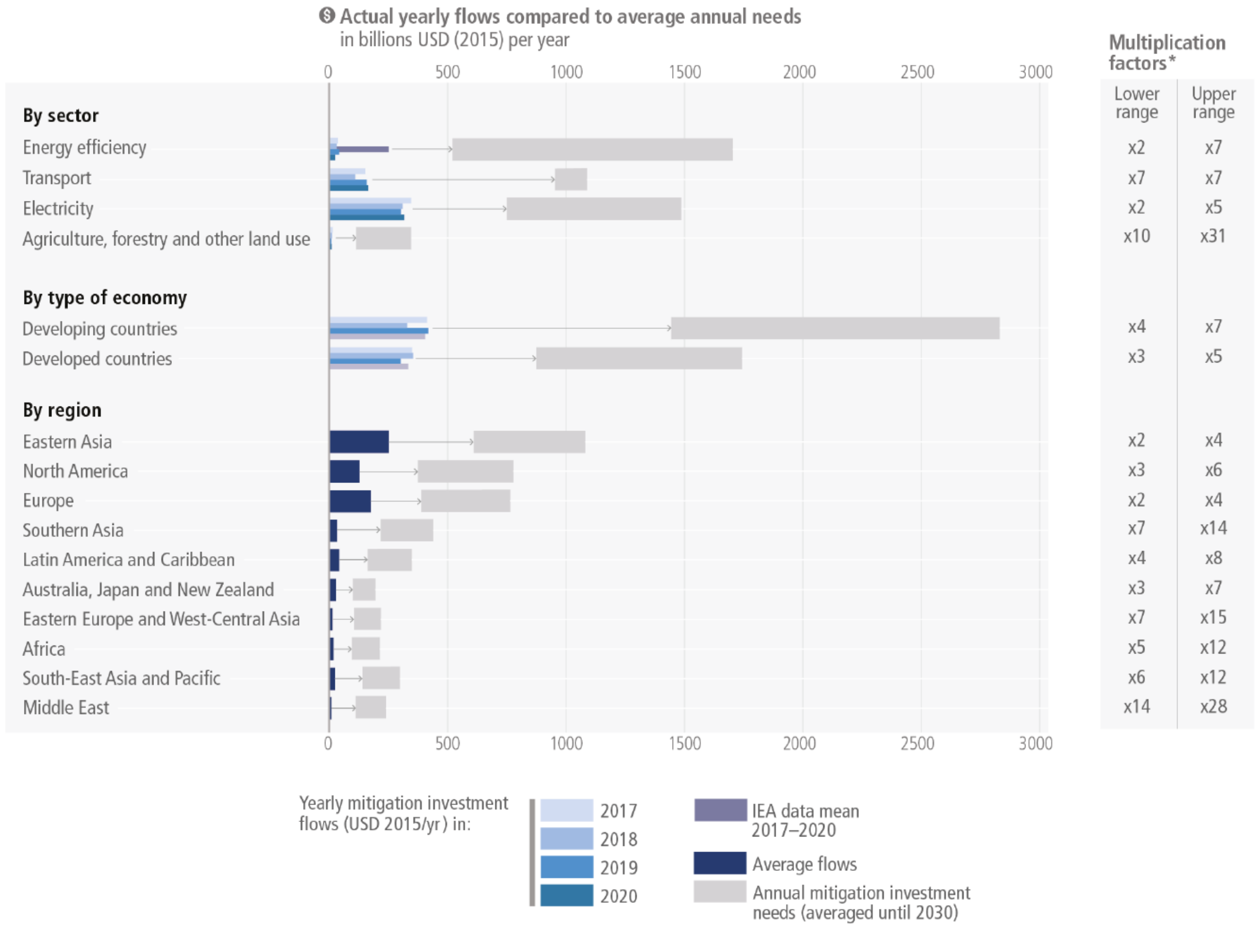
Table 3: LAC region GHG emissions scenarios by 2030

LAC region GHG Scenarios	GHG Emissions *(GtCO2eq)**	Implied absolute reduction vs BAU *(GtCO2eq)**	% reduction vs BAU
Historical 2019	3.24	na	na
BAU 2030	3.80	na	na
Unconditional NDC 2030	2.83	-0.97	-26%
Conditional NDC 2030	2.68	-1.12	-29%
2.0° C pathway	2.25	-1.55	-39%
1.5° C pathway	1.65	-2.15	-55%

** GHG emissions excluding Land Use Change and Forestry (LUCF)*
Source: Own elaboration based on Samaniego et al 2022

Finally, according to IPCC AR6 SYR report (2023), Latin America and the Caribbean actual yearly mitigation investment flows lag behind the average annual needs by a factor between x4 and x8 (lower and upper range).

Graph 8: Actual yearly mitigation investment flows versus needed by sector and region



Source: IPCC AR6 SYR (2023)

2. *Adaptation*

Samaniego et al (2022) states that one of the most notable changes in the updated NDCs in the LAC region is the greater emphasis on adaptation to climate change. Most countries with updated NDCs have strengthened the adaptation component in their NDCs, covering a larger number of sectors, adding greater detail in their adaptation actions, and showing a substantial progress in knowledge about vulnerability. Water, health, and agriculture sectors, as well as actions related to biodiversity, are the most important sectors for the adaptation processes in LAC countries (being mentioned in almost 95% of the cases).

The updated NDCs in the region also exhibit a greater degree of integration between mitigation and adaptation actions and seek to promote greater synergies between them. For example, Panama, Bolivia, and Costa Rica, are no longer separating mitigation and adaptation actions and are therefore structuring their actions under an "integrated approach of adaptation-mitigation" or "climate action". Honduras, Colombia and Chile have explicitly included "integrated" or "synergies" actions as priority lines of action. The NDCs of Colombia, Cuba, Mexico, Paraguay and Guatemala even present the adaptation communication first and then the mitigation commitments, underlining the relative importance of each topic in their NDC.

Several countries, including Costa Rica, Chile, Colombia, México, Panamá, have identified Nature-based solutions (NBS) as opportunities to reduce GHG emissions and, at the same time, increase climate resilience. Other countries as Argentina, Dominican Republic, Honduras and Nicaragua point to similar policies under the Ecosystem-based Adaptation (EbA) approach.

Graph 9: Sectors with Adaptation Actions in LAC counties NDCs

	Sectors with Adaptation Actions in NDCs											
Country	Water	Health	Agriculture	Biodiversity, Forestry, EbA	Infrastructure & Transport	Cities, HS, TP	Coastal zones & Oceans	Risk Mgmt	Tourism	Energy	Education	Social Dev
Brazil	▒	▒			▒	▒		▒				
Mexico	▒	▒	▒	▒	▒	▒	▒	▒		▒		
Argentina	▒	▒	▒	▒	▒	█	▒	▒	█	█	█	
Venezuela	▒	▒	▒	▒		▒	▒	▒			▒	▒
Colombia	█	▒	▒	▒	▒	▒	█	▒		▒		
Chile	▒	▒	▒	▒	▒	█	▒	█	█	▒		
Peru	▒	▒	▒	▒	█		▒	█	█			
Ecuador	▒	▒	▒	▒		▒		▒		▒		
Bolivia	▒		▒	▒						█		
Paraguay	▒	▒	▒	▒	▒	▒		▒		▒		
Dominican Republic	▒	▒	█	▒		▒	█	█	▒		█	
Cuba	▒	▒	▒	▒	█	▒	▒	█	█			
Uruguay	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒		▒
Guatemala	▒	▒	▒	▒	▒		▒	▒				
Honduras	▒	▒	▒	▒	█	█				█		█
Panama	▒	█	█	▒	█	█	█	█		█		
Nicaragua	▒	▒	▒	▒	▒	▒						
Costa Rica	▒	▒	▒	▒	▒	█	▒	▒	█	▒	█	
Jamaica	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒		
Suriname	▒	▒	▒	▒	▒		▒					
Grenada			▒	▒					▒			
Saint Lucia	▒	█	▒	▒	█	█	▒		█			

▒ Sectors already included in original NDCs
█ New sectors included in updated NDC

Source: Own elaboration based on Samaniego et al 2022 and ECLAC 2019
EbA: Ecosystem based Adaptation; HS: Human settlements; OT: Territorial Planning

Even though progress has been made in terms of incorporating adaptation in LAC policies and NDCs, according to the IPCC AR5 WGII, "a range of biophysical, institutional, financial, social, and cultural factors constrain the planning and implementation of adaptation options and potentially reduce their effectiveness (...). Real or perceived deficiencies in access to significant inputs of knowledge as well as human, social, and financial capital can and do constrain adaptation efforts in developing nations" (IPPC 2014).

Moreover, according to the IPCC AR6 WGII, "there is increased evidence of maladaptation across many sectors and regions, (...) which can create lock-ins of vulnerability, exposure and risks that are difficult and expensive to change and exacerbate existing inequalities (IPCC 2022).

III. Technological challenges

A. Status of science of the different SRM techniques

Solar Radiation Modification (SRM) refers to proposals to increase the reflection of shortwave radiation (sunlight) back to space to counteract anthropogenic warming and some of its harmful impacts (IPCC, 2022) (IPCC AR6 WGIII 2022 - Chapter 14 and WGI Chapters 4 and 5, 2021). Some of the main and more researched proposals include: Stratospheric Aerosol Injection (SAI), Marine Cloud Brightening (MCB), Cirrus Cloud Thinning (CCT), Ground-Based Albedo Modifications (GBAM), and Ocean Albedo Change (OAC).

- **Stratospheric Aerosol Injection (SAI):** Injection of reflective aerosol particles directly into the stratosphere (altitudes of 16–25 km) or a gas which then converts to aerosols that reflect sunlight.
- **Marine Cloud Brightening (MCB):** Spraying Sea salt or other particles in marine clouds (altitudes 0–3 km) to produce a larger number of smaller cloud droplets, making clouds more reflective (increasing the amount of sunlight reflected to space).
- **Cirrus Cloud Thinning (CCT):** Seeding to promote nucleation of cirrus clouds (altitudes of 6–13 km), that would increase the sedimentation rate of the ice crystals that compose these clouds, and therefore reducing optical thickness and cloud lifetime to allow more outgoing longwave radiation to escape to space.
- **Ground-Based Albedo Modifications (GBAM):** Whitening roofs, changes in land use management (e.g., no-till farming, bioengineering to make crop leaves more reflective), desert albedo enhancement, covering glaciers with reflective sheeting
- **Ocean Albedo Change (OAC):** Increase surface albedo of the ocean (e.g., by creating microbubbles or placing reflective foam on the surface).

Table 4: Characterization of SRM approaches

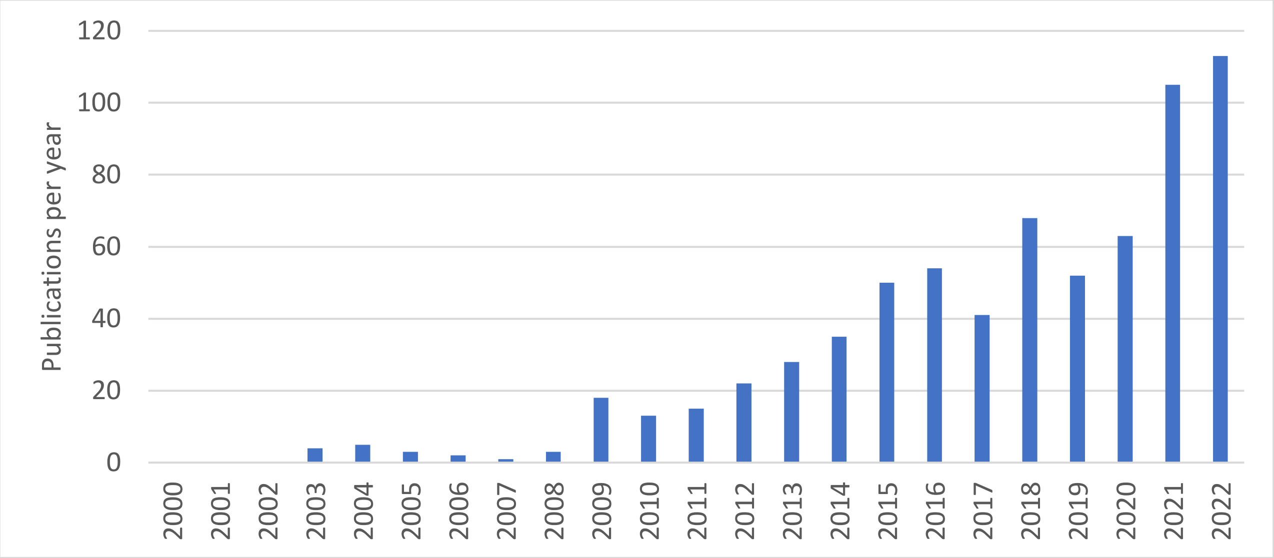
SRM approaches	Reach	Global mean negative radiation forcing	Time for deployment	Lifetime of effect	Estimated Costs
SAI	Global	-1 to -8 Wm^{-2},	~10 years;	1 to 3 years	~18 billion USD/y per 1° C of global mean cooling
MCB	Regional	-1 to -5 W m^{-2}	~10 years	1 to 7 days	1–2 billion USD/y per Wm^{-2}
CCT	Regional	-1 to -2 W m^{-2}	~10 years	~10 days	na
GBAM – Roof Whitening	Local	Max -0.1 W m^{-2};	~10 years	~10 years	~300 billion USD/y for a few tenths of a Wm^{-2}

SRM approaches	Reach	Global mean negative radiation forcing	Time for deployment	Lifetime of effect	Estimated Costs
GBAM – Desert albedo	Regional	-2 to -3 W m^{-2}	~10 years	< 10 years	several trillion USD/y for producing~2 Wm^{-2}
OAC	Regional	several Wm^{-2} achievable	~10 years	< 1 year	na

Source: UNEP 2023; Salter et al. 2014; Smith 2020

Published literature on SRM is steadily increasing (C2G 2023), with more than 100 papers and scientific articles published per year since 2021.

Graph 10: Evolution of published literature on SRM



Source: Own elaboration based on Science Direct search and other academic search engines
Note: Search term "solar geoengineering" In advanced search from Science Direct

1. Stratospheric Aerosol Injection (SAI)

SAI is the most researched SRM approach and there is more confidence for SAI than for other SRM approaches regarding the potential reduction in surface temperatures and amelioration of some climate change risks (IPCC AR6 WGIII, 2022). SAI also comprises the largest amount of evidence relating to its potential feasibility and effectiveness (UNEP 2023). In the same direction, NASEM (2021) states that there is substantial modelling and empirical evidence (using volcanic eruptions as a natural analogue) that SAI can induce cooling at a global scale, but large uncertainties remain regarding the cooling potential in relation to the amount and type of particles injected, the location of injection, and related to the effects of an increased aerosol burden on atmospheric chemistry, transport, and resulting regional and local effects on climate.

Unlike the highly turbulent troposphere, the stratosphere is relatively stable, and the aerosols in this level of the atmosphere can remain for one year or more before being transported to the troposphere and eventually removed by sedimentation and precipitation (NASEM 2021). SAI cooling effects would be inherently global (NASEM 2021), because aerosols spread relatively uniformly in longitude and, broadly, are transported poleward in latitude during their lifetime in the stratosphere.

IPCC AR6 WGI (2021) indicates that SAI could achieve a negative radiative forcing in a range from one to eight W m–2, depending on the amount and location of SO_2 injected into the stratosphere, based on several academic studies and models (Aquila et al., 2014; Pitari et al., 2014; Niemeier and Timmreck, 2015; Kravitz et al., 2017; MacMartin et al., 2017; Kleinschmitt et al., 2018; Tilmes et al., 2018; Dai et al., 2018; Lee et al., 2020; Visioni et al., 2020). Those modelling studies vary on the appropriate adjusting of the amount, latitude, altitude, and timing of the aerosol injection. Differences in model representation of aerosol microphysics, evolution of particle size, stratospheric dynamics and chemistry, and aerosol microphysics–radiation–circulation interactions all contribute to the uncertainty in the simulated cooling efficiency of SAI (IPCC AR6 WGI 2021).

Presently, there is substantial literature on climate model studies of equatorial or tropical stratospheric SO_2 injections. Tilmes et al. (2017), injected SO_2 at four locations (30, 15°N, 15 and 30°S) and showed that they resulted in different aerosol distributions and in different atmospheric and surface responses (Richter et al., 2022; Tilmes et al., 2018). Visioni et al 2023, performed a systematic intercomparison of the stratospheric and surface climate responses to the injection of SO_2 at different latitudes in the stratosphere. Smith et al. 2022 proposed a subpolar-focused stratospheric aerosol injection deployment scenario (in the Southern Hemisphere, the 60th parallel lies entirely in the Southern Ocean, south of the tip of Patagonia).

Regarding the type of aerosol particles used, sulphate particles (or its precursor gases such as SO_2, which would then be oxidized to H_2SO_4) have an advantage, given their analogy to material expelled by volcanoes. On the other hand, they absorb infrared radiation (IR) and can pose undesirable effects on atmospheric chemistry (NASEM 2021). IPCC AR6 WGI (2021) mentions that there is other aerosol types proposed in the literature, such as calcite ($CaCO_3$), titanium dioxide (TiO_2), aluminum oxide ($Al2O_3$), and engineered nanoparticles (Keith, 2010; Ferraro et al., 2011; Pope et al., 2012; Weisenstein et al., 2015; A.C. Jones et al., 2016; Keith et al., 2016), but are much less studied than sulphates.

In reference to the means of transportation up to the stratosphere for aerosol injection, NASEM (2021) found that initial broad technology assessments suggest that aircraft are likely to be the cheapest method of deployment; see, for example, McClellan et al. (2012) and Moriyama et al. (2017). More recent and detailed aircraft design studies (Bingaman et al., 2020; Janssens et al., 2020; Smith and Wagner, 2018) illustrate a very high probability of deployment being feasible at 20 km altitude, but with deployment being much more difficult at substantially higher altitudes. Smith et al. 2022 suggested that high-altitude injection at 25 km would substantially enhance the forcing efficacy of the aerosols compared to injections at 20 km, but also mentioned that concepts for deployment at 25 km would multiply costs, complexity, and operational risk.

In addition, relevant studies have involved theoretical analyses, social science research, climate model simulations and cost estimates (UNEP 2023). In particular regarding SAI costs Smith et al. 2020 states that relative to other climate interventions and solutions, SAI remains inexpensive, at about 18 billion dollars per year per degree Celsius of warming avoided (in 2020 USD), but also warns that a solar geoengineering program with substantial climate impact would lie well beyond the financial reach of individuals, small states, or other non-state potential rogue actors and would instead be the exclusive domain of large national economies or coalitions.

NASEM (2021) has identified that one of the key research priorities for SAI is to address critical gaps in knowledge about the evolution of the aerosol particle size distribution. Other areas of future research include stratospheric dynamics and chemistry, injection techniques (Zhang et al 2023), rates and locations, aerosol precursors and scattered sunlight / diffuse light (Kravitz et al., 2012; Madronich et al., 2018; Xia et al., 2016).

Regarding the Latin America and the Caribbean region, researchers from the National Scientific and Technical Research Council the National Scientific and Technical Research Council (CONICET) of Argentina and the University of Buenos Aires analysed the La Plata Basin hydroclimate response to SRM with SAI in terms of changes in mean and extreme temperature, rainfall, and river flows simulations from the Geoengineering Large Ensemble (GLENS). Results show robust impacts on the water cycle of the La Plata Basin due to SRM implementation, particularly associated with increased precipitation over the northern part of the region and a general reduced warming compared to the IPCC RCP8.5 scenario (Camilloni et al 2022). Zhang et al. 2018 modelled the impacts of a SAI on Caribbean coral reefs (with daily injections of SO_2 at a rate of 5Tg SO_2 per year in the period 2020-2069) and found that it could significantly mitigate future coral bleaching throughout the Caribbean Sea.

2. *Marine Cloud Brightening (MCB)*

Marine cloud brightening was originally suggested by cloud physicist John Latham in 1990, proposing the idea that the amount of solar radiation reflected by clouds might be deliberately increased by augmenting the existing population of aerosol particles with salt particles created from seawater. In 2012, further studies from Latham et al. confirmed that MCB could produce a globally averaged negative forcing of significance.

An analogue for MCB is the reflective, persistent 'ship tracks' observed after the passage of a sea-going vessel emitting combustion aerosols into susceptible clouds (Christensen and Stephens, 2011; Chen et al., 2012; Russell et al 2013; Gryspeerdt et al., 2019; Diamond et al 2020; IPCC AR6 WGI 2021; Chun et al 2023).

Relevant studies involve theoretical analyses, climate model simulations and observations of ship tracks (Christensenet al 2011; Chen et al 2012; UNEP One Atmosphere 2023). Modelling studies suggest that MCB has the potential to achieve a negative forcing of about 1 to 5 W m–2, depending on the deployment area and strategies of cloud seeding (Hill and Ming, 2012; Partanen et al., 2012; Alterskjær et al., 2013; Ahlm et al., 2017; Stjern et al., 2018; Diamond et al 2020; IPCC AR6 WGI 2021). Recently, Chun et al. 2023 investigated the processes controlling subtropical marine cloud microphysical, macrophysical, and radiative responses to aerosol injections. Engineering studies of delivery mechanisms for aerosol spray have taken place in laboratory (Cooper et al 2014; UNEP One Atmosphere 2023). Salter et al (2008) outlines the rationale and underlying engineering hardware (wind-driven spray vessels powered by Fletnner rotors) that may bring the strategy from concept to operation.

NASEM (2021) states that there are decades of research on aerosol and marine cloud interactions, including ship track studies, and yet despite this large research base, many uncertainties remain regarding MCB strategies, including limited understanding of aerosol-cloud interactions and how these interactions affect a cloud's total water content and lifespan (NASEM 2021; Christensen et al 2022). IPCC AR6 WGI (2021) also concludes that there are large uncertainties associated with cloud microphysics and aerosol–cloud-radiation interactions.

Unlike stratospheric aerosol injection, marine cloud brightening might be able to be used regionally, albeit in a limited manner (Latham et al 2014; Zhu et al 2021). NASEM 2021 also agrees that MCB would be implemented at the regional level, potentially allowing more targeted interventions. The ability of MCB to produce detectable cooling on a planetary scale is less well established (UNEP One Atmosphere 2023).

The Marine Cloud Brightening Project is an open, multi-institutional research collaboration conceived to advance understanding of cloud responses to aerosol particles, within the Atmospheric Intervention Research (AIR) Program at the University of Washington. It was originally formed in 2009 by Kelly Wasner. It operates in partnership with Palo Alto Research Center (PARC) where work is being undertaken to develop spray technology, and Pacific Northwest National Laboratory, a centre of excellence for climate modelling. Field tests were going to take place by 2018, but then delayed with no update.

Researchers from Southern Cross University's National Marine Science Centre in Coffs Harbour teamed up with the Sydney Institute of Marine Science, the University of Sydney, and Queensland University of Technology, and are researching and testing a prototype equipment developed in partnership with EmiControls of Italy. The first field experiment of marine cloud brightening was conducted over the coral reef in Australia in 2021 (Human Rights Council 2023; Tollefson 2021). Future trials will be funded through the Australian Federal Government's 220 million dollars research and development phase of the world-leading Reef Restoration and Adaptation science Program (RRAP), that seeks to help preserve and restore the Great Barrier Reef (Tollefson 2021).

Regarding the Latin America and Caribbean region, one of the main references identified is the Variability of the American Monsoon Systems (VAMOS) Ocean–Cloud–Atmosphere–Land Study Regional Experiment (VOCALS-REx), a field experiment conducted in 2008 off southern Peru and northern Chile, aimed at better understanding the coupled climate systems of the southeast Pacific (Wood et al 2011; Rutllant et al 2013; Mechoso et al 2014). VOCALS-REx focus upon i) links between aerosols, clouds and precipitation and their impacts on marine stratocumulus radiative properties, and ii) physical and chemical couplings between the upper ocean and the lower atmosphere. It involved five research aircraft, two ships and two surface sites in northern Chile. In late spring 2009, one year after VOCALS-Rex the Chilean Upwelling Experiment (CUpEx) in the nearshore region of 30°S focused on the ocean–atmosphere interaction in a major upwelling centre off northern Chile (Garreaud et al. 2011). CUpEx included two radiosonde stations, several ground stations, buoys, and marine radars. This experiment has confirmed findings of VOCALS-REx in the coastal Southeastern Pacific and provided additional detailed information on coastal processes.

Zhao et al. (2021) points that off the coasts of Peru and California locations with persistent marine stratocumulus have larger Effective Radiative Forcing (ERF).

Scientists from the Brazilian Instituto Federal do Piauí (IFPI) and Universidade Federal do Rio Grande do Norte (UFRN) have studied the clouds' microphysical properties in Northeast Brazil (de Abreu, 2021), but with focus on land and the relationship with lightning activity.

In addition, it is worth mentioning that Latham et al. (2012) highlight that GCM modelling confirms the results of studies by Jones et al. (2009), which show that MCB could produce unacceptable rainfall reduction in the Amazonian region of South America. On the other hand, Stjern et al. (2018) found that robust model responses include a slight precipitation increase over low-latitude land regions, such as large parts of South America among others.

3. *Cirrus Cloud Thinning (CCT)*

Cirrus clouds cover a percentage of the of the upper troposphere in the range of 17% to 30% (Rossow & Schiffer, 1999; Sassen et al., 2008; Gruber et al 2019). It is theorized that removing all cirrus clouds from the atmosphere could compensate more than the effect of CO_2 doubling, resulting in a net cooling effect of 5 to 6 W/m^2 (Gasparini & Lohmann, 2016; Hong et al., 2016; Gruber et al 2019). Several climate model simulations and theoretical analyses have been developed for the CCT approach, but no outdoor small-scale experimentation has been conducted. Tully et al. 2022 and Gasparini et al. 2020 coincide in that a consistent CCT approach among climate modelling groups is needed (ECHAM-HAM; CAM5 GCM, ECHAM6.3-HAM2.3). The feasibility of CCT is uncertain, in part because of the larger uncertainties associated with the ice nucleation processes (INPs) in high clouds (UNEP One Atmosphere 2023, Gasparini et al 2016; Gasparini et al., 2020; Penner et al 2015).

More recently, Villanueva et al. (2022) showed that INPs could decrease the heat-trapping effect of mixed-phase regime clouds over the polar oceans during winter, slowing down sea-ice melting and partially offsetting the ice-albedo feedback, and therefore estimated that mixed-phase regime cloud thinning (MCT) could offset about 25% of the expected increase in polar sea-surface temperature due to the doubling of CO_2. Liu and Shi (2021) concluded that the potential cooling effect of CCT is considerable, and the flexible seeding method is essential, but also warned that cirrus seeding leads to a significant warming effect of liquid and mixed-phase clouds, which counteracts the cooling effect of cirrus clouds. Gruber et al. (2019) affirms that the primary effect of seeding is found to be a reduction of ice crystal concentration in cirrus clouds, leading to increased outgoing longwave radiative fluxes at the top of the atmosphere, thereby creating a cooling effect.

On the other hand, Tully et al. (2022) concluded that CCT is unlikely to act as a feasible climate intervention strategy on the global scale.

No CCT academic or scientific piece of knowledge addressing Latin America and the Caribbean region in particular has been identified.

4. *Ground-Based Albedo Modifications (GBAM)*

According to IPCC AR6 WGI (2021), an increase in crop albedo or roof albedo in urban areas could help to reduce warming in densely populated and important agricultural regions, but the effect would be limited to local scales and ineffective at counteracting global warming (Crook et al., 2015; Zhang et al., 2016; Zhang et al 2022).

Although many albedo management strategies have been proposed in recent years, their quantity and influence are still limited and need to be further developed (Zhang et al 2022).

According to Geoengineering Monitor (2021), urban albedo enhancement has been considered and modelled by various researchers, among them Hashem Akbari of Concordia University in Montreal, who has promoted the idea of government grants to cover rooftops and tarmac with white paint (Akbari 2005). The CoolRoofs Initiative in New York City painted 50 hectares of roof surfaces with a bright, reflective coating (ETC Group and Heinrich Böll Foundation 2020). Scientists at Stanford University (2011) found that white roofs would provide some local cooling but at the expense of more global warming, largely because such cooling means less hot air rising and therefore fewer clouds forming and suggested that roofs covered in photovoltaic panels would do a better job, by producing electricity that then obviates the need for more fossil fuel–burning power plants (Biello 2014). Scientists from Conicet (Argentina) studied the solar reflectance index of façade coatings and concluded that it is possible to mitigate the heat island effect by using the appropriate selection of vertical cladding.

Peres et al studied the urban heat island (UHI) in Rio de Janeiro, Brazil, in a period of 30 years between 1984 and 2015 using remote sensing data and confirmed a UIH intensity between "urban" and "rural/urban low density" ("vegetation") areas of up to 7°C. Retro-reflective materials (RRM) applied as building coatings are a possible means to help counter urban heat islands (Yuan et al 2015).

Pavement materials with high surface albedo have been investigated, where Portland cement concrete slabs show higher surface albedo and lower internal temperatures than asphalt mixture slabs (Chen et al 2019; Zhang et al. 2022). Kousis et al. (2023) states that "cool pavements" (CPs) can maintain a lower surface temperature than conventional pavements and mitigate urban overheating. Xu et al. (2020) estimated that a hypothetical albedo change to all darker pavements in the US would produce a negative radiative forcing of a magnitude equivalent to that associated with a reduction in CO_2 emissions of more than 17 Mton per year. Villena Del Carpio et al. (2016) studied the results for the solar reflectance and temperature of 20 types of pavements used in Brazil for roads, parking lots, squares and sidewalks. Torres Convers et al. (2018) evaluated the mitigation of the heat island effect through colour in pavements in Colombia.

In 2009, researchers from the University of Bristol (UK) suggested that widespread cultivation of crops with more reflective leaves could result in significant decreases in summertime air temperatures in Europe (Singarayer et al 2009). Much of Africa and South America, with less intense arable cultivation and relatively zonally narrow continents, have little potential for achieving significant mitigation of warming (Ridgwell et al 2009). Kala et al (2021) showed that crop albedo enhancement reduces the frequency of heatwave days over Europe and North America by 10 to 20 days. Davin et al 2014 found that heat wave impacts could be attenuated locally by increasing surface albedo through crop residue management (no-till farming). There are concerns about the potential risks of increased reflectivity for the nutritional content of the plants, their photosynthetic capacity or on surrounding soil (Geoengineering Monitor 2021), these topics being still under-researched.

Regarding deserts, IPCC AR6 WGI (2021) stated that large changes in its albedo could in principle result in substantial global cooling but would severely alter the hydrological cycle and cause severe shifts in tropical precipitation. (Crook et al. 2015).

Another proposed approach is covering glaciers with reflective sheeting and therefore increasing its albedo. Back in 2009, a pilot funded by World Bank whitewashed the rocks surrounding the summit of Chalon Sombrero peak (4,756 meters above sea level) with paint, in an area some 100km west of the regional capital of Ayacucho, aiming to increase the sunlight reflection. Torres et al. (2018) and Fyffe et al. (2021) have studied Peruvian glaciers albedo. Several other international scientific papers have covered the topic of snow and glacier albedo characterization and enhancement (Zhang et al. 2017; Flanner et al. 2021; Hao et al. 2023).

5. Ocean Albedo Change (OAC)

Ocean albedo modification using microbubbles is an SRM approach that increases the reflectivity or albedo of the surface of the ocean. The ocean's normal average albedo is about 0.05 to 0.10, resulting in the absorption of approximately 93% of incident solar radiation (Seitz, 2011). White caps and white water have a relatively high albedo of about 0.22 which is similar to the albedo of clouds (Moore et al., 2000). In 2011, Harvard University Professor Russell MacGregor Seitz published a geoengineering approach which involves spraying or injecting micron-size bubbles of air into the surface waters of the ocean to increase albedo and cool the water (Seitz, 2011; Evans et al., 2010; Crook et al. 2014).

Zhao el at (2021) modelling predicts a −4.8±0.05 Wm−2 effective radiative forcing for OAC. It also found that for OAC there is large negative radiative forcing over low latitude ocean, especially the Southeast Pacific, India Ocean and South Atlantic. Crook et al. simulated ocean albedo enhancement by increasing albedo in HadGEM2 for all ice-free oceans by 0.03 to achieve an effective radiative forcing of ~ -2Wm-2.

Gabriel et al. (2017) simulated a scheme in which the albedo of the ocean surface is increased over the subtropical ocean gyres in the Southern Hemisphere with a stable reflective foam (G4Foam), comprised of tiny, highly reflective microbubbles, resulting in up to -1.5 Wm-2 vs a RCP6.0 pathway. It also found that heavily populated and highly cultivated regions throughout the tropics, including the Sahel, southern Asia, the Maritime Continent, Central America, and much of the Amazon experience a statistically significant increase in precipitation minus evaporation.

Robock (2011) points that the bubble method would bring its own list of risks, including: i) impacts on convection in the ocean once you cool the ocean surface, which would remove the bubbles; ii) a cooler ocean will also absorb CO2 more efficiently, enhancing ocean acidification; iii) artificial surfactants would be needed in some situations, the costs and environmental impacts of these chemicals may present problems. Kravitz et al. (2018) also mentioned that microbubbles have the potential to inhibit vertical mixing and available light in the euphotic zone, which could have profound effects on marine biota. It also warned about heat transport from land to ocean.

According to IPCC AR6 WGI (2021), the technology to increase ocean albedo at large scale does not exist today.

The Human Rights Council (2023) highlighted another method that is used by the Arctic Ice project, which aims to improve the Arctic's ice cap reflectivity by dispersing silica microbeads over the ice sheet, but also underlines that the project is criticized by indigenous communities. Field et al. (2018) detailed climate modelling simulating global sea ice albedo modification and revealed that it resulted in more than 1.5°C cooler temperatures over a large part of the Arctic, as compared to the untreated control case. It concludes that an albedo enhancement in the Arctic is a relatively new idea that needs to be explored with further research. Cvijanovic et al. (2015) also studied restoration of the Arctic ice via alteration of the ocean surface albedo.

6. *Overall SRM Status of Science*

According to IPCC AR6 in its WGI (2021) & WGIII reports (2022), recent modelling studies suggest it is conceptually possible to meet multiple climate objectives through optimally designed SRM strategies. Nevertheless, large uncertainties still exist for climate processes associated with SRM options (Kravitz and MacMartin 2020). Irvine et al. 2019 analysed several model simulations in which strong global warming was partially prevented by SRM and found that in nearly all regions key climate variables were closer to their pre-industrial levels with SRM than without.

According to IPCC AR6 SYN (2023) "Solar Radiation Modification (SRM) approaches, if they were to be implemented, introduce a widespread range of new risks to people and ecosystems, which are not well understood. SRM has the potential to offset warming within one or two decades and ameliorate some climate hazards but would not restore climate to a previous state, and substantial residual or overcompensating climate change would occur at regional and seasonal scales. Effects of SRM would depend on the specific approach used, and a sudden and sustained termination of SRM in a high CO2 emissions scenario would cause rapid climate change. SRM would not stop atmospheric CO2 concentrations from increasing nor reduce resulting ocean acidification under continued anthropogenic emissions. Large uncertainties and knowledge gaps are associated with the potential of SRM approaches to reduce climate change risks. Lack of robust and formal SRM governance poses risks as deployment by a limited number of states could create international tensions."[4]

IPCC AR6 WGIII (2022) also found that even though risk analyses have often used inputs from climate models with simplified representations of SRM, fewer have used inputs from climate models that explicitly simulated injection of gases or aerosols into the atmosphere, which include more complex cloud-radiative feedback.

UNEP (2023) report asserts that SRM is a complex, controversial and under-studied group of technologies, and yet some scientists and companies are accelerating towards deployment without a full understanding of the implications of their implementation. NASEM (2021) concluded that solar geoengineering research to date is ad hoc and fragmented, with substantial knowledge gaps and uncertainties in many critical areas. IPCC AR6 WGI (2021) Chapter 4 found that there is low confidence in understanding of the climate response to SRM at the regional scale. In addition, IPCC AR6 WGIII (2022) warned that there is large uncertainty in projected impacts of SRM on crop yields due in part to the limited number of studies. Moreover, in the same direction, UNEP (2023) stated that comprehensive assessments of the impacts of SRM deployment on human health are also lacking, and called for more research into geoengineering, in a wider sense. However, while SRM-related research may not yet be systematically tracked, it is underway internationally (C2G 2023).

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[4] WGI 4.6; WGII SPM B.5.5; WGIII 14.4.5.1; Cross-WG box SRM; SR1.5 SPM C.1.4

International research and collaboration on SRM are growing at a slow but steady pace (C2G 2023) like the Geoengineering Model Intercomparison Project (GeoMIP), the DEveloping country Governance REsearch and Evaluation for SRM Initiative (The DEGREES initiative), Geoengineering Large Ensemble Project (GLENS), SilverLining, among others.

- **GeoMIP** is an endorsed community coordinated project, as designated by the Working Group on Coupled Modelling (WGCM) of the World Climate Research Programme (WCRP), which serves to organize geoengineering simulations by prescribing the experiments which all participating climate models will perform. Idealized simulations of solar reduction have been simulated in a multi-model context under the GeoMIP, to understand the robust model responses to various standardized solar geoengineering simulation designs (Kravitz et al., 2011). Multi-model conclusions from these studies indicate that solar geoengineering would be effective at partially offsetting greenhouse-gas-induced temperature changes (Kravitz et al., 2013a), as well as changes in the hydrological cycle (Tilmes et al.., 2013), the cryosphere (Moore et al., 2014), extreme events (Curry et al., 2014; Aswathy et al., 2015), vegetation (Glienke et al., 2015), circulation (Guo et al., 2018; Gertler et al., 2020), agricultural yield potential (Xia et al., 2014), and numerous other areas. Other model intercomparison projects have also begun to explore potential SRM impacts (C2G 2023), for example the Agricultural Model Intercomparison and Improvement Project (AgMIP).

- **The DEGREES Initiative** (formerly SRMGI) is a non-governmental organization dedicated to putting the Global South at the centre of the SRM conversation. It aims to build the capacity of developing countries to evaluate SRM through i) outreach events that bring new people to the conversation, ii) research that builds expertise and an evidence base and iii) activities that build an international community of experts. It is one of the largest SRM research initiatives in the world by number of scientists, having supported over 150 researchers working across 26 projects hosted in 21 developing countries. Researchers from Argentina, Brazil, Chile, and Jamaica are among those who have benefited from the initiative through grants to fund their research. The DEGREES Initiative co-organized a first workshop in South America in Brazil in 2016, in partnership with the Brazil National Space Research Institute (Instituto Nacional de Pesquisas Espaciais or INPE). Later, in June 2019, the Brazilian Academy of Sciences followed up with a workshop exploring next steps for Brazil and South America in general. In a second workshop in South America in November 2019, The DEGREES Initiative partnered with the research team of the University of Buenos Aires and two local host institutions (Centro de Investigaciones del Mar y la Atmósfera - CIMA), and Instituto Franco-Argentino sobre Estudios de Clima y sus Impactos - IFAECI) to run an engagement workshop on SRM, the second one in South America. The workshop gave an opportunity to reflect on what SRM might mean for South America and to try to plot out some next steps for regional engagement.

- **GLENS** from the National Center for Atmospheric Research (NCAR) ensembles several stratospheric sulphate aerosol geoengineering simulations between 2020-2099 using the NCAR Community Earth System Model. It has investigated achieving multiple climate policy goals by adjusting the rate of stratospheric SO_2 injection at four different latitudes (30°N, 30°S, 15°N and 15°S). A study on the La Plata Basin in South America analysed the impacts of SAI deployment with GLENS simulations.

- **SilverLining** is a non-profit organization dedicated to ensuring that society has sufficient options to address near-term climate risk. It aims to define forward paths (roadmaps) for research and undertake critical studies to advance understanding of near-term climate risks and interventions. Solar climate intervention has been one of the key topics of research.

Recent statements from the UK Global Meteorological Office and American Meteorological Society advocate for more research into SRM to ensure any global discussions on addressing climate risk are based on a robust and broad range of evidence (C2G 2023).

Several national and transnational bodies have undertaken initial assessments of SRM (C2G 2023), including the US NASEM (2021; 2015); the Swiss Federal Office for the Environment (2020); the European Union (2015); the UK Research Council (2013), House of Commons (2010), and the Royal Society (2009).

The US Government, through the White House Office of Science and Technology Policy (OSTP), in coordination with relevant Federal agencies, and directed by the US Congress, has been working since 2022 on a five-year scientific assessment of solar and other rapid climate interventions in the context of near-term climate risks and hazards. The report (OSTP 2023), which was developed in coordination with the National Oceanic and Atmospheric Administration (NOAA) and other key federal agencies, identifies critical knowledge gaps and scopes potential research areas that could improve understanding of risks and benefits posed by solar radiation modification. According to the OSTP, "the report cautions that any potential comprehensive research program must encompass the societal as well as the scientific dimensions of solar radiation modification and highlights several key priority areas for further solar radiation modification research".

In 2021, the US NASEM proposed an agenda for a solar geoengineering research program comprising three main pillars: i) the context and goals for SG research (e.g. program development pathways, future conditions, integrated decision analysis, capacity building); ii) the impacts and technical dimensions (e.g. atmospheric processes, climate response, other impacts, monitoring and attribution, technology development and assessment); and iii) the social dimensions (e.g. public perceptions and engagement, political and economic dynamics, governance, ethics) (NASEM 2021).

The NASEM committee also suggested that a reasonable initial investment in SRM research would be in the range of 100–200 million dollars over 5 years. This budget should be allocated 20% to Context and Goals, 20% to Social Dimensions, 35% to Impacts and Technical Dimensions, and finally 25% dynamically allocated as new learning advances.

SRM-related research has been supported by public and private funding, the main SRM research funding initiatives being the following (C2G 2023):

- DEGREES's Modelling Fund announced in 2023 an additional USD 1 million for 15 new research projects into the impacts of SRM across Africa, Asia, and South America
- Harvard Solar Geoengineering Program, earmarked USD 16 million for outdoor experiments to advance understanding of stratospheric aerosol injection (SAI)
- European Union funded GENIE project with EUR €9 million in order to explore transdisciplinary dimensions of SRM

- US government funded Earth Radiation Budget project received USD 4 million in 2020 (and a further 9 million in both 2021 and 2022) for SRM-related research
- Germany's EUR €10.5 million Climate engineering project (2016-2019)
- Arctic Ice project with an annual USD 1 million budget exploring ways to restore Arctic Sea ice
- Australian-funded Reef Restoration and Adaptation Program (RRAP) (2020)
- Silver Lining safe climate research initiative supporting physical science SRM research programmes
- China's EUR €2 million government funded geoengineering research programme (2015-19)
- European Trans-disciplinary Assessment of Climate Engineering (2015) with EUR €1.3 million budget
- EU's EUR € 1.3 million Implications and Risks of Engineering Solar Radiation to Limit Climate Change programme (IMPLICC) (2009-2012)

B. Status of readiness of the different SRM techniques at the different levels

UNEP (2023) classifies the different stages of SRM development and readiness into three types: indoor SRM research investigations, small-scale outdoor SRM experiments and potential large-scale operational SRM deployments. For the purpose of this paper, this classification is also adopted here.

- **Indoor SRM research investigations** consisting of theoretical analysis, social science research, computer simulations using climate and Earth System models and laboratory experimentation.
- **Small-scale outdoor experimentation** involves releasing 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 would presumably need to last for decades or more to be effective.

As discussed in the previous chapter, although still fragmented and with considerable knowledge gaps, SRM research is slowly progressing. UNEP (2023) finds that there is little information on the risks of SRM and limited literature on the environmental and social impacts resulting from the application of these technologies.

On the other hand, several small-scale outdoor experiments were announced in the last decade, most of them cancelled or halted and only a few of them proceeding with limited scope, and neither of them involving any measurable local climate modification (see Section C - Annex b for a list of SRM outdoor experiments).

First SAI field trials took place in the Russia Federation back in 2009 when scientists tested aerosol formation in the lower troposphere using generators installed aboard helicopters. A few years later, in 2012, several UK universities (including Bristol, Cambridge and Oxford) announced the Stratospheric Particle Injection for

Climate Engineering (SPICE) project that planned to pump water into the atmosphere through a hosepipe attached to a balloon but was then cancelled amid issues related to a patent application blocker. Harvard University has been working on a project known as Stratospheric Controlled Perturbation Experiment (SCoPEx) since 2015, which intends to perform tests in Sweden. The SCoPEx project has been delayed several times and has currently no official planned date for its implementation. The US National Oceanic and Atmospheric Administration (NOAA) leads the Stratospheric Aerosol processes, Budget and Radiative Effects (SABRE) project since 2021 and has been conducting stratospheric flights (using balloons and more recently jets) testing potential delivery methods but with no planned material release into the stratosphere. In 2022, two different experiments have tested high altitude balloons releasing a few hundred grams of sulphur dioxide into the stratosphere with no results or measurements confirmed; the previous experiments include the US-based start-up Make Sunsets that claims to have deployed weather balloons which may have released reflective sulphur particles in the stratosphere in Baja California, Mexico, and the European Astrotech's Stratospheric Aerosol Transport and Nucleation (SATAN) experiment held in the UK.

Other SRM approaches showed much less activity in terms of outdoors experiments. Scientists from the Sydney Institute of Marine Science and the Southern Cross University have tested an MCB prototype 100km offshore Australia. In addition, the Arctic Ice Project (former ICE 911), a non-profit research organization in collaboration with SINTEF, have been working on a project that aims to spread hollow silica microspheres on top of ice in the Arctic (current progress is mainly in testing materials in lab conditions). According to Field et al. (2018), the largest field-testing area made by the Arctic Ice Project to date was 45,000 ft2 (4,180 m^2) of the 3M™ K1 microspheres materials on a section of North Meadow Lake in Barrow, Alaska, in May 2017. The Marine Cloud Brightening Project from the University of Washington aimed to first start field tests in 2018 but has been delayed, with no potential starting date in sight.

No operational large-scale SRM deployments were announced yet, nor have they taken place at the time of this assessment. The expert panel of UNEP (2023) concluded that the scientific, technical, social and environmental aspects of a large-scale deployment of SRM have not been fully assessed, that the evidence base is simply not there to make informed decisions, and therefore the deployment is not warranted at present.

The scientific community has been divided in relation to SRM research, experimentation and deployment, particularly in the last two years. In January 2022, an open letter led by Professor Biermann from Utrecht University and signed by almost 400 scientists worldwide, called for an international non-use agreement on solar geoengineering, arguing that its deployment cannot be governed globally in a fair, inclusive, and effective manner. Later, in early 2023, a group of scientists led by Professor Visioni from Cornell University and over 120 signatories acknowledged that SRM is risky, and called for balanced research, stating that SRM might help to meaningfully reduce climate-induced risks.

At the same time, another call for support for geoengineering research was published, signed by 110 scientists and biologists, mainly US-based. This last letter stressed the importance of proceeding with responsible research to objectively evaluate the potential for SRM to reduce climate risks and impacts, to understand and minimize the risks of SRM approaches, and to identify the information required for governance.

Recognized international media and science journals are also discussing SRM as this "hot topic" gains momentum. For example, TIME states that SRM is a controversial technology that is creating an unprecedented rift among climate scientists. The Washington Post warns that solar geoengineering is a "climate solution" that engenders worry and could trigger war. Nature finds solar geoengineering to be scary, acknowledging that for this reason, it should be researched. Finally, Science asks if solar geoengineering could cool the planet. Other publications referring to this issue include (none exhaustive list) (C2G, 2023): Al Jazeera, Associated Press, Bloomberg, Forbes, Foreign Policy, France24, The Guardian, Los Tiempos, Le Monde, The New Yorker, Politico, Reuters, Science, Thompson Reuters Foundation, Wired, UN Dispatch.

NASEM (2021) proposed a series of recommendations for future outdoor experimentation, including a dual threshold requirement based on: i) the expected global mean surface temperature change and ii) the mass of materials injected into the atmosphere. These thresholds should be established both for individual experiments as well as for the aggregated effects of all outdoor experiments conducted globally in a given year.

- **Temperature threshold:** For individual experiments, two orders of magnitude below detection limits, assuming that there are unlikely to be more than 10 experiments conducted each year by the international research community. This temperature threshold would therefore limit the global annual temperature change to be less than the detection limit by approximately one order of magnitude.
- **Material mass threshold:** Any outdoor substance released should be limited to a quantity of material at least two orders of magnitude smaller than the quantity that could cause detectable changes in global mean temperature or adverse environmental effects. This would translate to less than 1000kg released for an individual experiment and a total of less than 10,000 kg for aggregated experiments each year (NASEM 2021).

In comparison, and only as a reference of sulphur dioxide (SO_2) magnitudes, the 1991 volcano eruption of Mount Pinatubo spewed thousands of tons of SO_2 into the stratosphere, causing global temperatures to drop temporarily by about 1° F (or 0.5°C), according to the U.S. Geological Survey. Another case in point is that the United States alone releases approximately 1.8 million tons of SO_2 every year, from factories, power plants, cars and other sources.

It is then concluded that none of the SRM techniques is somewhere near to readiness for deployment, neither at the local nor the global reach, and, equally, neither at the small-scale nor at the large-scale.

Key areas of further research and experimentation are summarized below, looking in particular at those closing the existing gap regarding technology readiness (NASEM 2021):

- SAI
  - Explore plume dynamics (i.e., what happens after release from an aircraft in a coherent plume versus release uniformly mixed over a grid box of a climate model and how long that plume stays coherent).

  - Particle nucleation (which is influenced by plume dynamics) and subsequent growth (which will depend on the existing background aerosol concentrations), and how implementation choices impact outcomes.
  - Whether and how one could deliver a useful payload to a sufficient altitude, and what is a reasonable estimate of the economic and other costs for doing so.
  - Understanding how engine and air foil design choices alter chemistry and physics in the nearfield plume (in particular for high altitudes >25km).
  - Develop capabilities for direct injection of sulphate or alternative aerosol particles (e.g., for dispersion of solid aerosols).
  - Large-scale extraction and processing efficiencies for aerosol precursors.

- **MCB**
  - Capability to produce salt particles of an appropriate size distribution that can be lofted into, and serve as nuclei for, boundary layer clouds. Spray nozzles that can produce such particle sizes.
  - Development of appropriate ships (or other delivery approaches) with capacity to produce and distribute aerosols.
  - Ship's facilities for filtering and processing large volumes of water (to obtain salt particles created from seawater).
  - Improve understanding of the boundary layer dynamics and the conditions under which particle emissions may require added heat to overcome limitations in lofting of particles and mixing to cloud level.
- **All SRM approaches**
  - Designing an observational system for detection, monitoring, and attribution of SRM deployment and impacts

IV. Risk dimensions

A. Possible risks and eventual benefits of SRM in relation to environment, economic, social, and security factors, and in relation to the SDGs

Both IPCC AR6 SYR (2023) and UNEP One Atmosphere (2023) reports agree that a potential implementation of SRM approaches would introduce a widespread range of new risks to people and ecosystems, which are not well understood. There is an overall insufficiency of research on the wide scope of potential risk or risk reduction to human health, well-being and sustainable development from SRM and on their distribution across countries and vulnerable groups (Honegger et al. 2021a; Carlson et al. 2022).

According to US NASEM (2021), solar geoengineering raises concerns about new risks, uncertainties, and unintended impacts on natural ecosystems, agriculture, human health, and other critical areas of concern for society. Also, in terms of the magnitude of SRM deployment, the more intense the SRM deployment, the larger is the likelihood of the risks of side effects and also environmental risks (Heutel et al., 2018).

In addition, there are also benefits of potential SRM deployment as mentioned in the literature. Possible risks and benefits of SRM deployment are classified in this chapter in Climate, Environment & Ecosystems, Economic, Human & Social, Security and Others.

1. *Possible Benefits*

Table 5: Benefits of potential SRM deployment

Benefits of potential SRM deployment	
Climate	• Reduce global average warming, for instance, to hold global warming to 1.5°C or 2°C alongside ambitious conventional mitigation (Jones et al. 2018; MacMartin et al. 2018). • Bring down temperature after an overshoot (Tilmes et al. 2020). • Cool the planet within years (UNEP One Atmosphere 2023). • Helping to avoid irreversible climate tipping points while increased efforts are made to bring down atmospheric GHG concentrations (Felgenhauer et al 2022). • Offset some effects of increasing GHGs on the global and regional climate, including the increase in frequency and intensity of extremes of temperature and precipitation, melting of Arctic Sea ice and mountain glaciers, weakening of Atlantic meridional overturning circulation, changes in frequency and intensity of tropical cyclones, and decrease in soil moisture (IPCC AR6 WGI, Chapter 4 2021; Felgenhauer et al 2022)). • Reduce precipitation in some monsoon regions (IPCC AR6 WGI 2021). • Reduced tropospheric ozone in the mid and high latitudes (Felgenhauer et al 2022).

Benefits of potential SRM deployment	
Environment & Ecosystems	• Cooling caused by SRM would increase the global land and ocean CO_2 sinks (IPCC AR6 WGI 2021). • SAI would increase the fraction of diffuse sunlight, which is projected to increase photosynthesis in forested canopy (IPCC AR6 WGI 2021). • Reducing heat stress in low latitudes would increase plant productivity (Glienke et al. 2015; Duan et al. 2020) and reduce risk of heat stress to corals. • MCB may increase water availability over land in the tropical regions (Felgenhauer et al 2022).
Economic	• Direct economic cost of SAI itself is expected to be relatively low (Moriyama et al. 2017; Smith and Wagner 2018). Estimated at tens of billions of US dollars per year per 1°C of cooling. (about 20 billion USD per year per 1°C of cooling) (Smith, 2020, UNEP One Atmosphere 2023). • SAI that stabilises global temperature at its present-day level is projected to reduce income inequality between countries compared to the highest warming pathway (Harding et al. 2020).
Human & Social	• Health benefits of lower temperatures (includes decreased risk of malaria, heat strokes, etc.) • Roof albedo increase could potentially contribute to reducing urban heat-island effects (IPCC AR6 WGI 2021; Honegger et al 2018), improving quality of life in cities.
Security	• Counter-geoengineering[5] may promote international cooperation (Heyen 2018; Helwegen et al. 2019; Abatayo et al. 2020).
Others	• SAI may reduce high fire-risk weather in Australia, Europe and parts of the Americas, compared to global warming without SAI (Burton et al. 2018).

Source: Own elaboration based on: Abatayo et al. 2020; Burton et al. 2018; Duan et al. 2020; Felgenhauer et al 2022; Glienke et al. 2015; Harding et al. 2020; Helwegen et al. 2019; Heyen 2018; Honegger et al 2018; IPCC AR6 WGI 2021; Jones et al. 2018; MacMartin et al. 2018; Moriyama et al. 2017; Smith and Wagner 2018; Smith, 2020; Tilmes et al. 2020; UNEP One Atmosphere 2023.

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[5] Counter-geoengineering is described as the idea that a country might seek or threaten to counteract the cooling effect of solar geoengineering through technical means. It might either generate a radiative forcing counter to solar geoengineering or neutralize the geoengineering agent. (Parker et al 2018)

2. *Possible Risks*

Table 6: Risks of potential SRM deployment

Risks of potential SRM deployment	
Climate	• Introduces a 'mask' to the climate change problem by altering the Earth's radiation budget, rather than attempting to address the root cause of the problem, which is the increase in GHGs in the atmosphere (UNEP One Atmosphere 2023). • Effects only last as long as a deployment is maintained. The aerosols released by SRM deployments would persist in the stratosphere for 1–3 years for SAI. Tropospheric aerosols would persist for about ten days in the case of MCB. (UNEP One Atmosphere 2023). • Sudden and sustained termination would result in rapid warming, and abrupt changes to the water cycle (IPCC AR6 WGI 2021). It would increase risks for humans and ecosystems (UNEP One Atmosphere 2023). • Regional disparities in climate hazards (Felgenhauer et al 2022). • At the regional scale and seasonal timescale there could be considerable residual climate change and/or overcompensating change (IPCC AR6 WGIII 2022). • Regional precipitation changes (Felgenhauer et al 2022). • SAI may increase flood and drought risk in Europe compared to unmitigated warming (Jones et al. 2021). • SAI may cause potential delay in the ozone hole recovery, changes in surface ozone and UV radiation. SAI would potentially reduce average surface ozone concentration (Xia et al. 2017) mainly because of aerosol-induced reduction in stratospheric ozone in polar regions, resulting in reduced downward transport of ozone to the troposphere (Pitari et al. 2014; Tilmes et al. 2018).

Risks of potential SRM deployment	
Environment & Ecosystems	• Cooling would slow down the process of nitrogen mineralisation, which could decrease plant productivity (Glienke et al. 2015; Duan et al. 2020). • Sudden termination of SAI could place many thousands of species at risk of extinction because the resulting rapid warming would be too fast for species to adapt to the changing climate (Trisos et al. 2018; UNEP 2023). • Changes in land and ocean ecosystem productivity (IPCC AR6 WGIII 2022). • SRM approaches would not stop ocean acidification under continued anthropogenic emissions (IPCC AR6 WGI 2021, Chapter 5; UNEP 2023). • SAI cooling would reduce crop productivity at higher latitudes compared to a scenario without SRM by reducing the growing season length (Pongratz et al. 2012; Xia et al. 2014; Zhan et al. 2019). • SAI would reduce the direct and total available sunlight, which tends to reduce photosynthesis (IPCC AR6 WGIII 2022). • SAI could generate substantial impacts on large-scale biogeochemical cycles, with feedback to regional and global climate variability and change (Zarnetske et al. 2021). • SAI could cause acid rain if using sulphates (IPCC AR6 WGIII 2022). • Increased acid deposition in pristine areas in the high latitudes (Felgenhauer et al 2022). • Large-scale modification of land surfaces for GBAM may have strong trade-offs with biodiversity and other ecosystem services, including food security (Seneviratne et al. 2018). • GBAM and CCT, would alter photosynthesis and carbon uptake (IPCC AR6 WGIII 2022). • MCB may cause sea salt deposition over land. (Muri et al. 2015; Felgenhauer et al 2022) • MCB could cause changes in marine net primary productivity by reducing light availability in deployment regions, with important fishing regions off the west coast of South America showing both large increases and decreases in productivity (Partanen et al. 2016; Keller 2018).
Economic	• Economic risks associated with extreme weather events as an undesirable consequence of SRM deployment. • Costs could be widely underrated (Reynolds et al., 2016). • Might be planned or deployed in ways that maximise the benefits for wealthier populations while physical side-effects for poorer ones are not sufficiently considered (Honegger et al 2018).
Human & Social	• SAI using sulphate aerosols is projected to deplete the ozone layer, increasing mortality from skin cancer (IPCC AR6 WGIII 2022). • SAI could increase particulate matter, which would then contribute to increase mortality (IPCC AR6 WGIII 2022). • Changes in risk from infectious disease (e.g., mosquito-borne illnesses) or food security due to SRM influences on climate (Carlson et al. 2022). • Cooling in the tropics could redistribute malaria risk among developing countries, potentially increasing the number of people at risk of malaria (Carlson et al 2022). • Moral hazard of emissions abatement displacement (Felgenhauer et al 2022) and intentional climate modification.

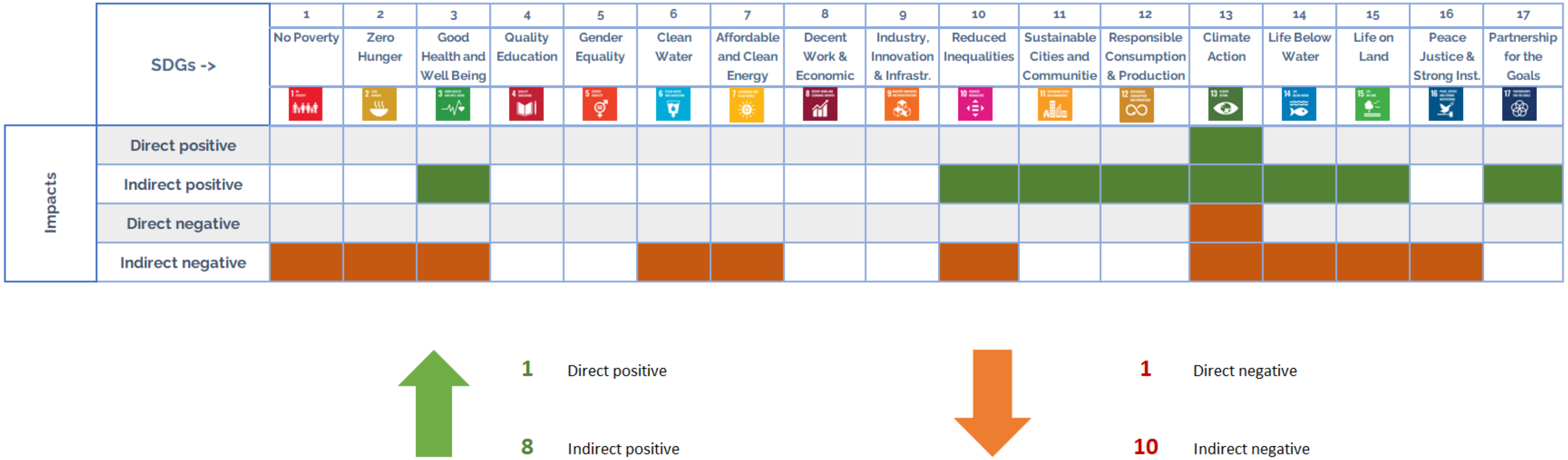
Risks of potential SRM deployment	
Security	• SRM may also introduce novel risks for international collaboration and peace. Conflicting temperature preferences between countries may lead to counter-geoengineering measures such as deliberate release of warming agents or destruction of deployment equipment (Parker et al. 2018). • SRM deployment could increase power imbalances between nations, spark conflicts and raise ethical, moral, legal, equity and justice issues. (UNEP One Atmosphere 2023). • Use of SRM could bring about an unknown political and social order, dividing states into climate interventionist and non-interventionist ones (Human Rights 2023).
Others	• SAI may generate changes to stratospheric dynamics and chemistry (IPCC AR6 WGIII 2022). • Potential interactions with a major volcanic eruption.

Source: Own elaboration based on: Carlson et al. 2022; Duan et al. 2020; Felgenhauer et al 2022; Glienke et al. 2015; Honegger et al 2018; Human Rights 2023; IPCC AR6 WGI 2021; IPCC AR6 WGIII 2022; IPCC AR6 WGIII 2022; Jones et al. 2021; Keller 2018; Muri et al. 2015; Parker et al. 2018; Partanen et al. 2016; Pitari et al. 2014; Pongratz et al. 2012; Reynolds et al., 2016; Seneviratne et al. 2018; Tilmes et al. 2018; Trisos et al. 2018; UNEP One Atmosphere 2023; Xia et al. 2014; Xia et al. 2017; Zarnetske et al. 2021; Zhan et al. 2019;

3. Impacts on SDGs from potential SRM deployment

The plausibility of SRM being deployed in a globally or regionally coordinated manner in the time window that is of primary relevance to the SDGs goals (pre-2030) appears rather limited (Honegger et al 2018). However, a potential large-scale deployment of SRM could have both positive and negative impacts on the United Nations Sustainable Development Goals (SDGs), being also valid and highly relevant for the post-2030 period. These impacts are also classified in this paper into direct and indirect sub-types.

Graph 11: Impact on the SDGs from SRM deployment



	SDGs ->	1 No Poverty	2 Zero Hunger	3 Good Health and Well Being	4 Quality Education	5 Gender Equality	6 Clean Water	7 Affordable and Clean Energy	8 Decent Work & Economic	9 Industry, Innovation & Infrastr.	10 Reduced Inequalities	11 Sustainable Cities and Communitie	12 Responsible Consumption & Production	13 Climate Action	14 Life Below Water	15 Life on Land	16 Peace Justice & Strong Inst.	17 Partnership for the Goals
Impacts	Direct positive													🟩				
	Indirect positive			🟩							🟩	🟩	🟩	🟩	🟩	🟩		🟩
	Direct negative													🟧				
	Indirect negative	🟧	🟧	🟧			🟧	🟧			🟧			🟧	🟧	🟧	🟧	

↑	1	Direct positive
	8	Indirect positive
↓	1	Direct negative
	10	Indirect negative

Source: Own elaboration based on Honegger et al 2018

a) SDG 13 Climate Action

The main direct positive impact of SRM deployment in Climate Action would be reducing global warming within years (UNEP 2023). There are also indirect positive impacts like reducing high fire-risk weather in some regions of the world (Burton et al. 2018).

On the other hand, an abrupt ending of the deployment of some SRM techniques resulting from governance failure, could also potentially drive very rapid temperature increases, known as 'termination shock'. A potential delay in ozone hole recovery is another relevant direct negative impact in Climate Action. The indirect negative impact is introducing an additional 'mask'[6] to the climate change problem while not addressing the root cause of increasing GHG emissions (IPCC AR6 WGI 2021).

b) SDG 14 Life Below Water and SDG 6 Clean Water

Reducing the heat stress in corals is an indirect positive impact of SRM deployment in SDG 14 Life Below Water. There are also indirect negative impacts like ocean acidification (IPCC AR6 WGI 2021, Chapter 5; UNEP 2023) (also affecting SDG 6 Clean Water) and changes in marine net primary productivity due to reduced sunlight availability.in deployment regions (Partanen et al. 2016; Keller 2018).

c) SDG 15 Life on Land and SDG 12 Responsible Consumption & Production and SDG 2 Zero Hunger

SAI deployment would generate indirect positive impacts in Life on Land as it is expected to increase the fraction of diffuse sunlight, and therefore increase photosynthesis in forested canopy. In addition, reducing the heat stress in low latitudes would increase plant productivity and crop yields. At the same time, the reduced direct and total available sunlight would tend to reduce photosynthesis. Cooling would also slow down the process of nitrogen mineralisation, which could decrease plant productivity (Glienke et al. 2015; Duan et al. 2020). All these benefits and risks generate implications for agricultural productivity and food security (Honegger et al 2018).

Another indirect negative impact would be the thousands of species at risk in case of a sudden termination of SRM deployment (Trisos et al. 2018; UNEP 2023).

d) SDG 10 Reduced Inequalities

Stabilizing global temperature is projected to reduce income inequalities between countries (indirect positive impact). On the other hand, a heterogeneous deployment of SRM would generate inequalities, most probably affecting low- and middle-income countries.

e) SDG 3 Good Health and Well Being

A potential SRM deployment would result in changes in risk from infectious disease (e.g., mosquito-borne illnesses) (IPCC AR6 WGIII 2022; Carlson et al 2022). Cooling in the tropics caused by SRM deployment could

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[6] IPCC AR6 WG1 (2021) SPM A.1.3 "…other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C…"

redistribute malaria risk among developing countries (indirect negative impact). On the other hand, lower temperatures could bring health benefits such as decreased risk of malaria, heat strokes, among others.

Another indirect negative impact would be increased mortality from skin cancer (IPCC AR6 WGIII 2022), given that SAI using sulphate aerosols is expected to deplete the ozone layer. In addition, SAI could increase particulate matter, which would increase mortality (IPCC AR6 WGIII 2022).

f) SDG 11 Sustainable Cities and Communities

Roof albedo increase could potentially contribute (indirect positive impact) to reducing urban heat-island effects and improving urban quality of life (IPCC AR6 WGI 2021; Honegger et al 2018).

g) SDG 16 Peace Justice & Strong Institutions and SDG 17 Partnership for the Goals

SRM deployment would introduce novel risks for international collaboration and peace, as conflicting temperature preferences between countries may lead to counter-geoengineering measures such as deliberate release of warming agents or destruction of deployment equipment. On the other hand, a potential SRM governance consensus would promote the partnership for the SDG goals, but also could reduce impetus and destroy existing partnerships toward SDGs.

h) Other indirect negative impacts

SRM deployment might have an indirect negative impact in SDG 1 No Poverty if it only maximises the benefits for wealthier populations while physical side-effects for poorer ones were not sufficiently considered (Honegger et al 2018).

In terms of SDG 7 Affordable and Clean Energy, in the case that precipitation is locally reduced by SRM deployment, hydropower yield could somewhat decrease (Honegger et al 2018).

B. “Risk-risk” analytical framework to support decision-making

As mentioned in previous chapters, a SRM deployment could offset some climate risks and reduce global warming, but it would also introduce a set of new climate, environmental, ecosystems, economic, human, social and security risks.

This risk-risk trade-off was first introduced by Graham and Wiener (1995) when proposing an analytical framework for identifying, understanding, and addressing the risk-risk phenomena. Under this framework, the risk that a policy aims to address is the target risk; and the additional risks that the application of the policy induces are countervailing risks, while the additional risks that the policy reduces are co-benefits. Therefore, it offers a more holistic approach to multiple risks in complex interconnected systems.

Felgenhauer et al (2022) explains that as a general principle, a good policy analysis should move from a narrow focus on a single target risk to a broader assessment of all important impacts, meaning the full portfolio or scope of important consequences that may arise from a decision (Graham and Wiener 1995; Dudley and Mannix 2018; Livermore and Revesz 2020; Wiener 2020; Fang and Xu 2013).

NASEM (2021) called explicitly for the use of a risk-risk analytical framework for evaluating SRM when stating that "risk-risk assessment (or risk trade-off analysis) provides a framework wherein the risks of one policy option are comparatively assessed in relation to the risks of others to identify options that maximize benefit. The relevant comparison would characterize the risk of climate change without [SRM] versus the risks of climate change with [SRM]—in both cases, looking across a range of greenhouse gas concentration pathway scenarios and including an array of other climate response actions".

UNEP (2023) also proposed that 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. However, it considers that there is insufficient information to make this risk-risk trade-off assessment with confidence for conceivable scenarios.

In 2022, C2G published a report in which it applied the risk-risk framework to SRM, comparing a world with SRM and a world without SRM in addressing climate change (Felgenhauer et al 2022). This applied risk-risk trade-off framework is intended to improve outcomes by helping analysts think beyond the direct costs and benefits associated with reducing the target risk alone. The general public and policymakers may encounter heuristics obstacles and biases that influence decision making regarding SRM implementation, and a risk-risk framework can help strengthen deliberation addressing the full portfolio of important impacts and help guide policies toward socially desirable outcomes informed by science. The consideration of the Pareto principle may provide an alternative approach to the understanding of the array of impacts to be contemplated.

The following table summarizes the risk-risk framework applied to SRM with focus in the key impacts in Latin American and the Caribbean region.

Table 7: Solar radiation modification within the risk vs. risk framework – Focus in LAC region

Risk-Risk framework applied to SRM	Impacts of adding SRM to mitigation and adaptation	
	Positive impacts	Negative impacts
Impact of SRM on Target Risk *(climate change impacts)*	**Climate benefits** • reduction in the frequency and intensity of extremes of temperature (e.g. reduced warning in La Plata basin (Camilloni et al. 2022). South and West of Brazil, Bolivia, Paraguay and East of Peru would suffer the greatest temperature changes in the world with increases of up to +7°C in a global warming scenario of +4°C • slowed melting of Antarctic Sea ice and mountain glaciers, and reduced loss of the Antarctic ice sheets slowing sea level rise • reduced weakening of the Atlantic meridional overturning circulation reduction in the intensity of tropical cyclones • reduced decline in soil moisture. (Central America, the Caribbean, the northern and eastern portion of South America and the south of Chile and Argentina would experience the largest drop in soil moisture in global warming scenarios) • slight reduction in atmospheric carbon dioxide concentrations	**Climate risks** • unintended climate changes (unintended warming or excessive cooling due to uncertainty in the estimates of the amount of SAI needed) • regional precipitation changes (e.g. increased precipitation in Central America and much of the Amazon (Gabriel et al. 2017), in northern portion of La Plata basin (Camilloni et al. 2022)) • MCB in the Pacific could produce persistent La Niña-like conditions and associated weather regimes (Hill and Ming 2012; Baughman et al. 2012).
Ancillary impacts of SRM *(non-climate change impacts)*	**Co-benefits** • reduced tropospheric ozone in high latitudes (Felgenhauer et al 2022). • increase in water availability over land in the tropical regions (MCB) (Felgenhauer et al 2022). • Fire danger would be reduced by SAI (Burton et al. 2018) • mitigate future coral bleaching throughout the Caribbean Sea (Zhang et al. 2018) • reduce the urban heat island effect in large LAC cities (GBAM) (IPCC AR6 WGI 2021; Honegger et al 2018).	**Countervailing risks** • increased acid deposition in pristine areas in the high latitudes (Felgenhauer et al 2022). • effects on stratospheric ozone. Antarctic ozone hole recovery could be delayed by 25– 50 years, and the hole could become deeper in the first ten years of SAI (Tilmes et al. 2020; Tilmes et al. 2021). • potential for international conflict and other societal risks • potential interactions with a major volcanic eruption • shock of sudden termination (UNEP 2023) • increase in salt deposition over land (MCB) (Muri et al. 2015; Felgenhauer et al 2022) • reduced crop yields*
	Positive or negative impacts • influence on motivation for emissions abatement policy or behaviour • light diffusion and dimming and its effects on human health, ecosystems, and agriculture • fishing regions off the west coast of South America showing both large increases and decreases in marine net primary productivity by reducing light availability (Partanen et al. 2016; Keller 2018) • effects on procedural and distributional justice, and other ethical concerns • changes in risk from infectious disease (e.g., mosquito-borne illnesses like malaria, dengue and Zika)	

** Note: Because of the divergence in results, the overall confidence in risk change for crop yields is low.*

Source: Adaptation from Felgenhauer et al (2022) "Solar Radiation Modification: A Risk-Risk Analysis"

Among its key insights Felgenhauer et al (2022) risk-risk report recommends that “new governance institutions or mechanisms may be needed to restrain harmful or unjust use of SRM, ensure that any deployment is beneficial and just, and assess and minimize any countervailing harms”.

V. SRM Governance dimensions[7]

A. International treaties and multilateral agreements and decisions relevant to SRM

Several international entities, protocols, treaties and multilateral agreements contain provisions applicable to SRM, partially covering the topic but none of them comprehensively (IPCC AR6 WGIII 2022; UNEP 2023; Geden, 2019), including the UN Convention on Biological Diversity, the UN Convention on the Law of the Sea, the Environmental Modification Convention (ENMOD), London Convention and London Protocol (LC/LP) and the Vienna Convention on the Protection of the Ozone Layer and its Montreal Protocol, UNESCO World Commission on the Ethics of Scientific Knowledge and Technology (COMEST), UN Convention on Environmental Impact Assessment in a Transboundary Context (UNECE), among the most relevant ones (Bodansky 2013; Jinnah and Nicholson 2019; Reynolds 2019; Geden, 2019).

More than four decades ago, the Environmental Modification Convention (ENMOD), signed in 1977, requested parties not to engage in "military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage or injury to another State party". Environmental modification techniques were defined as "any technique for changing – through the deliberate manipulation of natural processes – the dynamics, composition or structure of the earth, including its biota, lithosphere, hydrosphere and atmosphere, or of outer space".

The United Nations Convention on the Law of the Sea (UNCLOS), signed in 1982, encouraged states to "adopt laws and regulations to prevent, reduce and control pollution of the marine environment from or through the atmosphere". It explicitly refers to "the release of toxic, harmful or noxious substances, especially those which are persistent, from land-based sources, from or through the atmosphere".

The Montreal Protocol on Substances that Deplete the Ozone Layer is the landmark multilateral environmental agreement, signed in 1989, that regulates the production and consumption of nearly 100 man-made chemicals referred to as ozone depleting substances (UNEP 2022). The latest quadrennial assessment report published in 2022 by UN-backed Scientific Assessment Panel to the Montreal Protocol, examined the potential effects on ozone of the intentional addition of aerosols into the stratosphere. The panel cautions that unintended consequences of SAI "could also affect stratospheric temperatures, circulation and ozone production and destruction rates and transport" (World Meteorological Organization 2022).

The UN Convention on Environmental Impact Assessment in a Transboundary Context (UNECE 1991) called for parties to undertake environmental impact assessment, potentially including SRM activities (UNEP 2023).

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[7] Governances in this chapter refers to a process to guide decisions around research activities, including indoor research, small-scale outdoor experiments and SRM deployments. It would include norms, guidelines and codes of conduct (UNEP 2023).

The Convention on Biological Diversity (CBD) has sought to address and restrain geoengineering activities that may affect biodiversity in the past (CBD 2008, 2010, 2012, 2016):

- **COP 9 Decision IX/16 (2008)** "requests Parties and urges other Governments, in accordance with the precautionary approach, to ensure that *ocean fertilization activities* do not take place until there is an adequate scientific basis on which to justify such activities".
- **COP 10 Decision X/33 (2010)** extended the call from Decision IX/16 stating that "in the absence of science based, global, transparent and effective control and regulatory mechanisms for geo-engineering, and in accordance with the precautionary approach (…), that no *climate-related geo-engineering activities* that may affect biodiversity take place". However, the decision made an exception on "small scale scientific research studies that would be conducted in a controlled setting (…) and only if they are justified by the need to gather specific scientific data and are subject to a thorough prior assessment of the potential impacts on the environment".
- **COP 11 Decision XI/20 (2012)** reaffirmed the precautionary approach on decisions IX/16, IX30 and X/30, and stated that "there is no single geoengineering approach that currently meets basic criteria for effectiveness, safety and affordability, and that approaches may prove difficult to deploy or govern". In addition, it requested all CBD Parties to report, on a regular basis, on any geoengineering initiative.
- Further CBD's Recommendation XIX/7 (2015) and Decision XIII/14 (2016), reaffirmed decisions X/33 and XI/20.

CBD has also elaborated peer-reviewed technical reports on ocean fertilization (TS 45) and on the potential impacts of geoengineering on biodiversity and related regulatory matters (TS 66/2012 and its update TS 84/2016) (Williamson et al 2016).

In 2008 Parties to the London Convention and London Protocol (LC/LP) adopted a precautionary approach through resolution (LC-LP.1 2008), which stated that ocean fertilization activities fall within the purview of the LC/LP and that ocean fertilization activities other than legitimate scientific research should not be allowed (IMO 2022). Later in 2022, a statement (LC 44/LP 17) was adopted by the 44th Consultative Meeting of Contracting Parties to the London Convention and the 17th Meeting of Contracting Parties to the London Protocol, identifying the need to carefully evaluate marine geoengineering techniques, which may have potential for mitigating the effects of climate change but may have adverse impacts on the marine environment. These techniques include: i) enhancing ocean alkalinity, ii) the use of biomass for carbon sequestration such as macroalgae cultivation and artificial upwelling, and solar geoengineering techniques such as iii) marine cloud brightening and iv) deploying microbubbles/reflective particles/materials. In addition, it reaffirmed that past LC/LP resolutions on ocean fertilization and on marine geoengineering more broadly apply to all LC Contracting Parties (Geoengineering Monitor 2022; IMO 2022).

Another reference is the guidance prepared by the International Law Commission and adopted in 2021 by the UN General Assembly in Resolution 76/112 'Protection of the Atmosphere' (Guideline 7), which specifies that "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 (UNGA 2021; Felgenhauer et al 2022)).

In 2021, the Human Rights Council mandated its Advisory Committee to conduct a study on the impact of new technologies for climate protection on the enjoyment of human rights, to be released in its 54th session in August 2023. In its draft document A/HRC/AC/29/CRP.2, it states that "human rights approach should be also embedded in the process of building-up the governance framework that is urgently needed to tackle this global issue".

The UNESCO World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) is also exploring the ethical dimensions around SRM in relation to the application and interpretation of the UNESCO Declaration of Ethical Issues in Relation to Climate change (UNESCO 2022; C2G 2022). In its Conceptual Note SHS/COMEST-Ext12/2022/3, examines governance issues, including international law and the SDGs, before formulating ethical values and principles based on intercultural ethical dialogue, and policy recommendations for its Member States.

B. Status of the discussion and work on SRM governance

1. International level

There is a growing consensus that there are significant international governance gaps in relation to SRM approaches, being one of the key areas of future work considering the recommendations of a number of major documents recently disseminated on this field.

IPCC AR6 WGIII (2022) states that currently, there is no dedicated, formal international SRM governance regime in the different tiers or areas of competence: research, development, demonstration, or deployment. In the same direction, the US NASEM (2021) considers that there is currently no coordinated or systematic governance of solar geoengineering research.

According to IPCC AR6 SYR (2023), this lack of robust and formal SRM governance poses risks as an uncoordinated or poorly researched deployment by a limited number of states could create additional international tensions (Corry 2017; Lederer and Kreuter 2018). Several authors agree that unequal power relations could influence SRM research governance and have potential implications for policy (Winickoff et al. 2015; Frumhoff and Stephens 2018; Whyte 2018; Biermann and Möller 2019; McLaren and Corry 2021; NASEM 2021; Táíwò and Talati 2021).

In 2019, Switzerland and a group of countries including Burkina Faso, Federated States of Micronesia, Georgia, Liechtenstein, Mali, Mexico, Montenegro, Niger, Republic of Korea, and Senegal, proposed a draft resolution at the 4th United Nations Environment Assembly (UNEA) requesting that United Nations Environment Programme (UNEP) should lead an assessment of geoengineering technologies (including CDR and SRM). The proposal did not prosper as some parties (mainly United States, Saudi Arabia and Brazil) opposed introducing this new initiative through UNEA, arguing that it should instead be taken up by the UNFCCC (Chemnick, 2019).

Furthermore, the US NASEM (2021) mentions that governance and engagement efforts can benefit and help enable research by building trust, legitimacy, accountability, and social responsiveness. UNEP's expert panel concluded that a governance process would be valuable to guide decisions around research activities, including indoor research, small-scale outdoor experiments and SRM deployments (UNEP One Atmosphere, 2023).

Stilgoe (2015) and Nicholson et al. (2018) introduce the idea of a co-evolution of governance and SRM research, suggesting a range of governance principles summarized in:

- Guard against potential risks and harm.
- Enable appropriate research and development of scientific knowledge.
- Legitimise any future research or policymaking through active and informed public and expert community engagement.
- Ensure that SRM is considered only as a part of a broader, mitigation-centred portfolio of responses to climate change."

There are views that see SRM governance as a means of restriction while others as an enabler for research, decision making and deployment if applicable. At a midpoint other authors stress "the operationalization of the precautionary approach": preventing deployment until specific criteria regarding scientific consensus, impact assessments and governance issues are met (IPCC AR6 WGIII 2022; Tedsen and Homann 2013; Wieding et al. 2020).

There are also different opinions on the scope of governance in terms of SRM readiness stages. While Reynold (2019) affirm that governance should cover all interacting stages of research through to any potential, eventual deployment with rules, institutions, and norms, UNEP -in its One Atmosphere report from 2023- states that governance of SRM indoor research, small-scale outdoor experiments and large-scale operational deployment should be differentiated. The UNEP expert panel finds that: norms, guidelines, and voluntary codes of conduct for indoor research could help balance societal concerns with scientific inquiry; governance of small-scale outdoor experimentation could limit the potential of a 'slippery slope' from experimentation to large-scale deployment; and finally, governance of large-scale deployment would be valuable given the inherent risks (UNEP 2023).

In particular, for outdoor SRM atmospheric experiments, the US NASEM (2021) proposes that all these experiments should be subject to a permitting system, to be designed to encompass transboundary research and research performed by international research teams. It also defines that the specific elements of a permitting system would need to be developed by the entity that assumes responsibility for the permitting system.

At a higher level of abstraction and beyond SRM-specific governance, UNEP (2023) proposes a new broader framework for the governance of the stratosphere, that would address the changes that occur in the stratosphere from SAI experiments or deployment.

2. LAC region

Since 2016, a number of events aiming to raise awareness on SRM in Latin America and the Caribbean have taken place. In 2016, SRMGI (currently The DEGREES Initiative) and Brazil's National Institute for Space Research (INPE) hosted a Workshop on Science and Governance of Solar Radiation Management focused on Brazil. ECLAC and C2G have been working together to jointly host events on this subject in both regional and international fora. In July 2020, they worked with LEDS LAC on an "Introduction to SRM: Analysis of Potential Benefits and Risks in the Context of Latin America and the Caribbean". During the UN High-Level Political Forum in July 2022, they co-hosted a side event "Managing the risks of a global warming overshoot to safeguard sustainable development". In March 2023, C2G gave a presentation on SRM in a regional seminar "Latin America and the Caribbean: Visions for a better coexistence in low-carbon societies" organized by ECLAC, the Ibero-American Network of Climate Change Offices and Learning by Doing. And in May and July 2023, ECLAC and C2G organized "Managing the risks of lack of governance around solar radiation modification" during the Multi-stakeholder Forum on Science, Technology and Innovation for the SDGs (STI Forum) and "Risk-risk Analysis and Governance of Solar Radiation Modification to Safeguard Sustainable Development" (United Nations High-Level Political Forum).

In addition, C2G, the Inter-American Institute for Global Change Research (IAI) and The DEGREES Initiative co-organized the "Americas Conference on Solar Radiation Modification: Solar: Science, Governance and Implications for the Region" held in Jamaica in August 2022.

ECLAC and C2G have also published a report and performed webinars in the LAC region regarding the current understanding of the impact of Carbon Dioxide Removal approaches on the Sustainable Development Goals in Latin America and the Caribbean (Samaniego et al. 2021).

Regarding the Latin American and Caribbean region, the lack of international and national governance schemes is particularly relevant. In January 2023, the Government of Mexico, through inter-institutional coordination between the Ministry of Environment and Natural Resources (SEMARNAT) and the National Council of Science and Technology (CONACYT) announced their intention to ban solar geoengineering experimentation and large-scale deployments on Mexico's national territory (as stated in its Press Release 3/23). This decision was taken after news was made public of a small-scale commercial intervention of balloons filled with aerosols by a US-based start-up "Make Sunsets" in the state of Baja California Sur, without the consent of the Government of Mexico and the surrounding communities. CONACYT has informed that it will work with specialized experts to coordinate a rigorous review of existing scientific research. Since then, Make Sunsets has resumed its activities with the release in February 2023 of three balloons filled with sulphur (<10 grams) in Reno, Nevada, USA[8].

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[8] Make Sunsets blog post "3 Launches". Available from: https://makesunsets.com/blogs/news/3-launches

Section B – Potential options for next steps

After a review of recommendations on next steps delivered by the scientific community and the international agencies addressing the risks of and from overshoot with a particular focus on SRM, a list of potential options for next steps focused on Latin American and the Caribbean region considered key are listed below:

- Managing the risks posed by climate change primarily requires addressing its root causes: the increased concentration of greenhouse gases in the atmosphere, and the consequent impacts this is having on human systems and ecosystems in the LAC region. To address these root causes, **capacity-building efforts must primarily focus on increased and urgent action across the region to reduce atmospheric greenhouse gas emissions, and investment in adaptation and building resilience** to the climate change impacts that are already unavoidable.

- In addition to building capacity for increased mitigation and adaptation, recognizing the increasing risk of and from temperature overshoot, **consideration could also be given to strengthening regional understanding of potential 'emergency' options such as Solar Radiation Modification (SRM)** that are coming under increasing scrutiny internationally.

- **Strengthening regional capacity for, and delivery of scientific research into the potential impacts of climate overshoot scenarios, and of SRM technologies (if ever implemented) – on low- and middle-income countries** could help to address issues around ethics, equity and consent relating to SRM in decision-making and governance.

- **Ensuring decision-making and governance is informed by indigenous peoples and local communities' knowledge and those of other affected or underrepresented groups such as young people** could help to address issues around ethics, equity and consent relating to SRM.

- **Building capacity for greater transdisciplinary integration in research, linking physical, social, and ethical dimensions, and enabling robust public engagement** will help to address the complex and interacting uncertainties and knowledge gaps around SRM.

- **Building capacity for undertaking risk-risk assessments in climate policy analysis and decision-making concerning SRM could help enable a more comprehensive assessment, comparison, and management of risks** associated with climate change, emissions reductions, carbon removal, adaptation, and SRM itself. This could also help to address issues around ethics, equity and consent relating to SRM.

- **Continued study and quantifying of the potential impacts and risks of and from a likely temperature overshoot for the LAC region** during the next decades could provide important intelligence to inform decision-making and strengthen preparedness to better manage risks.

- **Monitoring the status of SRM-related research and knowledge in the region and internationally** could help to strengthen the regional evidence-base for decision-making and identify knowledge gaps to be addressed in future research.

- **Identifying SRM-related policy questions for researchers in the LAC region to address,** could help to ensure science-policy interactions that effectively target and address knowledge gaps important for the region.

- **Collaborating with international partners to downscale climate modelling data to strengthen regional climate and SRM impact analysis** could help to strengthen both regional and international understanding of potential SRM impacts.

- **Encouraging LAC region participation and collaboration within the international SRM scientific research community**, e.g. through discussion workshops; developing regional models and simulations, among others could help build relationships and networks to strengthen both regional and international understanding and capacity.

- **Enhancing qualitative and quantitative understanding of the risks to the LAC region - in terms of environment, ecosystems, health, social, security and other dimensions - posed by a potential implementation of SRM approaches in overshoot scenarios** could help to ensure decision-making domestically, regionally, and internationally aligned with regional priorities.

- **Explore the possible financial sources available to fund a comprehensive transdisciplinary research program to better understand the potential of SRM as an emergency option and consequent impacts in the LAC region.**

- **Strengthening regulatory capacity across the region to ensure any SRM scientific research undertaken in the region is considered and implemented in a responsible way, and in compliance with agreed regional and international governance processes and frameworks** will help to ensure knowledge gaps are addressed in a socially acceptable and responsible manner.

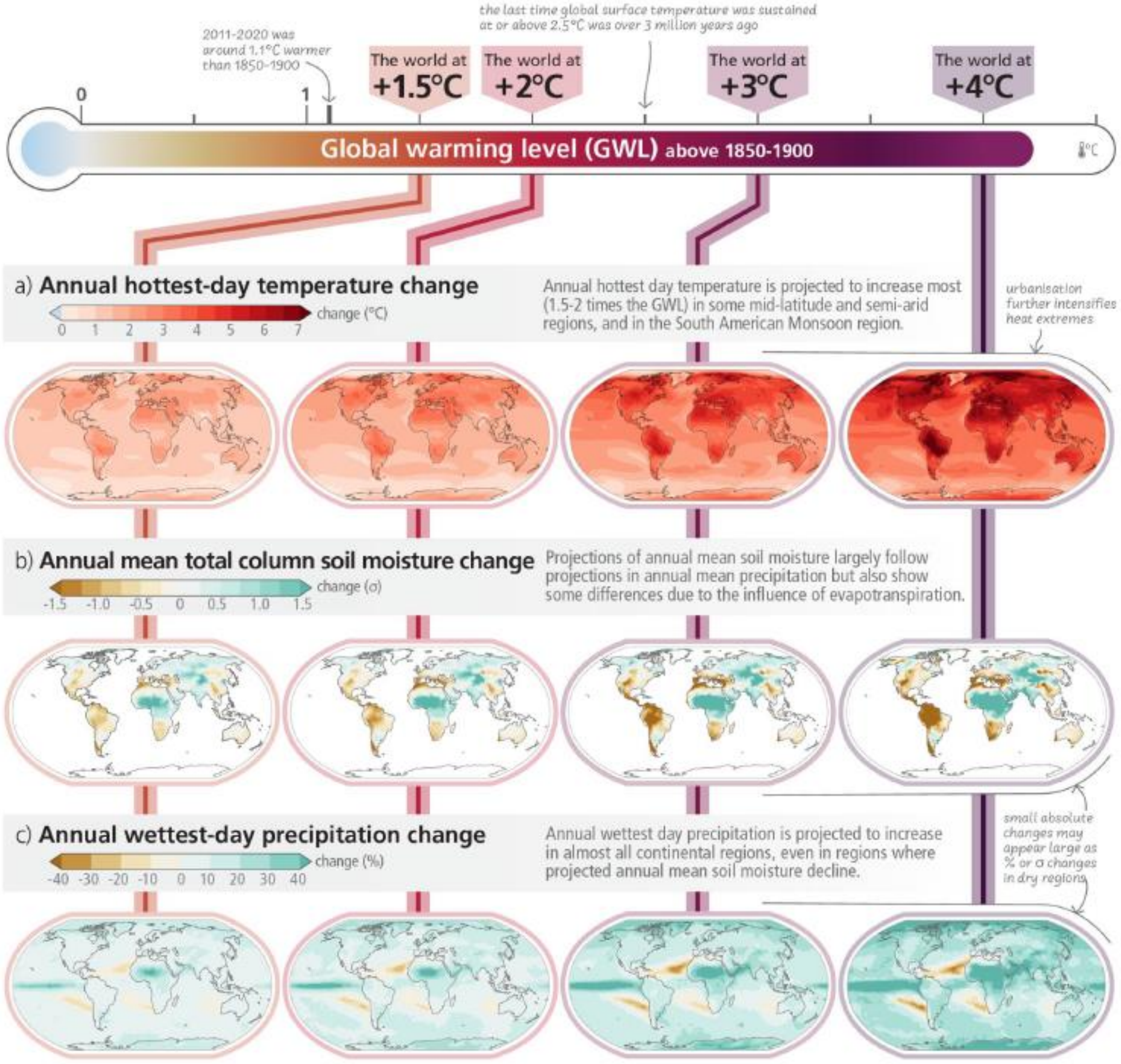
- **Identifying and assessing diverse proposals and options for international and regional governance processes around SRM that best consider LAC interests and circumstances,** and climate political stance will help to ensure that future governance is well aligned with regional priorities.

Section C - Annexes

A. Projected regional changes in key climate variables (IPCC AR6 SYR 2023)

IPCC AR6 SYR (2023) projects the effects of global warming levels (from +1.5°C to +4°C over 1850-1900 baseline) in key climate variables such as a) annual hottest-day temperature change, b) annual mean total column soil moisture change, c) annual wettest-day precipitation change, at a regional detail.

Graph 12: Projected regional changes in key climate variables at different global warming levels



2011-2020 was around 1.1°C warmer than 1850-1900

the last time global surface temperature was sustained at or above 2.5°C was over 3 million years ago

Annual hottest day temperature is projected to increase most (1.5-2 times the GWL) in some mid-latitude and semi-arid regions, and in the South American Monsoon region.

urbanisation further intensifies heat extremes

Projections of annual mean soil moisture largely follow projections in annual mean precipitation but also show some differences due to the influence of evapotranspiration.

Annual wettest day precipitation is projected to increase in almost all continental regions, even in regions where projected annual mean soil moisture decline.

small absolute changes may appear large as % or σ changes in dry regions

Source: IPCC AR6 SYR (2023) Figure3.1

In Latin America and the Caribbean region, the main impacts are estimated to be the following:

- **annual hottest-day temperature change:** South and West of Brazil, Bolivia, Paraguay, and East of Peru would suffer the greatest temperature changes in the world with increases of up to +7°C in a global warming scenario of +4°C.
- **annual mean total column soil moisture change**: Central America, the Caribbean, the northern and eastern portion of South America (including Venezuela, Colombia, Ecuador, Peru, and western Brazil) and the south of Chile and Argentina would experience the largest drop in soil moisture, while the Central portion of Argentina would show a moderate increase in soil moisture.
- **annual wettest-day precipitation changes**: the Pacific coast of northern Chile and southern Peru, as well as the Caribbean are expected to experience a significant drop in precipitations.

B. List of SRM outdoor experiments

The following table describes the main SRM experiments, either completed, announced/planned, or delayed/cancelled.

Table 8: Characterization of SRM outdoor experiments

Experiment	SRM approach	Entity	Country	Year	Scope	Status / Results
Stratospheric Aerosol Transport and Nucleation (SATAN)	SAI	European Astrotech	UK	2022	High-altitude weather balloon (15 miles) that released 400 grams of sulphur dioxide into the stratosphere	Completed Results not disclosed
Make Sunsets	SAI	Make Sunsets	US & Mexico (Baja California Sur)	2022-2023	Two high-altitude weather balloon that released a few grams of sulphur dioxide into the stratosphere. Altitude not confirmed.	Completed No instrumentation on board
Stratospheric Aerosol processes, Budget and Radiative Effects (SABRE)	SAI	National Oceanic and Atmospheric Administration	Alaska., US	2021-present	Conducting stratospheric flights, using balloons and more recently jets (WB-57 research aircraft). No material release is intended.	Test flights started in 2022 More research flights planned for 2024 and 2025
Stratospheric Controlled Perturbation Experiment (SCoPEx)	SAI	Harvard University	Sweden	2015-present	High-altitude balloon (20 km) fitted with repurposed airboat propellers to release up to 2kg of calcium carbonate to create a perturbed air mass roughly 1km long and 100m in diameter	Delayed. Outdoor Experimentation not started
Great Barrier Reef	MCB	Sydney Institute of Marine Science and Southern Cross University	Australia	2021	Cone-shaped turbine that blew a mist of seawater off the back of a repurposed ferry boat, 100km offshore	Completed. A separate vessel 5km away carrying atmospheric modelling equipment was able to detect the mist created by the prototype.
Marine Cloud Brightening Project	MCB	University of Washington	US	2018	Conduct limited sea area (small-scale) field experiments with the spray technology from ships to provide new understanding of the interactions between aerosols and clouds	Delayed. Outdoor Experimentation not started

Experiment	SRM approach	Entity	Country	Year	Scope	Status / Results
Artic Ice Project	OAC	Non-profit research organization + SINTEF	Not defined (Artic)	2013-present	Spread hollow silica microspheres (reflective sand 35 microns in diameter) on top of ice in the Arctic	No date confirmed. Outdoor Experimentation not started. Materials testing in lab.
Stratospheric Particle Injection for Climate Engineering (SPICE)	SAI	Several UK universities and Cambridge-based Marshall Aerospace	UK	2012	150 litres of water pumped into the atmosphere through a 1-kilometre hosepipe attached to a balloon	Cancelled amid patent application blocker
Field Studies Russia	SAI	Institute of Global Climate and Ecology, Roshydromet and Russian Academy of Sciences	Russia	2009	Tested aerosol formation in the lower troposphere using generators installed aboard helicopters. Altitude 2.5km.	Completed Published paper affirms that measured results are in satisfactory agreement with the results of theoretical and experimental studies in simulation chambers.

Source: UNEP 2023, Make Sunsets, SCoPEx, Artic Ice Project, NOAA

Bibliographical references

Abatayo, A.; Bosetti, V.; Casari, M.; Ghidoni, R. and Tavoni, M. (2020). Solar geoengineering may lead to excessive cooling and high strategic uncertainty. Proc. Natl. Acad. Sci., 117(24), 13393–13398, doi:10.1073/pnas.1916637117.

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

Akbari, A. (2005): Cool Colored Roofs to Save Energy and Improve Air Quality. Lawrence Berkeley National Laboratory http://aceee.org/proceedings-paper/ss04/panel01/paper01

Alchapar, Noelia; Correa, Erica and Cantón, María (2012). Solar reflectance index of façade coatings: mitigation potential of urban heat islands. Ambiente Construído. 12. 107-123. 10.1590/S1678-86212012000300008.

Alterskjær, K. and J.E. Kristjánsson (2013). The sign of the radiative forcing from marine cloud brightening depends on both particle size and injection amount. Geophysical Research Letters, 40(1), 210–215, doi:10.1029/2012gl054286.

Aquila, V., C.I. Garfinkel, P.A. Newman, L.D. Oman, and D.W. Waugh (2014). Modifications of the quasi-biennial oscillation by a geoengineering perturbation of the stratospheric aerosol layer. Geophysical Research Letters, 41(5), 1738–1744, doi:10.1002/2013gl058818

Aswathy, V. N., O. Boucher, M. Quaas, U. Niemeier, H. Muri, J. Mülmenstädt, and J. Quaas (2015). 'Climate extremes in multi-model simulations of stratospheric aerosol and marine cloud brightening climate engineering', Atmospheric Chemistry and Physics, 15: 9593-610, https://acp.copernicus.org/articles/15/9593/2015/

Baughman, E.; Gnanadesikan, A; Degaetano, A. and Adcroft, A. (2012). 'Investigation of the Surface and Circulation Impacts of Cloud-Brightening Geoengineering', Journal of Climate, 25: 7527-43. https://doi.org/10.1175/JCLI-D-11-00282.1

Biello, D. (2014). Cool Roofs Might Be Enough to Save Cities from Climate Overheating, in Scientific American, published: February 14, 2014, https://www.scientificamerican.com/article/cool-roofs-might-be-enough-to-save-cities-from-climateoverheating/.

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

Bingaman, D. C., Rice, C. V.; Smith, W. and Vogel, P. (2020). A Stratospheric Aerosol Injection Lofter Aircraft Concept: Brimstone Angel. Presented at AIAA Scitech 2020 Forum, Orlando, FL. Reston, VA: American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2020-0618

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

Buck, H., Geden, O., Sugiyama, M. and Corry, O. (2020). Pandemic politics—lessons for solar geoengineering. Communications Earth and Environment. 2020; 1,16. https://doi.org/10.1038/s43247-020-00018-1

Burton, C.; Betts, R. A.; Jones, C. D. and Williams, K. (2018). Will fire danger be reduced by using solar radiation management to limit global warming to 1.5°C compared to 2.0°C? Geophysical Research Letters, 2018 DOI: 10.1002/2018GL077848

Camilloni, I.; Montroull, N.; Gulizia, C.; Saurral, R.I (2022). La Plata Basin Hydroclimate Response to Solar Radiation Modification With Stratospheric Aerosol Injection. Front. Clim. 2022, 4, 763983. https://doi.org/10.3389/fclim.2022.763983

Carlson, C. J.; Colwell, R.; Hossain, M. S.; Rahman, M. M; Robock, A.; Ryan, S. J (2022). Solar geoengineering could redistribute malaria risk in developing countries. Nature Communications. 2022; 13: 2150. https://doi.org/10.1038/s41467-022-29613-w

Carnegie Climate Governance Initiative (C2G) (2022). Briefing note on Solar Radiation Modification. Available from: https://www.c2g2.net/wp-content/uploads/C2GBrief-SRM-Moral.pdf

Carnegie Climate Governance Initiative (C2G) (2023). Global status of activities relating to Solar Radiation Modification and its governance. https://www.c2g2.net/wp-content/uploads/20220210-C2G-Global-SRM-Activity-Update.pdf

CBD Secretariat (2012). Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters, Montreal, Technical Series No. 66, 152 pages. https://www.cbd.int/doc/publications/cbd-ts-66-en.pdf

CDB (2008). COP 9 Decision IX/16. Available from: https://www.cbd.int/decision/cop/?id=11659

CDB (2010). COP 10 Decision X/33. Available from: https://www.cbd.int/decision/cop/?id=12299

CDB (2012). COP 11 Decision XI/20. Available from: https://www.cbd.int/decision/cop/?id=13383

CDB (2016). Decision XIII/14. Available from: https://www.cbd.int/meetings/COP-13

Chemnick, J. (2019). U.S. blocks U.N. resolution on geoengineering. E&E News, March 15, 2019. https://www.scientificamerican.com/article/u-s-blocks-u-n-resolution-on-geoengineering/.

Chen, J.; Zhou, Z.; Wu, J.; Hou, S.; Liu, M. (2019). Field and Laboratory Measurement of Albedo and Heat Transfer for Pavement Materials. Constr. Build. Mater. 2019, 202, 46–57. https://doi.org/10.1016/j.conbuildmat.2019.01.028

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

Christensen MW; Gettelman A; Cermak J; Dagan G; Diamond M; Douglas A; Feingold G; Glassmeier F; Goren T; Grosvenor DP; Gryspeerdt E; Kahn R; Li Z; Ma PL; Malavelle F; McCoy IL; McCoy DT; McFarquhar G; Mülmenstädt J; Pal S; Possner A; Povey A; Quaas J; Rosenfeld D; Schmidt A; Schrödner R; Sorooshian A; Stier P; Toll V; Watson-Parris D; Wood R; Yang M and Yuan, T (2022). Opportunistic experiments to constrain aerosol effective radiative forcing. Atmos Chem Phys. 2022 Jan;22(1):641-674. doi: 10.5194/acp-22-641-2022. Epub 2022 Jan 17. PMID: 35136405; PMCID: PMC8819675.

Christensen, M. W. and Stephens, G. L (2011). Microphysical and macrophysical responses of marine stratocumulus polluted by underlying ships: Evidence of cloud deepening. Journal of Geophysical Research. 2011; 116: D03201. 30. https://doi.org/10.1029/2010JD014638

Chun, J.-Y., Wood, R., Blossey, P., and Doherty, S. J. (2023). Atmos. Chem. Microphysical, macrophysical and radiative responses of subtropical marine clouds to aerosol injections, Phys., 23, 1345–1368, https://doi.org/10.5194/acp-23-1345-2023, 2023.

Cooper, G., Foster, J., Galbraith, L., Jain, S., Neukermans, A., and Ormond, B. (2014). 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. https://doi.org/10.1098/rsta.2014.0055

Corey, G.; Robock, A.; Xia, L. and Zambri, B. (2016). The G4Foam Experiment: Global Climate Impacts of Regional Ocean Albedo Modification. 10.5194/acp-2016-849.

Corey, G.; Robock, A.; Xia, L.; Zambri, B. and Kravitz, B. (2017). The G4Foam Experiment: Global climate impacts of regional ocean albedo modification. Atmospheric Chemistry and Physics. 17. 595-613. 10.5194/acp-17-595-2017.

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

Crook, J. A., Jackson, L. S., Osprey, S. M., and Forster, P. M. (2015). A comparison of temperature and precipitation responses to different Earth radiation management geoengineering schemes. Journal of Geophysical Research: Atmospheres, 120(18), 9352–9373. doi:10.1002/2015jd023269.

Crook, J.A. and Forster, P. (2014). Comparison of surface albedo feedback in climate models and observations. Geophysical Research Letters. 41. doi:10.1002/2014GL059280.

Curry, C.L.; Sillmann, S.; Bronaugh, D.; Alterskjaer,K.; Cole, J. N. S.; Ji, D.; Kravitz, B.; Kristjánsson, J.; Moore, J.; Muri, H.; Niemeier, U.; Robock, A.; Tilmes, S. and Yang, S. (2014). A multimodel examination of climate extremes in an idealized geoengineering experiment. Journal of Geophysical Research: Atmospheres, 119(7), 3900–3923, doi:10.1002/2013jd020648.

Cvijanovic, I., Caldeira, K. and MacMartin, D. G. (2015) Impacts of ocean albedo alteration on Arctic sea ice restoration and Northern Hemisphere climate. Environmental Research Letters. 2015; 10: 44020. doi:10.1088/1748-9326/10/4/044020

Dai, Z., Weisenstein, D.K. and Keith, D.W. (2018). Tailoring Meridional and Seasonal Radiative Forcing by Sulfate Aerosol Solar Geoengineering. Geophysical Research Letters, 45(2), 1030–1039, doi:10.1002/2017gl076472.

de Abreu LP, Gonçalves WA, Mattos EV, Mutti PR, Rodrigues DT, da Silva MPA (2021). Clouds' Microphysical Properties and Their Relationship with Lightning Activity in Northeast Brazil. Remote Sensing. 2021; 13(21):4491. https://doi.org/10.3390/rs13214491.

De la Garza, A. (2023). A Controversial Technology Is Creating an Unprecedented Rift Among Climate Scientists. March 2023 – TIME - https://time.com/6264143/geoengineering-climate-scientists-divided/.

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

Diamond, M. S.; Director, H. M.; Eastman, R. ; Possner A. and Wood, R. (2020). Cloud Brightening from Shipping in Subtropical Low Clouds. Diamond, Substantial. AGU Advances, 1, e2019AV000111. https://doi-org.offcampus.lib.washington.edu/10.1029/2019AV000111 [AGU Advances Editor Highlight].

Duan, L., L. Cao, G. Bala, and Caldeira, K. (2020). A Model-Based Investigation of Terrestrial Plant Carbon Uptake Response to Four Radiation Modification Approaches. J. Geophys. Res. Atmos., 125(9), e2019jd031883,doi:10.1029/2019jd031883.

Dudley, S.E., and Mannix, B.F. (2018). 'Improving Regulatory Benefit-Cost Analysis', Journal of Law & Politics, XXXIV: 1-20. https://www.lawandpolitics.org/hifi/files/content/JLP_Vol.34.1.pdf

EEAP (2019). Environmental Effects and Interactions of Stratospheric Ozone Depletion, UV Radiation, and Climate Change. 2018 Assessment Report. Nairobi: Environmental Effects Assessment Panel, United Nations Environment Programme (UNEP) 390 pp. https://ozone.unep.org/science/assessment/eeap.

ETC Group and Heinrich Böll Foundation (2020) Geoengineering Map, https://map.geoengineeringmonitor.org; Field,et al. (2018) Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering, in Earth's Future, Vol. 6(6):882 - 901, https://doi.org/10.1029/2018EF000820; Jay (2019) Arctic Geoengineering Experiment Is Dangerous, LacksCommunity Consent: Inupiaq Organizer, in Geoengineering Monitor, published: February 14, 2019, http://www.geoengineeringmonitor.org/2019/02/arctic-geoengineering-experiment-is-dangerous-lackscommunity-consent-inupiaq-organizer/

Evans, J.R.G; Stride, ., E.P.J.; Edirisinghe, M.J.; Andrews, D.J. and Simons, R.R. (2010). Can oceanic foams limit global warming? Clim. Res., 42(2), 155–160, doi:10.3354/cr00885.

Fang, B, and Xu, J. (2013). 'Introducing a Risk-Risk Tradeoff Analysis into the Policy-making Process', China Public Administration Review, 14: 9-25.

Felgenhauer, T., Bala, G., Borsuk, M., Brune, M., Camilloni, I., Wiener, J.B., Xu, J. (2022). Solar Radiation Modification: A Risk-Risk Analysis, Carnegie Climate Governance Initiative (C2G), March, New York, NY: https://www.c2g2.net/wp-content/uploads/202203-C2G-RR-Full.pdf

Ferraro, A.J., Highwood, E.J. and Charlton-Perez, A.J. (2011). Stratospheric heating by potential geoengineering aerosols. Geophysical Research Letters, 38(24), 1–6, doi:10.1029/2011gl049761.

Field, L.; Ivanova, D.; Bhattacharyya, S.; Mlaker, V.; Sholtz, A.; Decca, R.; Manzara, A.; Johnson, D.; Christodoulou, E.; Walter, P.; and Katuri, K.. (2018). Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering. Earth's Future. 6. 10.1029/2018EF000820.

Flanner, M.; Arnheim, J.; Cook, J.; Dang, C.; He, C.; Huang, X.; Singh, D.; Skiles, M.; Whicker, C. and Zender, C. (2021). SNICAR-AD v3: A Community Tool for Modeling Spectral Snow Albedo. doi:10.5194/gmd-2021-182.

Frumhoff P.C. and Stephens J.C. (2018). Towards legitimacy of the solar geoengineering research enterprise. Philosophical Transactions of the Royal Society. A 376. https://doi.org/10.1098/rsta.2016.0459

Garreaud, R.; Rutllant, J.; Muñoz, R.; Rahn, D.; Ramos, M. and Figueroa, D. (2010). VOCALS-CUpEx: the Chilean upwelling experiment. Atmospheric Chemistry and Physics Discussions. 11. 10.5194/acp-11-2015-2011.

Gasparini, B. and Lohmann, U. (2016). Why cirrus cloud seeding cannot substantially cool the planet. Journal of Geophysical Research: Atmospheres, 121(9), 4877–4893, doi:10.1002/2015jd024666.

Gasparini, B., McGraw, Z.; Storelvmo, T. and Lohmann, U. (2020). To what extent can cirrus cloud seeding counteract global warming? Environmental Research Letters, 15(5), 54002, doi:10.1088/1748-9326/ab71a3.

Geden, O. and Droege, S. (2019) The Anticipatory Governance of Solar Radiation Management. Council on Foreign Relations. https://www.cfr.org/report/anticipatory-governance-solar-radiation-management

Gertler, C. G., O'Gorman, P. A., Kravitz, B., Moore, J. C., Phipps, S. J., & Watanabe, S. (2020). Weakening of the Extratropical Storm Tracks in Solar Geoengineering Scenarios. Geophysical Research Letters, 47(11), e2020GL087348, doi:10.1029/2020gl087348.

Glienke, S., Irvine, P. J. and Lawrence, M. G. (2015). The impact of geoengineering on vegetation in experiment G1 of the GeoMIP. Journal of Geophysical Research: Atmospheres 120(19):10196-110213. https://doi.org/10.1002/2015jd024202.

Graham, D., and Baert Wiener, J. (1995). 'Confronting Risk Tradeoffs.' in John D. Graham and Jonathan Baert Wiener (eds.), Risk vs. Risk: Tradeoffs in Protecting Health and the Environment (Harvard University Press: Cambridge, MA). https://www.hup.harvard.edu/catalog.php?isbn=9780674773073

Gruber, S.; Blahak, U.; Haenel, F.; Kottmeier, C.; Leisner, T.; Muskatel, H.; Storelvmo, T.; Vogel, B. (2019). A Process Study on Thinning of Arctic Winter Cirrus Clouds With High-Resolution ICON-ART Simulations. Journal of Geophysical Research: Atmospheres. 124. 10.1029/2018JD029815.

Gryspeerdt, ESmith, T.W.P.; O'Keeffe, E.; Christensen, M.W. and Goldsworth, F.W. (2019). The Impact of Ship Emission Controls Recorded by Cloud Properties. Geophysical Research Letters, 46(21), 12547–12555, doi:10.1029/2019gl084700.

Guo, A., Moore, J. C., and Ji, D. (2018). Tropical atmospheric circulation response to the G1 sunshade geoengineering radiative forcing experiment, Atmos. Chem. Phys., 18, 8689–8706, https://doi.org/10.5194/acp-18-8689-2018.

Hao, D.; Bisht, G.; He, C.; Bair, E.; Huang, H.; Dang, C.; Rittger, K.; Gu, Y.; Wang, H.; Qian, Y. and Leung, L. (2022). Improving snow albedo modeling in E3SM land model (version 2.0) and assessing its impacts on snow and surface fluxes over the Tibetan Plateau. doi: 10.5194/gmd-2022-67.

Harding, A.R., Ricke, K.; Heyen, D.; MacMartin, D.G. and Moreno-Cruz, J. (2020). Climate econometric models indicate solar geoengineering would reduce inter-country income inequality. Nat. Commun., 11(1), 1–9, doi:10.1038/s41467-019-13957-x.

Helwegen, K.G., Wieners, C.E.; Frank, J.E.and Dijkstra, H.A. (2019). Complementing CO2 emission reduction by solar radiation management might strongly enhance future welfare. Earth Syst. Dyn., 10(3), 453–472, doi:10.5194/esd-10-453-2019.

Heutel, G.; Moreno-Cruz, J. and Shayegh, S. (2018). Solar geoengineering, uncertainty, and the price of carbon, Journal of Environmental Economics and Management, Elsevier, vol. 87(C), pages 24-41. https://doi.org/10.1016/j.jeem.2017.11.002

Heyen, D.l; Horton, J. and Moreno-Cruz, J. (2018). Strategic Implications of Counter-Geoengineering: Clash or Cooperation?, CESifo Working Paper, No. 7180, Center for Economic Studies and ifo Institute (CESifo), Munic https://doi.org/10.1016/j.jeem.2019.03.005

Hill, S. and Ming, Y. (2012). Nonlinear climate response to regional brightening of tropical marine stratocumulus. Geophysical Research Letters, 39(15), L15707, doi:10.1029/2012gl052064.

Honegger, M., Derwent, H., Harrison, N., Michaelowa, A., and Schäfer, S. (2018). Carbon Removal and Solar Geoengineering: Potential implications for delivery of the Sustainable Development Goals. Carnegie Climate Geoengineering Governance Initiative, May 2018, New York, U.S. https://www.c2g2.net/wp-content/uploads/C2G2-Geoeng-SDGs_20180521.pdf

Hong, Y., Liu, G. and Li, J.-L.F. (2016). Assessing the Radiative Effects of Global Ice Clouds Based on CloudSat and CALIPSO Measurements. Journal of Climate, 29(21), 7651–7674, doi:10.1175/jcli-d-15-0799.1.

IPCC (2014). Climate Change 2014: Adaptation Opportunities, Constraints, and Limits [Klein, R.J.T., G.F. Midgley, B.L. Preston, M. Alam, F.G.H. Berkhout, K. Dow, and M.R. Shaw, 2014: Adaptation opportunities, constraints, and limits. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 899-943. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap16_FINAL.pdf

IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

IPCC (2022). Strengthening and Implementing the Global Response. In Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty (pp. 313-444). Cambridge: Cambridge University Press. doi:10.1017/9781009157940.006 https://www.cambridge.org/core/books/global-warming-of-15c/strengthening-and-implementing-the-global-response/51C0BCDC8572D2705245720919BF03F5

IPCC (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Summary for Policymakers, Technical Summary and Frequently Asked Questions. Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33. doi:10.1017/9781009325844.001.

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. doi: 10.1017/9781009157926.

IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland,184 pp. doi: 10.59327/IPCC/AR6-9789291691647.

Irvine, P.; Kerry E.; He, J.; Horowitz, L.; Vecchi, G. and Keith, D. (2019). Halving warming with idealized solar geoengineering moderates key climate hazards. Nature Climate Change. doi: 10.1038/s41558-019-0398-8.

Izrael, Y.A., Zakharov, V.M. and Petrov, N.N. (2009). Field studies of a geo-engineering method of maintaining a modern climate with aerosol particles. Russ. Meteorol. Hydrol. 34, 635–638 (2009). https://doi.org/10.3103/S106837390910001X.

Janssens, M., de Vries, I. E. and Hulshoff, S. J. (2020). Steered stratospheric aerosol injection (Part 1): Aircraft and operation design. Climatic Change (Submitted). https://www.agu.org/fall-meeting

Jinnah, S., Nicholson, S. and Flegal, J. (2019). Toward legitimate governance of solar geoengineering research: A role for sub-state actors. Ethics, Policy and Environment. https://doi.org/10.1080/21550085.2018.1562526.

Jones, A., Hayward, J. and Boucher, O. (2009). Climate impacts of geoengineering marine stratocumulus clouds. J. Geophys. Res. 114, D10106. (doi:10.1029/2008JD011450).

Jones, A.; Haywood, J.; Jones, A.; Tilmes, S.; Kravitz, B. and Robocket, A. (2021). North Atlantic Oscillation response in GeoMIP experiments G6solar and G6sulfur: why detailed modelling is needed for understanding regional implications of solar radiation management. Atmospheric Chemistry and Physics, 21(2), 1287–1304, doi:10.5194/acp-21-1287-2021.

Jones, C.D.; Arora, V; Friedlingstein, P.; Bopp, L.; Brovkin, V.; Dunne, J.; Graven, H.; Hoffman, F.; Ilyina, T.; John, J.; Jung, M.; Kawamiya, M.; Koven, C.; Pongratz, J.; Raddatz, T.; Randerson, J. and Zaehle, S. (2016). C4MIP – The

Coupled Climate–Carbon Cycle Model Intercomparison Project: experimental protocol for CMIP6. Geoscientific Model Development, 9(8), 2853–2880, doi:10.5194/gmd-9-2853-2016.

Kala, J.; Hirsch, A.; Ziehn, T.; Perkins-Kirkpatrick, S.; De Kauwe, M. and Pitman, A. (2022). Corrigendum to: Assessing the potential for crop albedo enhancement in reducing heatwave frequency, duration, and intensity under future climate change. Weather and Climate Extremes. 36. 100428. 10.1016/j.wace.2022.100428.

Keith, D.W. (2010). Photophoretic levitation of engineered aerosols for geoengineering. Proceedings of the National Academy of Sciences, 107(38), 16428–16431, doi:10.1073/pnas.1009519107.

Keith, D.W., Weisenstein, D.K.; Dykema, J.A. and Keutsch, F.N. (2016). Stratospheric solar geoengineering without ozone loss. Proceedings of the National Academy of Sciences, 113(52), 14910–14914, doi:10.1073/pnas.1615572113.

Keller, D.P.; Lenton, A.; Scott, V.; Vaughan, N.; Bauer, N.; Ji, D; Jones, C.; Kravitz, B. Muri, H. and Zickfeld, K. (2018). The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6. Geoscientific Model Development, 11(3), 1133–1160, doi:10.5194/gmd-11-1133-2018.

Kingsley, E. and Symons, J. (2014). China and the blunt temptations of geo-engineering: The role of solar radiation management in China's strategic response to climate change. The Pacific Review. 27. 10.1080/09512748.2013.807865.

Kleinschmitt, C., Boucher, O. and Platt, U. (2018): Sensitivity of the radiative forcing by stratospheric sulfur geoengineering to the amount and strategy of the SO2 injection studied with the LMDZ-S3A model. Atmospheric Chemistry and Physics, 18(4), 2769–2786, doi:10.5194/acp-18-2769-2018.

Kousis, I. and Pisello, A. (2023). Evaluating the performance of cool pavements for urban heat island mitigation under realistic conditions: A systematic review and meta-analysis. Urban Climate. 49. 10.1016/j.uclim.2023.101470.

Kravitz, B., MacMartin, D. G. and Caldeira, K. (2012). Geoengineering: Whiter skies? Geophysical Research Letters 39(11). https://doi.org/10.1029/2012GL051652.

Kravitz, B., MacMartin, D. G., Visioni, D., Boucher, O., Cole, J. N. S., Haywood, J., Jones, A., Lurton, T., Nabat, P., Niemeier, U., Robock, A., Séférian, R., and Tilmes, S. (2021). Comparing different generations of idealized solar geoengineering simulations in the Geoengineering Model Intercomparison Project (GeoMIP), Atmos. Chem. Phys., 21, 4231–4247, https://doi.org/10.5194/acp-21-4231-2021, 2021.

Kravitz, B., Robock, A., Boucher, O., Schmidt, H., Taylor, K. E., Stenchikov, G., and Schulz, M. (2011). The geoengineering model intercomparison project (GeoMIP). Atmospheric Science Letters, 12(2), 162-167. https://doi.org/10.1002/asl.316

Kravitz, B.; Caldeira, K.; Boucher, O.; Robock, A.; Rasch, P.; Alterskjær, K.; Bou Karam, D.; Cole, J.; Curry, C.; Haywood, J.; Irvine, P.; Ji, D.; Jones, A.; Kristjánsson, J.; Lunt, D.; Moore, J.; Niemeier, U.; Schmidt, H.; Schulz, M.; Singh, B.; Tilmes, S.; Watanabe, S.; Yang, S. and Yoon, J. (2013): Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres, 118(15), 8320–8332, doi:10.1002/jgrd.50646.

Kravitz, B.; Caldeira, K.; Boucher, O.; Robock, A.; Rasch, P.; Alterskjær, K.; Bou Karam, D.; Cole, J.; Curry, C.; Haywood, J.; Irvine, P.; Ji, D.; Jones, A.; Kristjánsson, J.; Lunt, D.; Moore, J.; Niemeier, U.; Schmidt, H.; Schulz, M.; Singh, B.; Tilmes, S.; Watanabe, S.; Yang, S. and Yoon, J. (2017). First Simulations of Designing Stratospheric Sulfate Aerosol Geoengineering to Meet Multiple Simultaneous Climate Objectives. Journal of Geophysical Research: Atmospheres, 122(23), 12616–12634, doi:10.1002/2017jd026874.

Kravitz, B.; Rasch, P. ; Wang, H.; Robock, A.; Gabriel, C.; Boucher, O.; Cole, J.; Haywood, J.; Ji, D.; Jones, A.; Lenton, A.; Moore, J.; Muri, H.; Niemeier, U.; Phipps, S.; Schmidt, H.; Watanabe, S.; Yang, S.; Yoon, J. (2018). The climate effects of increasing ocean albedo: An idealized representation of solar geoengineering. Atmospheric Chemistry and Physics. 18. 13097-13113. 10.5194/acp-18-13097-2018.

Latham J., Bower K., Choularton T., Coe H., Connolly P., Cooper G., Craft T., Foster J., Gadian A., Galbraith L., Iacovides H., Johnston D., Launder B., Leslie B., Meyer J., Neukermans A., Ormond B., Parkes B., Rasch P. J., Rush J., Salter S., Stevenson T., Wang H., Wang Q., and Wood R. (2012) Marine Cloud Brightening. Phil Trans Roy. Soc. A, 2012, 370, 4217-4262, doi: 10.1098/rsta.2012.0086, 2012.

Latham, J. (1990). Control of global warming?. Nature 347, 339–340 (1990). https://doi.org/10.1038/347339b0.

Lederer, M. and Kreuter, J. (2018). Organising the unthinkable in times of crises: Will climate engineering become the weapon of last resort in the Anthropocene? Organization, 25(4), 472–490, doi:10.1177/1350508418759186.

Lee, W., MacMartin, D.; Visioni, D. and Kravitz, B. (2020). Expanding the design space of stratospheric aerosol geoengineering to include precipitation based objectives and explore trade-offs. Earth System Dynamics, 11(4), 1051–1072, doi:10.5194/esd-11-1051-2020.

Liu, J. andShi, X. (2021). Estimating the potential cooling effect of cirrus thinning achieved via the seeding approach. Atmospheric Chemistry and Physics. 21. 10609-10624. doi:10.5194/acp-21-10609-2021.

Livermore, M.A., and Revesz, R.L. (2020). Reviving Rationality: Saving Cost-Benefit Analysis for the Sake of the Environment and Our Health (Oxford University Press: New York, NY). London Convention/Protocol, 2010: Resolution LC-LP.2 on the assessment framework for scientific research involving ocean fertilization (14 October 2010). Document LC 32/15, Annex 5, 2 pp. https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/LCLPDocuments/LC-LP.2(2010).pdf

MacMartin, D. G., Ricke, K. L. and Keith, D. W. (2018). Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2018; 376, 20160454. https://doi.org/10.1098/rsta.2016.0454

MacMartin, D.G.; Kravitz, B.; Tilmes, S.; Richter, J.; Michael J. Mills, M.; Lamarque, J.F.; Tribbia, J. and Vitt, F. (2017). The Climate Response to Stratospheric Aerosol Geoengineering Can Be Tailored Using Multiple Injection Locations. Journal of Geophysical Research: Atmospheres, 122(23), 12574–12590, doi:10.1002/2017jd026868.

Madronich, S., Tilmes, S.; Kravitz, B.; MacMartin, D. G. and Richter, J. H. (2018). Response of surface ultraviolet and visible radiation to stratospheric SO2 injections. Atmosphere 9(11):432. https://doi.org/10.3390/atmos9110432

McClellan, J., Keith, D. W. and Apt, J. (2012). Cost analysis of stratospheric albedo modification delivery systems. Environmental Research Letters 7(3):034019. https://doi.org/10.1088/1748-9326/7/3/034019.

McLaren, D. and Corry, O. (2021). The politics and governance of research into solar geoengineering. WIREs Climate Change. 2021;12: e707. https://doi.org/10.1002/wcc.707

Mechoso, C. R.; Wood, R.; Weller, R.; Bretherton, C. S.; Clarke, A. D.; Coe, H.; Fairall, C.; Farrar, J. T. ; Feingold, G.; Garreaud, R.; Grados, C.; McWilliams, J. ; de Szoeke, S. P.; Yuter, S. E. and Zuidema, P. (2014). Ocean–Cloud–Atmosphere–Land Interactions in the Southeastern Pacific: The VOCALS Program. Bull. Amer. Meteor. Soc., 95, 357–375, https://doi.org/10.1175/BAMS-D-11-00246.1.

Mengying, Z.; Cao, L.; Lei, D.; Govindasamy, B. and Caldeira, K. (2021). Climate More Responsive to Marine Cloud Brightening Than Ocean Albedo Modification: A Model Study. Journal of Geophysical Research: Atmospheres. 126. 10.1029/2020JD033256.

Moore, K.D., Voss, K.J. and Gordon, H.R. (2000). Spectral reflectance of whitecaps: Their contribution to water-leaving radiance. Journal of Geophysical Research: Oceans, 105(C3), pp.6493-6499. https://doi.org/10.1029/1999JC900334

Moriyama, R., Sugiyama, M.; Kurosawa, A.; Masuda, K.; Tsuzuki, K. and Ishimoto, Y. (2017). The cost of stratospheric climate engineering revisited. Mitigation and Adaptation Strategies for Global Change 22(8):1207-1228. https://doi.org/10.1007/s11027-016-9723-y.

Muri, H., Niemeier, U. and Kristjánsson, J.E. (2015). Tropical rainforest response to marine sky brightening climate engineering. Geophys. Res. Lett., 42(8), 2951–2960, doi:10.1002/2015gl063363.

National Academies of Sciences, Engineering, and Medicine - NASEM (2021). Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. Washington, DC: The National Academies Press. https://doi.org/10.17226/25762.

Nicholson, S., Jinnah, S. and Gillespie, A. (2018). Solar radiation management: a proposal for immediate polycentric governance. Climate Policy 18(3):322-334. https://doi.org/10.1080/14693062.2017.1400944.

Niemeier, U. and Timmreck, C. (2015). What is the limit of climate engineering by stratospheric injection of SO2? Atmospheric Chemistry and Physics, 15(16), 9129–9141, doi:10.5194/acp-15-9129-2015

NOAA Research (2023). NOAA research in the stratosphere is taking off. https://research.noaa.gov/article/ArtMID/587/ArticleID/2945/NOAA-research-in-the-stratosphere-is-taking-off.

OSTP. (2023). Congressionally Mandated Research Plan and an Initial Research Governance Framework Related to Solar Radiation Modification. Office of Science and Technology Policy, Washington, DC, USA. https://www.whitehouse.gov/ostp/news-updates/2023/06/30/congressionally-mandated-report-on-solar-radiation-modification/

Parker, A. and Irvine, P. J. (2018). The Risk of Termination Shock from Solar Geoengineering. Earths Future. 2018; 6: 456–467. https://doi.org/10.1002/2017EF000735

Partanen, A.-I., Keller, D.P. Korhonen, H. and Matthews, H.D. (2016). Impacts of sea spray geoengineering on ocean biogeochemistry. Geophys. Res. Lett., 43(14), 7600–7608, doi:10.1002/2016gl070111.

Penner, J.E., Zhou, C. and Liu, X. (2015). Can cirrus cloud seeding be used for geoengineering? Geophysical Research Letters, 42(20), 8775–8782, doi:10.1002/2015gl065992.

Peres, L.; Andrews L.; Rotunno Filho, O; Franca, J. (2018). The urban heat island in Rio de Janeiro, Brazil, in the last 30 years using remote sensing data. International Journal of Applied Earth Observation and Geoinformation. 64. 104-116. 10.1016/j.jag.2017.08.012.

Pitari, G.; Aquila, V.; Kravitz, B.; Robock, A.; Watanabe, S.; Cionni, I.; De Luca, N.; Di Genova, G.; Mancini, E.; and Tilmes, S. (2014). Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres, 119(5), 2629–2653, doi:10.1002/2013jd020566.

Pongratz, J., Lobell, D.B.; Cao, L. and Caldeira, K. (2012). Crop yields in a geoengineered climate. Nat. Clim. Change, 2(2), 101–105, doi:10.1038/nclimate1373.

Pope, F., Braesicke, P., Grainger, R. et al (2012). Stratospheric aerosol particles and solar-radiation management. Nature Clim Change 2, 713–719 (2012). https://doi.org/10.1038/nclimate1528

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

Reynolds, J. L., Parker, A., and Irvine, P. (2016). Five solar geoengineering tropes that have outstayed their welcome. Earth's Future, 4(12), 562–568. https://doi.org/10.1002/2016EF000416

Richter, J. H., Visioni, D., MacMartin, D. G., Bailey, D. A., Rosenbloom, N., Dobbins, B., Lee, W. R., Tye, M., and Lamarque, J.-F.: (2022). Assessing Responses and Impacts of Solar climate intervention on the Earth system with stratospheric aerosol injection (ARISE-SAI): protocol and initial results from the first simulations, Geosci. Model Dev., 15, 8221–8243, https://doi.org/10.5194/gmd-15-8221-2022

Ridgwell, A.; Singarayer, J.; Hetherington, A. and Valdes, P. (2009). Tackling Regional Climate Change By Leaf Albedo Bio-geoengineering. Current biology : CB. 19. 146-50. 10.1016/j.cub.2008.12.025.

Robock, A. (2011). Bubble, bubble, toil and trouble. Climatic Change, 105(3-4), 383–385. doi:10.1007/s10584-010-0017-1.

Rossow, W.B., and Schiffer, R.A. (1999). Advances in understanding clouds from ISCCP. Bull. Amer. Meteorol. Soc., 80, 2261-2288, doi:10.1175/1520-0477(1999)080<2261:AIUCFI>2.0.CO;2.

Russell, L.; Sorooshian, A.; Seinfeld, J.; Albrecht, B.; Nenes, A.; Ahlm, L.; Chen, Y.; Coggon, M.; Craven, J.; Flagan, R.; Frossard, A.; Jung, E.; Lin, J.; Metcalf, A.; Modini, R.; Mülmenstädt, J.; Roberts, G.; Shingler, T.; Wonaschütz, A. (2013). Eastern Pacific Emitted Aerosol Cloud Experiment. Bulletin of the American Meteorological Society. 94. 709-729. 10.1175/BAMS-D-12-00015.1. https://www.jstor.org/stable/26219536

Rutllant, J. A., Muñoz, R. C., and Garreaud, R. D.(2013). Meteorological observations on the northern Chilean coast during VOCALS-REx, Atmos. Chem. Phys., 13, 3409–3422, https://doi.org/10.5194/acp-13-3409-2013

Salter S, Sortino G, Latham J. (2008). Sea-going hardware for the cloud albedo method of reversing global warming. Philos Trans A Math Phys Eng Sci. 2008 Nov 13;366(1882):3989-4006. DOI: 10.1098/rsta.2008.0136

Samaniego J., Alatorre, J. Van der Borght, R. and Ferrer, J. (2022). Panorama de las actualizaciones de las contribuciones determinadas a nivel nacional de cara a la COP 26, Documentos de Proyectos (LC/TS.2021/190), Santiago, Comisión Económica para América Latina y el Caribe (CEPAL), 2022. https://www.cepal.org/es/publicaciones/47733-panorama-actualizaciones-contribuciones-determinadas-nivel-nacional-cara-la-cop

Samaniego, Schmidt, Carlino and others (2021). "Current understanding of the potential impact of Carbon Dioxide Removal approaches on the SDGs in selected countries in Latin America and the Caribbean. Final Report", Carnegie Climate Governance Initative (C2G)/ Economic Commission for Latin America and the Caribbean (ECLAC), March 2021. https://repositorio.cepal.org/items/c7d03245-4747-427a-acb2-b23eb17daf4a

Secretaría de Medio Ambiente y Recursos Naturales de México (2023). Comunicado de prensa conjunto Núm. 3/23 " La experimentación con geoingeniería solar no será permitida en México" https://www.gob.mx/semarnat/prensa/la-experimentacion-con-geoingenieria-solar-no-sera-permitida-en-mexico

Seitz, R. (2011). Bright water: hydrosols, water conservation and climate change. Climatic Change, 105(3-4), pp.365-381. https://doi.org/10.1007/s10584-010-9965-8

Seneviratne, S. I., Phipps, S. J., Pitman, A. J., Hirsch, A. L., Davin, E. L., Donat, M. G. and others (2018). Land radiative management as contributor to regional-scale climate adaptation and mitigation. Nature Geoscience. 2018; 11: 88–96. https://doi.org/10.1038/s41561-017-0057-5

Singarayer, J.; Ridgwell, A. and Irvine, P. (2009). Assessing the benefits of crop albedo bio-geoengineering. Environmental Research Letters. 4. 045110. DOI 10.1088/1748-9326/4/4/045110

Smith, W. (2020). The cost of stratospheric aerosol injection through 2100, <i>Environmental Research Letters</i>, vol. 15, no. 11, 2020. doi:10.1088/1748-9326/aba7e7.

Smith, W. and Wagner, G. (2018). Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. Environmental Research Letters. 2018; 13. DOI 10.1088/1748-9326/aae98d

Smith, W.; Bhattarai, U.; Bingaman, D.; Mace, J. and Rice, C. (2022). Review of possible very high-altitude platforms for stratospheric aerosol injection. Environmental Research Communications. 4. 031002. doi:10.1088/2515-7620/ac4f5d.

Smith, W.; Bhattarai, U.; Macmartin, D.; Lee, W.; Visioni, D.; Kravitz, B. and Rice, C. (2022). A subpolar-focused stratospheric aerosol injection deployment scenario. Environmental Research Communications. 4. 095009. doi:10.1088/2515-7620/ac8cd3.

Stilgoe, J. (2015). Experiment Earth: Responsible Innovation in Geoengineering. New York: Routledge. https://www.routledge.com/Experiment-Earth-Responsible-innovation-in-geoengineering/Stilgoe/p/book/9781138691940

Stjern, C. W., Muri, H., Ahlm, L., Boucher, O., Cole, J. N. S., Ji, D., Jones, A., Haywood, J., Kravitz, B., Lenton, A., Moore, J. C., Niemeier, U., Phipps, S. J., Schmidt, H., Watanabe, S., and Kristjánsson, J. E. (218). Response to marine cloud brightening in a multi-model ensemble, Atmos. Chem. Phys., 18, 621–634, https://doi.org/10.5194/acp-18-621-2018

Táíwò, O.O. and Talati, S. (2021). Who Are the Engineers? Solar Geoengineering Research and Justice. Glob. Environ. Polit., 22(1), 1–7, doi:10.1162/glep_a_00620.

Tedsen, E. and Homann, G. (2013): Implementing the Precautionary Principle for Climate Engineering. Carbon Clim. Law Rev., 7(2), 90–100, doi:10.21552/cclr/2013/2/250.

The Degrees Initiative (2011). Philanthropy - Degrees Modelling Fund (formerly DECIMALS) https://www.degrees.ngo/aboutusold/early-days/#:~:text=The%20Degrees%20Initiative%20was%20launched,Academy%20of%20Sciences%20(TWAS).

The Royal Society (2009). Geoengineering the climate: Science, governance and uncertainty, ISBN:978-0-85403-773-5, https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2009/8693.pdf.

Tilmes, S. and other authors (2013). The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres, 118(19), 11036–11058, doi:10.1002/jgrd.50868.

Tilmes, S. and other authors (2017). Sensitivity of aerosol distribution and climate response to stratospheric SO2 injection locations. Journal of Geophysical Research: Atmospheres, 122(23), 12591–12615, doi:10.1002/2017jd026888.

Tilmes, S., MacMartin, D. G., Lenaerts, J. T. M., van Kampenhout, L., Muntjewerf, L., Xia, L. and other authors (2020). Reaching 1.5 and 2.0°C global surface temperature targets using stratospheric aerosol geoengineering. Earth System Dynamics. 2020; 11, 579–601. https://doi.org/10.5194/esd-11-579-2020

Tilmes, S., Richter, J. H., Kravitz, B., MacMartin, D. G., Glanville, A. S., Visioni, D. and other authors (2021). Sensitivity of Total Column Ozone to Stratospheric Sulfur Injection Strategies. Geophysical Research Letters. 2021; 48: 1–10. https://doi.org/10.1029/2021GL094058

Tilmes, S.; Richter, J.; Kravitz, B.; Macmartin, D.; Mills, M.; Simpson, I.; Glanville, A.; Fasullo, J.; Phillips, A.; Lamarque, J-F.; Tribbia, J.; Edwards, J.; Mickelson, S. and Gosh, S. (2018). CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project. Bulletin of the American Meteorological Society. 99. 10.1175/BAMS-D-17-0267.1. https://doi.org/10.1175/BAMS-D-17-0267.1

Tollefson J. (2021). Can artificially altered clouds save the Great Barrier Reef? Nature. 2021 Aug;596(7873):476-478. doi: 10.1038/d41586-021-02290-3. PMID: 34433949.

Torres Convers, D.; Soto Barragán, E.; Harvey, J. (2018). Mitigación del efecto isla calor mediante el color en los pavimentos. Colombia. http://repository.unipiloto.edu.co/handle/20.500.12277/5689

Trisos, C. H., Amatulli, G., Gurevitch, J., Robock, A., Xia, L. and Zambri, B. (2018). Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination. Nature Ecology and Evolution. 2018; 2: 475–482. https://doi.org/10.1038/s41559-017-0431-0

Tully, C.; Neubauer, D.; Omanovic, N. and Lohmann, U. (2022). Cirrus cloud thinning using a more physically-based ice microphysics scheme in the ECHAM-HAM GCM. https://doi.org/10.5194/acp-22-11455-2022

UNESCO (2021). World Commission on the Ethics of Scientific Knowledge and Technology (COMEST Concept note of COMEST on the ethics of climate engineering. Available from: https://unesdoc.unesco.org/ark:/48223/pf0000379991

United Nations Economic Commission for Europe (1991). Convention on Environmental Impact Assessment in a Transboundary Context. Available from: https://unece.org/fileadmin/DAM/env/eia/documents/legaltexts/Espoo_Convention_authentic_ENG.pdf

United Nations Environment Programme (2022). https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol

United Nations Environment Programme (2023). One Atmosphere: An independent expert review on Solar Radiation Modification research and deployment. Kenya, Nairobi. https://www.unep.org/resources/report/Solar-Radiation-Modification-research-deployment

United Nations Human Rights Council (2023). Impact of new technologies for climate protection on the enjoyment of human rights. https://www.ohchr.org/en/hr-bodies/hrc/advisory-committee/impact-of-new-technologies

Victor, D. (2019). Governing the deployment of geoengineering: Institutions, preparedness, and the problem of rogue actors. In Governance of the Deployment of Solar Geoengineering. R. N. Stavins and R. C. Stowe, eds. Cambridge, MA: Harvard Project on Climate Agreements. https://geoengineering.environment.harvard.edu/files/sgrp/files/harvard_project_sg_governance_briefs_volume_feb_2019.pdf

Villanueva, D.; Possner, A.; Neubauer, D. Gasparini, B.; Lohmann, U. and Tesche, M. (2022). Mixed-phase regime cloud thinning could help restore sea ice. Environmental Research Letters. 17. doi:10.1088/1748-9326/aca16d

Villena Del Carpio, J.; Marinoski, D.; Trichês, G.; Lamberts, R. and Melo, J. (2016). Urban pavements used in Brazil: Characterization of solar reflectance and temperature verification in the field. Solar Energy. 134. 72-81. https://doi.org/10.1016/j.solener.2016.04.044

Visioni, D. and other authors (2020). Seasonally Modulated Stratospheric Aerosol Geoengineering Alters the Climate Outcomes. Geophysical Research Letters, 47(12), e2020GL088337, doi:10.1029/2020gl088337.

Visioni, D.; Bednarz, E.; Lee, W.; Kravitz, B.; Jones, A.; Haywood, J. and Macmartin, D. (2023). Climate response to off-equatorial stratospheric sulfur injections in three Earth system models – Part 1: Experimental protocols and surface changes. Atmospheric Chemistry and Physics. 23. 663-685. doi: 10.5194/acp-23-663-2023.

Voosen, P (2023). Could solar geoengineering cool the planet? U.S. gets serious about finding out. Feb 2023 – Washington Post - https://www.washingtonpost.com/climate-environment/2023/02/27/geoengineering-security-war/.

Weisenstein, D., Keith, D. and Dykema, J. (2015). Solar geoengineering using solid aerosol in the stratosphere. Atmospheric Chemistry and Physics, 15, 11835–11859, doi:10.5194/acp-15-11835-2015.

Whyte, K. P. (2018). Indigeneity in geoengineering discourses: Some considerations. Ethics, Policy & Environment 21(3):289-307. https://doi.org/10.1080/21550085.2018.1562529

Wieding, J., Stubenrauch, J. and Ekardt, F. (2020). Human Rights and Precautionary Principle: Limits to Geoengineering, SRM, and IPCC Scenarios. Sustainability, 12(21), 8858, doi:10.3390/su12218858.

Wiener, J. B. (2015). Towards an effective system of monitoring, reporting, and verification. In Scott Barrett, Carlo Carraro and Jaime de Melo (eds.), Towards a Workable and Effective Climate Regime (Centre for Economic Policy Research (CEPR) Press and Fondation pour les études et recherches sur le développement international (Ferdi): London, UK and Clermont-Ferrand, France). https://cepr.org/publications/books-and-reports/towards-workable-and-effective-climate-regime

Williamson, P., and Bodle, R. (2016). Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework. Technical Series No.84. Secretariat of the Convention on Biological Diversity, Montreal, 158 pages. https://www.cbd.int/doc/publications/cbd-ts-84-en.pdf

Winickoff, D. E., Flegal, J. A. and Asrat, A. (2015). Engaging the Global South on climate engineering research. Nature Climate Change 5:627. https://doi.org/10.1038/nclimate2632

Wood, R., and Coauthors, (2011). The VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx): Goals, platforms, and field operations. Atmos. Chem. Phys., 11, 627–654. https://doi.org/10.5194/acp-11-627-2011

World Meteorological Organization (WMO) (2022). https://public.wmo.int/en/media/press-release/ozone-layer-recovery-track-helping-avoid-global-warming-05%C2%B0c

Xia, L., Nowack, P.J.; Tilmes, S. and Robock, A. (2017). Impacts of stratospheric sulfate geoengineering on tropospheric ozone. Atmospheric Chemistry and Physics, 17(19), 11913–11928, doi:10.5194/acp-17-11913-2017.

Xia, L., Robock, A.; Tilmes, S. and Neely III, R. R. (2016). Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate. Atmospheric Chemistry and Physics 16(3):1479-1489. https://doi.org/10.5194/acp-16-1479-2016

Xia, L.; Robock, A.; Cole, J.; Curry, C.; Ji, D.; Jones, A.; Kravitz, B.; Moore, J.; Muri, H.; Niemeier, U.; Singh, B.; Tilmes, S.; Watanabe, S. and Yoon, J. (2014). Solar Radiation Management Impacts on Agriculture in China: A Case Study in the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres. 119. doi:10.1002/2013JD020630.

Xu, X.; Swei, O.; Xu, L.; Schlosser, C.; Gregory, J. and Kirchain, R. (2020). Quantifying Location-Specific Impacts of Pavement Albedo on Radiative Forcing Using an Analytical Approach Environmental Science & Technology 2020 54 (4), 2411-2421 DOI: 10.1021/acs.est.9b04556

Yuan, J.; Farnham, C.; Emura, K. (2015). Development of a Retro-Reflective Material as Building Coating and Evaluation on Albedo of Urban Canyons and Building Heat Loads. Energy Build. 2015, 103, 107–117. https://doi.org/10.1016/j.enbuild.2015.06.055

Zarnetske, P. L., Gurevitch, J.; Franklin, J.; Groffman, P.; Harrison, C.; Hellmann, J.; Hoffman, F.; Kothari,S.; Robock, A.; Tilmes, S; Visioni, D.; Wu, J.; Xia, L. and Yang, C. (2021). Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth. Proceedings of the National Academy. doi:10.1073/pnas.1921854118

Zhang X, Jiao Z, Zhao C, Qu Y, Liu Q, Zhang H, Tong Y, Wang C, Li S, Guo J, Zhu Z, Yin S and Cui L (2022). Review of Land Surface Albedo: Variance Characteristics, Climate Effect and Management Strategy. Remote Sensing. 2022; 14(6):1382. https://doi.org/10.3390/rs14061382.

Zhang, J., Zhang, K.; Liu, J. and Ban-Weiss, G. (2016). Revisiting the climate impacts of cool roofs around the globe using an Earth system model. Environmental Research Letters, 11(8), 84014, doi:10.1088/1748-9326/11/8/084014.

Zhang, Y.; Kang, S.; Cong, Z.; Schmale, J.; Sprenger, M.; Li, C.; Yang, W.; Gao, T.; Sillanpää, M.; Li, X.; Liu, Y.; Chen, P. and Xuelei, Z. (2017). Light-absorbing impurities enhance glacier albedo reduction in the southeastern Tibetan plateau: Light-Absorbing Impurities in Snow. Journal of Geophysical Research: Atmospheres. 122. doi:10.1002/2016JD026397.

Zhang, Y.; Macmartin, D.; Visioni, D.; Bednarz, E. and Kravitz, B. (2023). Introducing a Comprehensive Set of Stratospheric Aerosol Injection Strategies. doi:10.5194/egusphere-2023-117.

Zhang, Z., Jones, A. and Crabbe, M.J.C. (2018). Impacts of stratospheric aerosol geoengineering strategy on Caribbean coral reefs, International Journal of Climate Change Strategies and Management, Vol. 10 No. 4, pp. 523-532. https://doi.org/10.1108/IJCCSM-05-2017-0104.

Zhu, Y,; Zhang, Z.; Crabbe, M. J.C. (2021). Extreme climate response to marine cloud brightening in the arid Sahara-Sahel-Arabian Peninsula zone. In International Journal of Climate Change Strategies and Management. doi:10.1108/IJCCSM-06-2020-0051.